SIP 106

GHG EMISSIONS INVENTORY FOR ASPHALT MIX PRODUCTION IN THE UNITED STATES

Current Industry Practices and Opportunities to Reduce Future Emissions

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ACKNOWLEDGMENTS

The authors would like to thank Heather Dylla for reviewing early drafts of this report and providing insightful comments. The authors also thank Mark Buncher, John Hickey, Tom Lorenz, Amlan Mukherjee, and Ron Sines for their time discussing the project approach, GHG emission reduction strategies, and data quality considerations.

Cover Photo: North Venice, FL, Asphalt Plant, courtesy Ajax Paving

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EXECUTIVE SUMMARY

The asphalt pavement production industry has set an ambitious goal of achieving net zero greenhouse gas (GHG) emissions associated with the production of asphalt pavements. To reach net zero carbon, the industry must understand, identify, and continue to reduce both the carbon intensity of materials used in, and energy consumption associated with, the production of asphalt pavement mixtures.

The focus of this report is to assess and document a cradle-to-gate emissions inventory for asphalt pavement mixtures for the years 2009-2019. The emissions inventory includes three primary life cycle stages:

- A1 – GHG emissions associated with upstream raw materials inputs like extraction and processing of asphalt binder, aggregate, and asphalt modifiers;
- A2 – GHG emissions associated with transportation of raw materials to the mix production facility; and
- A3 – GHG emissions associated with production of asphalt pavement mixtures at the asphalt plant, including upstream energy processes such as electricity production and transmission.

This report is the first national cradle-to-gate assessment of GHG emissions associated with the production of asphalt pavement mixtures focused on the A1-A3 life cycle stages. Unless indicated, GHG emission values identified in this report are cradle-to-gate and are intended to convey the types of processes that might be implemented to reduce GHG emissions. Although this report provides an estimate for the national average GHG emissions associated with asphalt mix production, it is not an industry average Environmental Product Declaration (EPD) and should not be used as a benchmark for project-level decision making during procurement or project delivery.

From 2009 to 2019, the average cradle-to-gate emission intensity ranged from 50.2 to 52.1 kg CO_2e /ton of mix produced. Based on annual asphalt mix production rates, total emissions ranged from 17.6 to 21.7 million metric tonne (MMT) CO_2e per year, with the greatest emissions occurring in 2019 due to that year's increased production rates relative to prior years. Cradle-to-gate emissions associated with asphalt mix production represented approximately 0.3% of total U.S. GHG emissions in 2019.

In 2019, industry's focus on environmentally sustainable practices during asphalt mix production, like increasing recycled materials and using lower-carbon fuels, reduced that year's total GHG emissions by 2.9 MMT CO_2e, equivalent to the annual emissions from approximately 630,000 passenger vehicles. Almost 90% of these avoided emissions were achieved through the use of reclaimed asphalt pavement (RAP). For example, each ton of RAP used in new asphalt mixtures reduced 2019 GHG emissions by approximately 27 kg CO_2e.

Nationwide, increasing the amount of RAP in new asphalt mixtures by one percentage point (e.g., from 21.1% to 22.1%) would result in 0.14 MMT CO_2e in avoided emissions, equivalent to the annual emissions from approximately 30,000 passenger vehicles.

Cradle-to-gate GHG emissions could be reduced by up to 24% relative to 2019 emissions by implementing certain environmentally preferable technologies and practices including:

- increased use of recycled materials;
- increased use of natural gas as a burner fuel;
- reduction of aggregate moisture content to further reduce burner fuel consumption;

- increased use of warm-mix asphalt (WMA) technologies to reduce asphalt mix production temperatures; and
- reduced electricity consumption through energy efficiency measures.

Achieving such GHG emissions reductions can be accelerated by revising agency specifications that currently limit the use of RAP and other recycled materials, and by offering economic incentives to offset the cost of capital improvements, low-carbon fuels, and reduced carbon intensity materials. Economic incentives may include tax credits, grants, rebates, and project-level incentives.

Even with widespread adoption of readily available technologies and practices, the 24% reduction in GHG emissions is not sufficient to achieve net zero GHG emissions. New technologies and additional innovative practices will need to be developed and implemented to achieve more significant GHG emission reductions. Potential long-term research and implementation strategies include the following:

- Materials-related emission reduction strategies
  - Implementation of carbon capture, utilization, and storage (CCUS) technologies during extraction of crude oils used for asphalt binder production
  - Development and use of carbon-sequestering bio-based binders and binder extenders
  - Development of carbon sequestering synthetic aggregates
- Transportation-related emission reduction strategies
  - Increased use of locally derived recycled materials in markets with limited local supplies of natural aggregates
  - Deployment of alternative fuels for trucking operations
- Mix production-related emission reduction strategies
  - Use of alternative energy sources
  - Technologies that reduce burner fuel consumption

1 INTRODUCTION

Asphalt pavements are the backbone of America's surface transportation infrastructure. With 94% of U.S. roads surfaced with asphalt (FHWA, 2020a), pavement engineers choose asphalt due to a combination of its engineering properties and cost effectiveness. A national goal to reduce greenhouse gas (GHG) emissions and achieve net zero by 2050 (Exec. Order No. 14008, 2021) has been set, thus it becomes critically important to understand the role of the asphalt pavement industry in reducing emissions. **This report compiles the first national inventory of GHG emissions for the U.S. asphalt pavement industry, explores the potential emission reductions that can be achieved through deployment of readily available technologies and practices, and identifies future research and implementation needs to further reduce GHG emissions.**

1.1 Asphalt Mixture Materials and Production

At the most basic level, asphalt mixtures are composed of approximately 93-96% aggregates and 4-7% asphalt binder. Asphalt binder is sometimes modified to enhance performance by adding small quantities of polymers such as styrene-butadiene-styrene (SBS) or recycled tire rubber (RTR), typically less than 10% by weight of asphalt binder, or less than 1% by weight of total mix. Asphalt mixtures are produced in asphalt plants, which use a rotary drum to dry the aggregates and heat them to approximately 300 °F. Asphalt plants can burn a variety of fuels, but the most common are natural gas, used oil, propane, and diesel fuel. The aggregates are then blended with asphalt binder and recycled materials (as described in the following paragraphs) to produce asphalt mixtures that are temporarily stored in silos.

Asphalt mixtures are transported to the paving jobsite by truck and placed while at elevated temperatures. Approximately 3,000 asphalt plants across the United States produced 421.9 million tons of asphalt mixture in 2019 (Williams et al., 2020).

Recycled materials are commonly used in asphalt mixtures to replace virgin aggregates, the asphalt binder, or both. Reclaimed asphalt pavement (RAP) is the most common recycled material, with asphalt mixtures containing an average RAP content of more than 21% of the mix by weight (Williams et al., 2020). Recycled asphalt shingles (RAS) are also used in certain markets, typically constituting 1-5% of the mix by weight in mixes that use RAS.

In accordance with FHWA's Recycled Materials Policy, recycled materials should get first consideration in material selection provided they are reviewed for engineering, environmental, and economic suitability (FHWA, 2015). Newcomb et al. (2016) provided an overview of the economic and environmental benefits of using RAP and RAS in asphalt mixtures. They found that avoided GHG emissions of up to 16% can be achieved for asphalt pavement materials and construction through use of RAP and RAS. Similarly, Williams et al. (2020) found that use of RAP avoided 2.4 million metric tonnes (MMT) of GHG emissions and yielded $3.3 billion in economic savings in 2019.

Polymers can increase the upstream GHG emissions associated with asphalt mixture production. For example, Mukherjee (2021) found that an asphalt mixture that uses asphalt binder modified with 3.5% SBS would increase cradle-to-gate GHG emissions by 9%. On the other hand, a more holistic cradle-to-grave assessment is needed to evaluate how the enhanced performance of polymer modified asphalt binders that yield thinner pavement sections or longer lasting roads can offset the increased upfront emissions and potentially reduce overall life cycle GHG emissions (Butt et al., 2012).

Warm-mix asphalt (WMA) technologies allow asphalt mixtures to be produced at reduced temperature, typically in the range of 25-50°F lower than conventional hot-mix asphalt (HMA), although temperature reductions as high as 90 °F have been documented (NASEM, 2014). WMA technologies are sometimes used as a compaction aid without reducing the mix production temperature. Williams et al. (2020) found that approximately 19% of asphalt mixtures produced in 2019 used WMA technologies to reduce the mix production temperature at least 10°F. (An additional 20% of asphalt mixtures produced in 2019 used WMA technologies as a compaction aid without reducing the mix production temperature.) They estimated that production of asphalt mixtures at reduced temperatures avoided GHG emissions of 0.05-0.21 MMT in 2019, depending on the actual temperature reduction achieved.

1.2 Goal and Scope

This study has two primary goals. The first is to estimate the total GHG emissions associated with the U.S. asphalt mix production industry. The second is to estimate the potential emission reductions that can be achieved by increased utilization of available practices and technologies. Under the life cycle framework provided in ISO 21930, the scope of this analysis focuses on cradle-to-gate emissions (Figure 1). This includes extraction and manufacturing of raw materials (A1), transporting those materials to the asphalt plant (A2), and plant operations (A3). This is the same scope reported in environmental product declarations (EPDs) for asphalt mixtures (NAPA, 2022). This study also includes an estimate of GHG emissions associated with end-of-life transport (C2).

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

Figure 1. Life Cycle Framework under ISO 21930. This study focuses on the cradle-to-gate life cycle stages (A1-A3) and end-of-life transport (C2).

While this study focuses on the cradle-to-gate emissions associated with asphalt mixture production, a holistic life cycle approach is required to fully understand the opportunities to reduce GHG emissions throughout the asphalt pavement value chain. Shacat et al. (2022) provide a detailed analysis of GHG emission sources and opportunities to reduce emissions throughout the asphalt pavement life cycle.

1.3. Methodology

A first-order estimate of the U.S. asphalt pavement industry's cradle-to-gate (A1-A3) GHG emissions inventory for the years 2009-2019 was calculated using the life cycle assessment (LCA) model developed by Mukherjee (2021). **This study is the first comprehensive assessment of GHG emissions associated with asphalt mix production at a national level.** The input dataset was assembled from a combination of publicly available datasets that were used to compile a representative average asphalt plant (fuel and electricity consumption), mix design (aggregates, asphalt binder, and recycled materials), and material transport distances for each ton of mix produced in the United States. GHG emissions for each life cycle stage were then calculated in the openLCA software platform using the LCA model developed by Mukherjee (2021). A summary of the assumptions, calculations, and data sources is provided in Appendix A. Data quality considerations are discussed in Appendix B.

The data inputs and methodology used for this study are generally consistent with the Product Category Rules (PCR) for Asphalt Mixtures (NAPA, 2022) and therefore provide a reasonable first-order national benchmark for GHG emissions reported in EPDs for asphalt mixtures. However, this study is not intended to be an industry average EPD and it does not meet the requirements for industry average EPDs. Deviations from the PCR are discussed in Appendix A.

The national average benchmark for cradle-to-gate GHG emissions associated with asphalt mixture production is intended to provide appropriate context to understand the impacts of policy changes and industry adoption of new technologies and practices at the national level. However, it is not appropriate for use as an agency- or project-level global warming potential (GWP) limit or benchmark. Factors such as aggregate transport distance, local availability of fuels, local availability of recycled materials, regional climatic conditions, agency specifications, and other variables can significantly affect cradle-to-gate GHG emissions. Agency- or project-level GWP limits or benchmarks should be established through a comprehensive program of collecting and analyzing EPDs developed by asphalt pavement material suppliers for the mix types specified by the agency to establish and account for regional and mix type-specific variability.

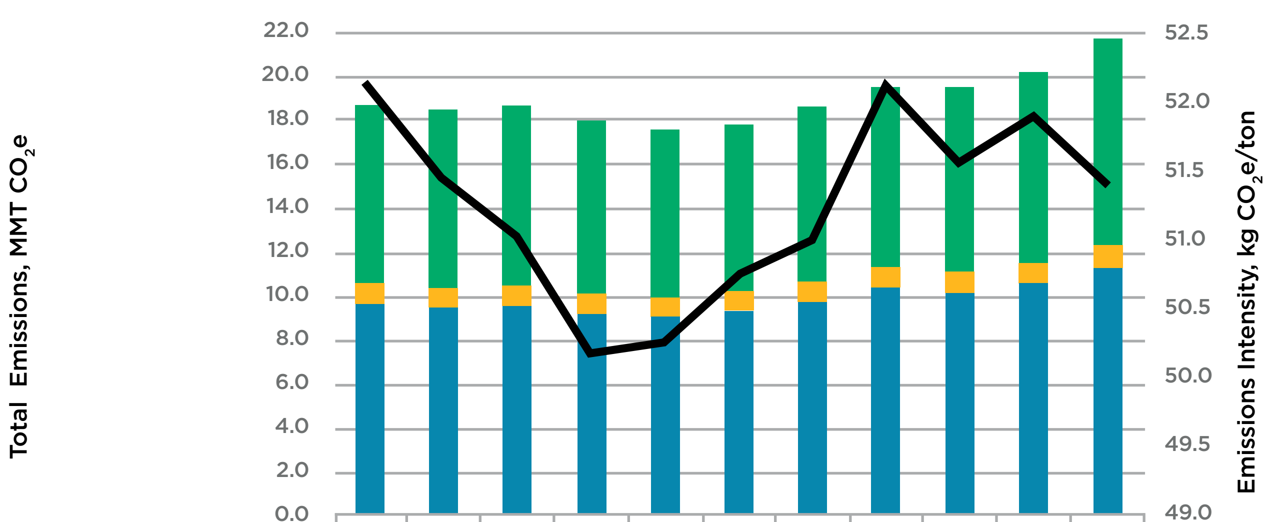
Aberdeen, WA, Asphalt Plant, courtesy Lakeside Industries

2 GHG EMISSIONS INVENTORY

Total cradle-to-gate (A1-A3) GHG emissions for U.S. asphalt mix production (MMT CO_2e) and emission intensity (kg CO_2e/ton of mix produced) are shown in Figure 2. Total cradle-to-gate emissions ranged from 17.6 to 21.7 MMT CO_2e per year. The dominant factors are emissions during the asphalt mix production stage (A3) and extraction and processing of raw materials (A1).

The average cradle-to-gate emission intensity ranged from 50.2 to 52.1 kg CO_2e/ton of mix produced. The lowest GHG emission intensity of 50.2 kg CO_2e/ton, which was observed in 2012 and 2013, coincided with the industry's highest percentage of natural gas consumption for energy as a fuel (Table A-4), as well as the lowest virgin asphalt binder content (Table A-2). The highest GHG emission intensity (52.1 kg CO_2e/ton) was observed in 2009 and 2016, with 2016 having the highest reported virgin asphalt binder content, despite the substantially increased RAP use in 2016 relative to 2009 (Table A-2). This demonstrates the importance of quantifying both RAP use and virgin asphalt binder use to calculate GHG emissions associated with asphalt mix production.

The cradle-to-gate emissions presented in Figure 2 do not include emissions associated with transporting RAP from the paving jobsite to the initial storage or processing location, which is considered an end-of-life process (C2) under ISO 21930 (Figure 1). An industry survey indicated that the average C2 transport distance for RAP is 33 miles (Shacat, 2022). Table 1 presents GHG emissions associated with end-of-life RAP transport (C2), which were calculated using an emission factor for truck transport of 0.1514 kg CO_2e/ton-mile per Mukherjee (2021).



	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Emissions (A1-A3)	18.7	18.5	18.7	18.1	17.6	17.9	18.6	19.5	19.5	20.2	21.7
Mix Production (A3)	8.1	8.1	8.2	8.0	7.7	7.7	8.0	8.2	8.4	8.6	9.4
Transportation (A2)	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	1.0	1.0
Materials (A1)	9.7	9.5	9.6	9.2	9.0	9.3	9.7	10.4	10.2	10.6	11.3
Emissions Intensity	52.1	51.4	51.0	50.2	50.2	50.7	51.0	52.1	51.5	51.9	51.4

Figure 2. Total cradle-to-gate (A1-A3) emissions and emission intensity for U.S. asphalt mix production, 2009-2019. The vertical scale of the secondary y-axis (Emissions Intensity) has a non-zero intercept to better illustrate the changes in emissions intensity over time.

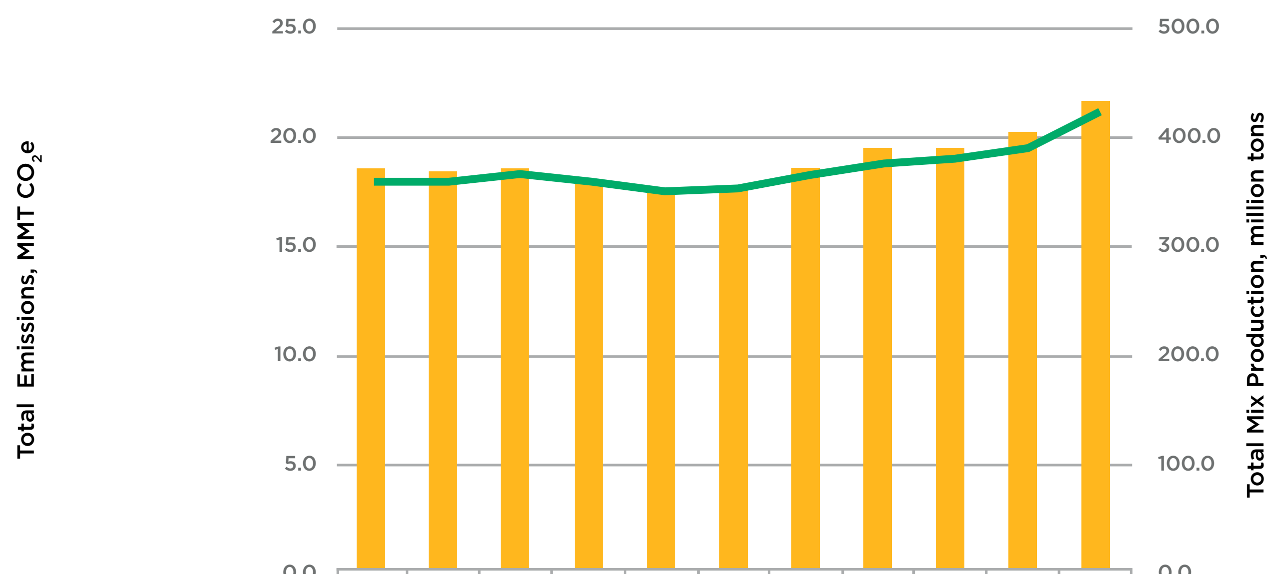
Table 1. GHG emissions associated with transporting RAP from paving jobsites to the initial stockpiling or processing location (C2).

Parameter	Units	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
RAP Accepted by Mix Producers[1]	million tons	67.2	73.5	79.1	71.3	76.1	75.8	78.0	81.8	79.9	101.1	97.0
GHG Emissions, End-of-Life RAP Transport (C2)	MMT CO_2e	0.3	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.5	0.5

[1] As reported in the IS-138 series of documents, estimates are based on RAP used in asphalt mixtures, as aggregate, as cold-mix asphalt, in other applications, and landfilled.

2.1 General Trends in GHG Emissions

The highest annual cradle-to-gate GHG emissions value was observed in 2019. This coincided with the greatest annual mix production tonnage during the period 2009-2019 (Figure 3). This shows that the emission reductions associated with increased use of RAP were not sufficient to offset the combined effects of decreased RAS utilization, decreased utilization of natural gas as a burner fuel, relatively high modified asphalt binder content, and increased annual mix production in 2019. (See Appendix A for annual data for these parameters.)



	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Total Emissions (A1-A3)	18.7	18.5	18.7	18.1	17.6	17.9	18.6	19.5	19.5	20.2	21.7
Total Mix Production	358.4	359.9	366.0	360.3	350.7	352.0	364.9	374.9	379.4	389.3	421.9

Figure 3. Total cradle-to-gate (A1-A3) GHG emissions and total mix production for the U.S. asphalt industry, 2009-2019.

2.2 Relative Contribution of Asphalt Mix Production to U.S. GHG Emissions

The U.S. GHG Emissions Inventory (U.S. EPA, 2021) provides a national context for understanding the relative contribution of asphalt mix production to U.S. GHG emissions. Table 2 presents total U.S. GHG emissions and emissions for key sectors (transportation, highway transportation, and industrial) that are relevant to the asphalt mix production industry along with the relative emissions from asphalt mix production. The cradle-to-gate emissions reported in this study include emissions from both the industrial sector and the transportation sector as defined in the U.S. GHG Emissions Inventory (U.S. EPA, 2021).

Cradle-to-gate (A1-A3) GHG emissions for asphalt mix production in the United States were approximately 21.7 MMT CO_2e in 2019. This represents 0.3% of the total U.S. GHG emissions inventory of 6,558.3 MMT CO_2e (Table 2) and 1.3% of industrial emissions.

While these may seem like small percentages, this does not mean that emissions associated with asphalt mix production are insignificant, since no single industry represents more than a few percent of total industrial emissions. For example, process-related emissions from iron and steel production and cement production (a material input for concrete) were 41.3 and 40.9 MMT CO_2e (respectively) in 2019 (also included in Table 2), roughly double the cradle-to-gate emissions for asphalt mix production (Table 2). The process-related emissions for iron and steel production and cement production (e.g., calcination from cement production) reported in Table 2 do not include emissions from fuel and electricity consumption and do not represent the complete cradle-to-gate life cycle stages. Thus, these values are intended to provide a contextual reference even though they have different scopes and are not directly comparable.

North Shore Asphalt Facility, courtesy Barriere Construction, A CRH Co.

Table 2. Comparison of 2019 cradle-to-gate (A1-A3) GHG emissions for asphalt mix production to the U.S. emissions inventory for related sectors.

Sector	2019 Emissions, MMT CO_2e	Percentage of U.S. Emissions from Each Sector, 2019	Percentage of Emissions for Sector from Asphalt Mix Production, Cradle-to-Gate
Total United States Emissions[1]	**6,558.3**		**0.3%**
Transportation Emissions from Fossil Fuel Combustion[2]	1,821.9	27.8%	1.2%
Highway Transportation Emissions from Fossil Fuel Combustion[4]	1,481.2	22.6%	1.5%
Industrial Emissions[3]	1,661.5	25.3%	1.3%
Iron and Steel Production and Metallurgical Coke Production, Process Emissions[5]	41.3	0.6%	
Cement Production, Process Emissions[6]	40.9	0.6%	
Asphalt Mix Production, Cradle-to-Gate[7]	21.7	0.3%	

[1] From U.S. EPA (2021), Table ES-2.

[2] From U.S. EPA (2021), Table ES-3.

[3] From U.S. EPA (2021), Tables ES-3 and ES-4.

[4] U.S. EPA (2021) indicates that 81.3% of the fossil fuel combustion emissions in the transportation sector reported in Table ES-3 was from cars and trucks.

[5] U.S. EPA (2021), Table ES-2. This value only includes process-related emissions (e.g., use of metallurgical coke) and does not include emissions associated with fuel or electricity consumption during iron, steel, and metallurgical coke production. This value also does not include upstream processes associated with raw material extraction or downstream processes associated with transportation and end product manufacturing.

[6] From U.S. EPA (2021), Table ES-2. This value only represents process-related emissions during cement production (viz., calcination). Calcination represents 60% of GHG emissions during cement production, and fuel combustion represents the remaining 40% of GHG emissions (PCA, 2011). This value does not include GHG emissions from fuel combustion during cement production. It also does not include upstream processes associated with raw material extraction or downstream processes associated with transportation and end product manufacturing.

[7] This value represents cradle-to-gate emissions (A1-A3) as defined by ISO 21930. It includes upstream processes associated with extraction and manufacturing of raw materials and downstream processes associated with transportation (i.e., transporting those materials to the asphalt plant), and end product manufacturing (i.e., plant operations).

Emissions from the transportation sector are included in Table 2 to provide additional context since asphalt pavements are a critical part of transportation infrastructure. Emissions associated with asphalt mix production are equal to 1.5% of emissions from highway transportation, which is consistent with Chappat and Bilal (2003), who found that vehicle emissions were 10 to 400 times greater than emissions associated with materials, construction, and maintenance of the roads they travel on. Similarly, Amarh et al. (2021) found that 98% of the life cycle GHG emissions for recycled asphalt pavement projects in Virginia were caused by vehicle fuel consumption during the use stage.

2.3 Avoided Emissions Associated with Current Industry Practices

The asphalt pavement industry has a long history of using recycled materials, such as RAP and RAS, and adopting other technologies and practices to reduce environmental impacts. Such practices include the choice of fuels consumed for asphalt mix production, stockpile management to reduce aggregate moisture content and reduce burner fuel consumption, adoption of WMA technologies, and electrical system upgrades such as variable frequency drives for high-powered motors. The dataset used in this analysis provides an opportunity to quantify the direct impact of two of these practices: use of recycled materials and the choice of fuels consumed for asphalt mix production.

Use of RAP and RAS

To assess avoided emissions from the asphalt pavement industry's use of RAP and RAS, a scenario was developed in which no RAP or RAS is used, and the average virgin binder content of asphalt mixtures increased by adding the estimated recycled binder content of RAP and RAS. Use of RAP and RAS yielded 3.0 MMT in avoided cradle-to-gate GHG emissions in 2019, compared to what the emissions would be if no RAP or RAS were used. Most of the avoided emissions (approximately 2.9 MMT CO_2e) were from use of RAP due to the relatively low quantities of RAS used in asphalt mixtures. Adding the emissions associated with end-of-life RAP transport (C2, see Table 1) reduces the avoided emissions associated with use of RAP to 2.4 MMT CO_2e. The benefits of avoided emissions from not sending RAP and RAS to a landfill are not accounted for in this estimate.

Each ton of RAP used in new asphalt mixtures in 2019 resulted in 27 kg CO_2e of avoided upstream emissions. Assuming a payload of 20 tons per truckload of RAP, approximately 1 metric tonne CO_2e of avoided emissions can be achieved for every two truckloads of RAP that are used in new asphalt mixtures.

Nationwide, increasing the amount of RAP in new asphalt mixtures by one percentage point (e.g., from 21.1% to 22.1%) would result in 0.14 MMT CO_2e in avoided emissions, equivalent to approximately 30,000 passenger vehicles assuming typical passenger vehicle emissions of 4.6 tonne CO_2e per year (U.S. EPA, 2018).

Fuel Consumption

The U.S. industrial sector consumption of natural gas represented 51.7% of total fossil fuel consumption in 2019 (EIA, 2021a). The blend of fuels consumed by the asphalt mix production industry is significantly cleaner, in part due to greater natural gas consumption (69%).

To assess the avoided emissions associated with the blend of fuels consumed by the asphalt mix production industry relative to the U.S. industrial sector as a whole, a scenario was developed in which the 2019 average relative consumption of natural gas was adjusted to 51.7% and the other fuels (diesel fuel, residual fuel oil, propane, and used oil) were adjusted according to their 2019 relative quantities. The output from this scenario indicates that the asphalt mix production industry's 2019 emissions would increase by 0.4 MMT CO_2e if the relative consumption of natural gas were comparable to the overall U.S industrial sector.

Overall Avoided Emissions from Current Industry Practices

Together, the use of recycled materials and the blend of fuels consumed during asphalt mix production resulted in avoided emissions of 3.4 MMT CO_2e in 2019 (Figure 4). Including the GHG emissions associated with end-of-life RAP transport (Table 1) reduces the avoided GHG emissions associated with industry practices to 2.9 MMT. Assuming that a typical passenger vehicle emits 4.6 tonne CO_2e per year (U.S. EPA, 2018), the avoided emissions of 2.9 MMT CO_2e from the industry's use of recycled materials and the blend of fuels consumed relative to the U.S. industrial sector are equivalent to the annual emissions of approximately 630,000 passenger vehicles.

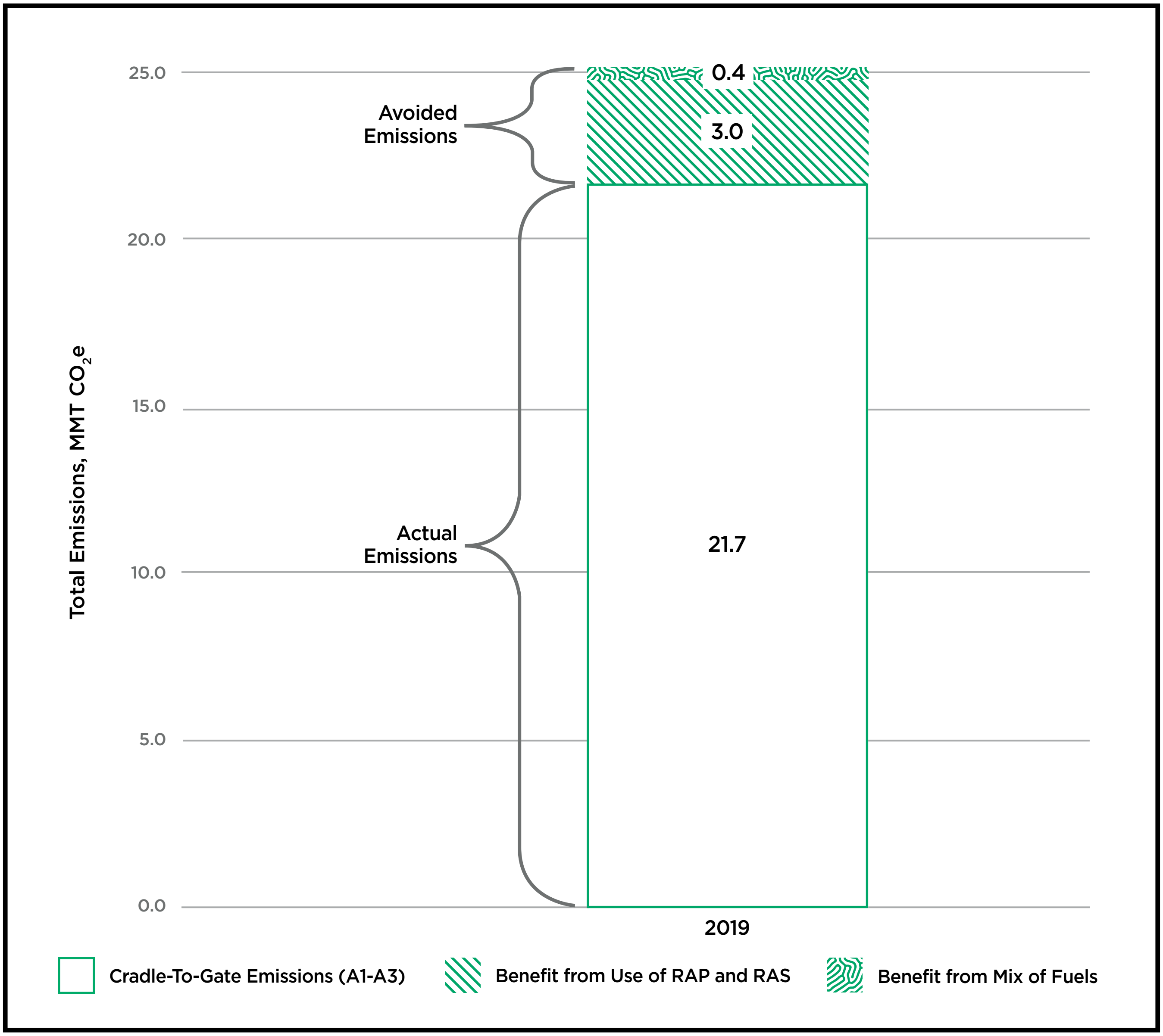


Figure 4. Cradle-to-Gate (A1-A3) GHG emissions and avoided emissions achieved through use of recycled materials and type of fuel consumed at asphalt plants in 2019.

Gillette, WY, Asphalt Plant, courtesy Simon, a Colas Co.

3 POTENTIAL EMISSION REDUCTIONS FROM DEPLOYMENT OF AVAILABLE TECHNOLOGIES AND PRACTICES

Technologies and practices already exist that asphalt mix producers can use to help the United States meet its goal of achieving net zero GHG emissions in all sectors by 2050. To this end, a scenario analysis was conducted to quantify the additional emission reductions that are readily achievable. The practices that were evaluated include increased use of recycled materials, increased use of natural gas as a burner fuel, reduction of aggregate moisture content, increased use of WMA technologies to reduce asphalt mix production temperatures, and reduced electricity consumption through energy efficiency measures.

3.1 Inputs and Assumptions for Emission Reduction Scenarios

Three scenarios were developed to evaluate the potential emission reductions that can be achieved over short-term, intermediate, and long-term time horizons. A summary is provided in Table 3 of the operational improvements that would be needed for each scenario. Details regarding each emission reduction practice are provided below.

Table 3. General parameters for GHG emission reduction scenarios.

Parameter	2019 Baseline	Short-Term	Intermediate	Long-Term
RAP Content	21%	25%	30%	40%
Natural Gas Consumption as Percentage of Fuel Combusted	69%	72%	75%	90%
Aggregate Moisture Content Reduction	N/A	0.25%	0.50%	1.0%
Asphalt Mix Production Temperature Reduction	N/A	10 °F	25 °F	40 °F
Reduction in Electricity Consumption Intensity	3.32 kWh/ton	5%	10%	20%

N/A – National baseline has not been established.

3.1.1 Use of Recycled Materials

Use of RAP

As previously discussed, use of RAP reduces upstream GHG emissions by replacing virgin materials and reducing upstream emissions associated with raw material extraction and processing. Under the short-term, intermediate, and long-term scenarios, the industry's average RAP content would increase from the 2019 baseline of 21% to 25, 30, and 40%, respectively. Mix composition under these scenarios was calculated consistent to the methodology presented in Appendix A. Other relevant parameters, including total mix production, RAS content, and raw material transport distances, were held constant at the 2019 baseline.

Accelerated test track studies have shown that asphalt mixtures with RAP contents as high as 50% can perform extremely well if designed and constructed appropriately (West et al., 2021). The most significant barrier to increasing use of RAP in new asphalt mixtures is limitations in existing agency specifications (Williams et al., 2020). However, adoption of Balanced Mix Design (BMD) specifications offers an opportunity to increase the use of recycled materials with confidence that pavement life will meet or exceed agency expectations (Yin and West, 2021).

3.1.2 Energy Inputs

Many options are available to reduce GHG emissions associated with energy consumption during asphalt mix production. For this analysis, four specific practices were considered: increasing the percentage of natural gas consumed as a burner fuel, decreasing the aggregate moisture content, utilizing WMA technologies to reduce mix production temperature, and reducing the intensity of electricity consumption through energy conservation measures. The assumptions for each of these practices are provided in this section. The resulting energy inputs for the short-term, intermediate, and long-term scenarios are provided in Table 4.

Table 4. Energy parameters for GHG emission reduction scenarios.

Parameter	Units	2019 Baseline	Short-Term	Intermediate	Long-Term
Electricity	million kWh	1,400.7	1,330.7	1,260.6	1,120.6
Reduction in Electrical Intensity	percent	N/A	5%	10%	20%
Fuel Consumption	trillion Btu	121.9	114.9	105.7	93.6
Reduction in Fuel Intensity	percent	N/A	6%	13%	23%
Diesel Fuel	million gal	120.3	104.0	85.4	30.3
Natural Gas	million MCF	81.5	79.6	76.3	81.1
Propane	million gal	72.0	62.3	51.1	18.1
Residual Fuel Oil	million gal	13.8	11.9	9.8	3.5
Used Oil	million gal	86.8	75.0	61.6	21.8

Type of Fuel Consumed
The asphalt mix production industry already uses clean-burning natural gas at a higher rate than the U.S. manufacturing industry (see Section 2.3). To assess the potential reductions that could be achieved by further increasing use of natural gas, the three scenarios adjust the amount of natural gas in the 2019 mix of fuels from a baseline of 69% to 72, 75, and 90%, respectively. The quantities of other fuels were adjusted to be consistent relative to each other.

Generally, natural gas is considered the burner fuel of choice for asphalt plants due to its low cost, reduced emissions, and reduced maintenance requirements relative to liquid fuels. When natural gas is not available, plants typically burn used oil or diesel fuel instead. However, there is a growing market for using liquid natural gas (LNG), which can be easily transported to asphalt plants by truck (Johns, 2019).

Reduction of Aggregate Moisture Content
A significant amount of energy is required to evaporate aggregate moisture in an asphalt plant. At a nominal aggregate moisture content of 5%, evaporation accounts for more than 40% of burner fuel consumption. Methods to reduce the moisture content of aggregates include sloping the grade under stockpiles, paving under stockpiles, and building structures to cover stockpiles (Young, 2007). For the short-term, intermediate, and long-term scenarios, the effects of reducing aggregate moisture by 0.25, 0.5, and 1% were evaluated by reducing the average energy intensity for asphalt mix production by 27,100 Btu/ton for each 1% reduction in aggregate moisture per Young (2007). For example, the asphalt mix production energy intensity was reduced by 6,775 Btu/ton for the 0.25% aggregate moisture reduction scenario.

Use of WMA Technologies to Reduce Mix Production Temperature
WMA technologies have been demonstrated to reduce burner fuel consumption by 1,100 Btu/°F/ton (NASEM, 2014). For this analysis, a conservative assumption of 1,000 Btu/°F/ton was used. For the short-term, intermediate, and long-term scenarios, average mix production temperature reductions of 10, 25, and 40 °F were modeled.

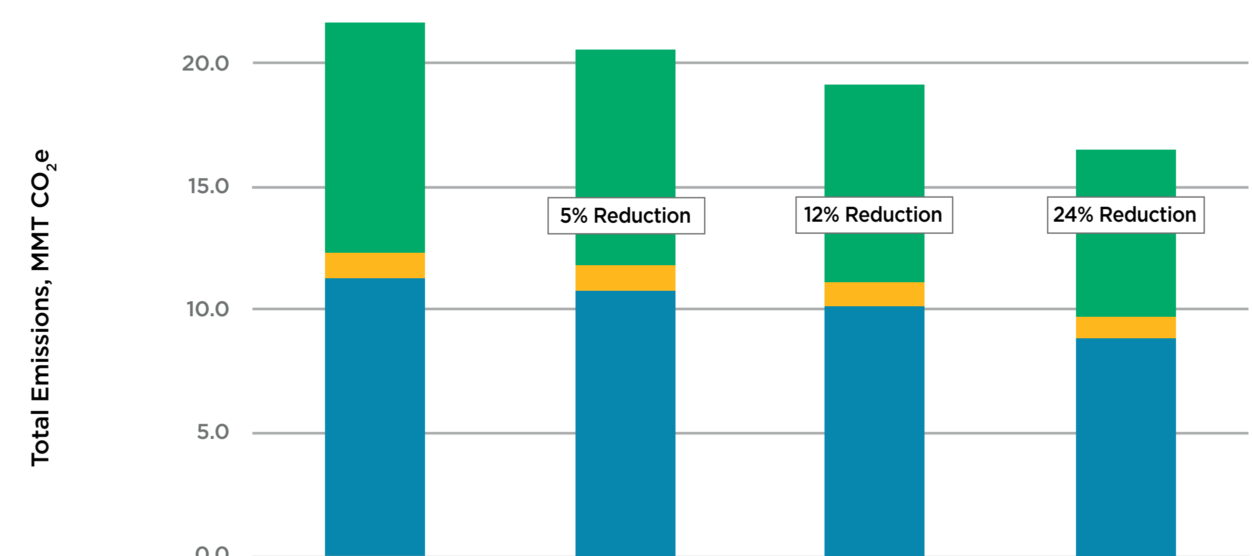
Electrical Energy Efficiency
There are numerous opportunities to reduce electricity consumption at asphalt plants. For this analysis, reductions in electrical intensity of 5, 10, and 20% were modeled for the short-term, intermediate, and long-term emission reduction scenarios. Capital improvements such as installation of variable frequency drives (VFDs) for motors, pumps, and fans can substantially decrease electricity consumption. Energy efficiency measures that aim to decrease burner fuel consumption through more efficient heating and drying of aggregates also tend to decrease electricity consumption by reducing the volume of air handled by the baghouse fan. According to the Fan Laws, the change in electrical power required to run a fan is proportional to the cube of the change in air volume (Neese, 2019). Thus, a modest reduction in air volume can yield a significant reduction in fan power. For example, a co-benefit of reducing the aggregate moisture content is a reduction in the volume of exhaust gas (water vapor) that must be handled by the baghouse fan. Reducing the aggregate moisture content by 1% (e.g., from 5% to 4%) would reduce the fan volume required for a drum plant by 14% (Young, 2007), allowing for a substantial reduction in electricity consumption.

3.2 Results of Emission Reduction Scenarios
Potential GHG emissions associated with achieving these short-term, intermediate, and long-term emission reduction scenarios are provided in Figure 5. The inputs and assumptions associated with these scenarios are described in Section 3.1. Achievement of these goals would reduce total cradle-to-gate (A1-A3) GHG emissions associated with asphalt mix production by 5, 12, and 24%, respectively. This demonstrates that meaningful reductions in GHG emissions can be achieved through

adoption of readily available technologies and practices such as increased use of RAP, increased utilization of natural gas as a burner fuel, management of aggregate stockpiles to reduce moisture content, and use of WMA technologies to reduce mix production temperatures.

While accelerating the adoption of these readily available technologies and practices is technologically feasible, doing so may be hindered by policy and economic barriers. From a policy perspective, the industry's use of RAP is often constrained by agency specifications (Williams et al., 2020). But revising agency specifications across the country is a daunting task. There are hundreds of specifying agencies that include state departments of transportation (DOTs), tollway authorities, local governments, federal agencies, and others. The process of revising specifications can take years due to the conservative nature of engineers and agencies' aversion to risk. On the other hand, agency adoption of BMD policies offers an opportunity to allow industry to increase the use of RAP and other innovative materials without sacrificing mixture quality and performance.

Another policy barrier to increased use of RAP is the practice by a few agencies of retaining ownership of RAP instead of transferring ownership to the paving contractor. Typically, these agencies use the RAP for low-value applications such as shoulder dressing and maintenance of unpaved roadways, both of which could be substituted by using unbound aggregates. Policies that allow paving contractors to retain ownership and recycle RAP into new asphalt mixtures would yield net GHG emission reductions due to reduced upstream emissions from avoided use of virgin asphalt binder.



	2019 Baseline	Short	Intermediate	Long-Term
Total (A1-A3)	21.7	20.6	19.1	16.5
Mix Production (A3)	9.4	8.8	8.0	6.8
Transportation (A2)	1.0	1.0	1.0	0.9
Raw Materials (A1)	11.3	10.8	10.1	8.8

Figure 5. Potential cradle-to-gate GHG emissions associated with achieving short-term, intermediate, and long-term goals.

Economic barriers represent another obstacle to adopting these readily available technologies and practices due to the low bid environment of the asphalt paving industry. Financial incentives such as tax credits and rebates to offset the cost of capital improvements would help accelerate industry adoption of energy efficiency retrofits. Financial incentives, including mechanisms such as corporate tax credits, grants, and project level incentives, could also help offset the differential costs of low-carbon fuels and materials.

Even with widespread adoption of readily available technologies and practices, the 24% reduction in GHG emissions modeled in these scenarios is not sufficient to achieve net zero emissions across the asphalt paving industry. The following section describes the research and implementation efforts that are needed to achieve more ambitious GHG emissions based on the current state of knowledge.

Jacksonville, FL, Asphalt Plant, courtesy Duval Asphalt

4 RESEARCH AND IMPLEMENTATION NEEDS FOR MORE AMBITIOUS GHG EMISSION REDUCTIONS

New technologies and practices will need to be developed and implemented to achieve more significant GHG emission reduction goals associated with the cradle-to-gate stages (A1-A3) of asphalt mix production. Potential materials-related emission reduction strategies include the implementation of carbon capture, utilization, and storage (CCUS) technologies during extraction of crude oils used for asphalt binder production, development and use of carbon-sequestering bio-based binders and binder extenders, and development of carbon-sequestering synthetic aggregates. Transportation-related emission reduction strategies include the increased use of locally derived recycled materials in markets with limited local supplies of natural aggregates and deployment of alternative fuels for trucking operations. Potential strategies for reducing emissions associated with asphalt mix production include use of alternative energy sources and use of technologies that reduce the intensity of burner fuel consumption. These strategies are evaluated in more detail in this section.

4.1 Raw Materials (A1)

Asphalt Binder

From a raw materials perspective, asphalt binder production is the most significant contributor of upstream GHG emissions in an asphalt mixture, comprising 94% of the emissions associated with raw materials (A1) and 53% of cradle-to-gate emissions (A1-A3) (Shacat et al., 2022).

Some aspects of asphalt binder production, such as transportation of crude oil and finished products within the binder production value chain, are likely to see reduced GHG emissions in the coming years as a result of national and international commitments to reduce GHG emissions in the transportation sector. But the most significant contributor to GHG emissions within the asphalt binder production value chain is crude oil extraction (Figure 6), which is largely driven by the GHG intensity of extracting Canadian oil sands (Asphalt Institute, 2019). Despite ongoing efforts to reduce the GHG emissions during oil sand extraction through CCUS technologies, significant policy-related and economic hurdles must be overcome to reduce the carbon footprint of this process (Israel et al., 2020). To put it simply, CCUS will continue to be cost prohibitive until significant economic incentives are available.

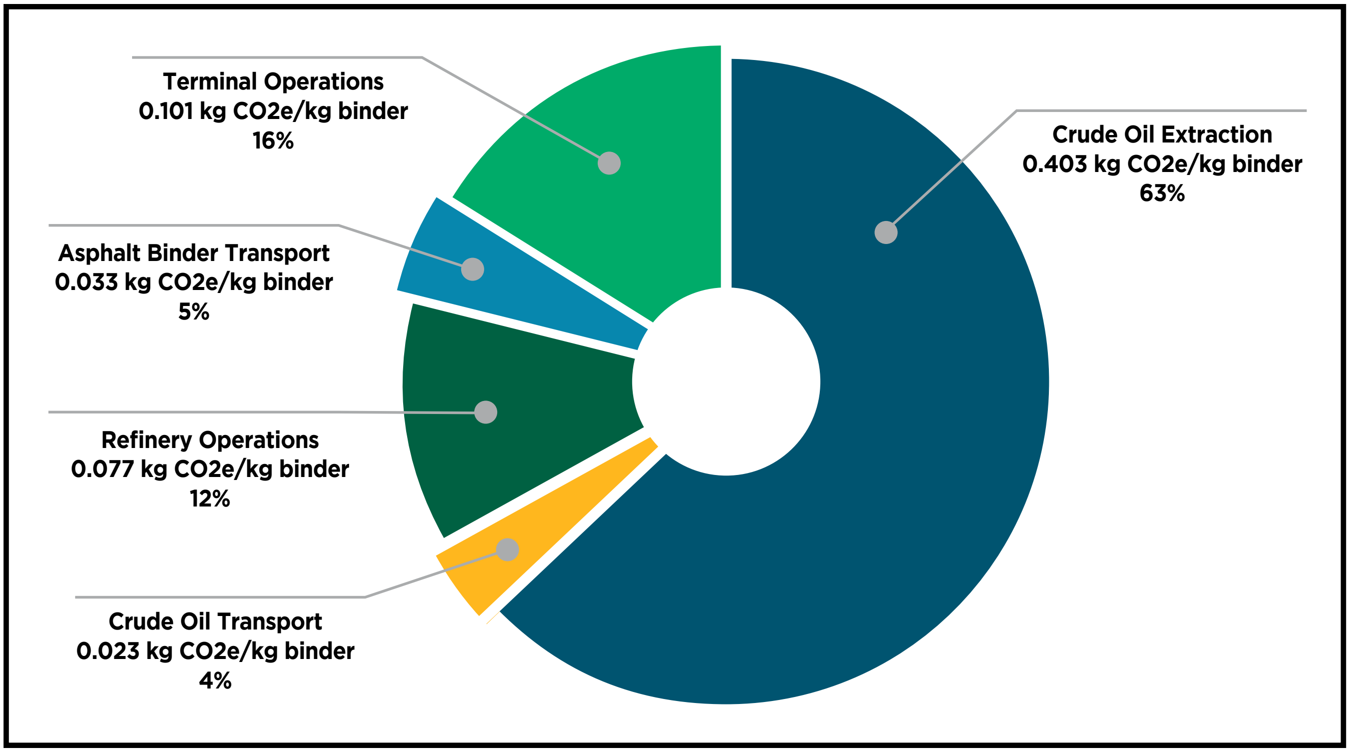


Figure 6. GHG Emissions Associated with Asphalt Binder Production. From Asphalt Institute (2019).

Another opportunity to reduce the upstream GHG emissions associated with asphalt binder is the use of carbon-sequestering bio-based binders and binder extenders. Various feedstock materials have been investigated, including animal fat, palm oil, lignin, and swine manure (Kousis et al., 2020; Khandelwal, 2019; Samieadel et al., 2018). A review of alternative asphalt binder extenders indicates that performance of pavements made with these materials is a primary concern from an engineering perspective, although the BMD framework allows an opportunity to address this concern through performance testing during the asphalt mix design process (Hand, 2018). **A significant research effort will be needed to further develop these innovative asphalt binder technologies, assess their life cycle GHG emissions, and bring them to market.**

Aggregates

The GHG emissions associated with extracting and processing aggregates are relatively small, limiting the potential of reducing GHG emissions by substituting virgin materials with recycled materials. However, the development of synthetic aggregates offers an opportunity to sequester atmospheric CO_2 into the mineral structure of the aggregates (Rowland, 2020). This technology was developed for the concrete industry and has not been evaluated or tested for use in asphalt mixtures.

4.2 Transportation (A2)

Transportation of raw materials represents a relatively minor portion of the cradle-to-gate (A1-A3) GHG emissions associated with asphalt mix production at a national level, but can be significant in markets with limited aggregate supplies due to local geology and other supply constraints (Shacat et al., 2022). In these areas, use of locally derived recycled aggregate materials (including RAP) can be leveraged as an opportunity to reduce transportation-related GHG emissions.

Another opportunity to reduce GHG emissions associated with transportation is the development and deployment of alternative fuels for trucking operations, including advanced biofuels such as renewable diesel and renewable natural gas, hydrogen fuel cells, and battery electric heavy-duty vehicles (Shacat et al., 2022). How quickly these technologies are adopted in the asphalt mix production supply chain will depend on their cost effectiveness and the availability of financial incentives to accelerate implementation.

4.3 Mix Production (A3)

The primary source of GHG emissions during asphalt mix production is burner fuel consumption for the heating and drying of aggregates. There are many different pathways to significantly reduce emissions from burner fuel consumption beyond the energy efficiency measures modeled in this study. They can generally be classified as either use of alternative energy sources or use of technologies that reduce the intensity of burner fuel consumption.

Alternative Energy Sources

Alternative energy sources for burner fuel consumption include use of low carbon fuels and electrification of process heating requirements. Programs at the state level such as California's Low Carbon Fuel Standard (LCFS) have accelerated production and consumption of low carbon fuels including renewable natural gas (RNG), biodiesel, and renewable diesel in that state's transportation sector (Boutwell, 2018). Development of similar programs for the industrial sector could enable supply of low carbon fuels for asphalt mix production at competitive prices. It should be noted, however, that the ability of LCFS programs to actually mitigate climate change is an area of active research and debate (Plevin et al., 2017).

Another potential energy source is electrification of process heating requirements at asphalt plants to replace burner fuels altogether. While microwave technologies have been developed for producing asphalt pavements (e.g., Lombardo, 2015), no such units are commercially available. An analysis of electrifying thermal processes in other industries suggests that various technologies may be available, although economic considerations present barriers to implementation (Hasanbeigi et al., 2021).

Reducing Burner Fuel Consumption Intensity

As documented in this report, asphalt mixtures produced at reduced temperatures using WMA technologies can reduce the energy intensity of asphalt mix production. The mix production temperature reductions achieved with most WMA technologies are generally in the range of 25-50 °F (Prowell et al., 2012). A practical limit to the reductions in fuel consumption using WMA technologies is the need to completely dry the aggregates to ensure proper coating and adhesion of the asphalt binder to the aggregates. Development and implementation of technologies that are not constrained by this limitation, generically referred to as half-warm mix asphalt, offers an opportunity to further reduce mix production temperatures and substantially reduce the energy intensity of asphalt mix production (EAPA, 2014). Another option is adoption of cold central plant recycling (CCPR) technology, which produces asphalt mixtures with high RAP contents at ambient temperatures (FHWA, 2020b). Further research, including the ongoing National Cooperative Highway Research Program (NCHRP) 09-62 project, Rapid Tests and Specifications for Construction of Asphalt-Treated Cold Recycled Pavements, is needed to support broader deployment of CCPR technologies.

5 SUMMARY AND CONCLUSIONS

This report compiled the first national assessment of the U.S. asphalt paving industry's GHG emissions during the cradle-to-gate stages (A1-A3) of asphalt mixture production and end-of-life transport (C2) for asphalt pavements for the period 2009-2019. The industry's cradle-to-gate GHG emissions represented 0.3% of total GHG emissions in the United States in 2019. Current practices related to the use of recycled materials and the type of fuel consumed by asphalt plants resulted in avoided emissions of 2.9 MMT in 2019, equivalent to the emissions of 630,000 passenger vehicles.

A scenario analysis was conducted to evaluate the potential emission reductions associated with adoption of readily available technologies and practices including:

- increased use of recycled materials,
- increased use of natural gas as a burner fuel,
- reduction of aggregate moisture content to reduce burner fuel consumption,
- increased use of WMA technologies to reduce asphalt mix production temperatures, and
- reduced electricity consumption through energy efficiency measures.

Achieving short-term, intermediate, and long-term goals could reduce the industry's cradle-to-gate GHG emissions by 5, 12, and 24%, respectively, relative to 2019 mix production and emissions (Figure 5). Several policy changes are needed to accelerate adoption of the technologies and practices needed to achieve these emission reductions. Revision of agency specifications is required to increase the industry's use of RAP and other recycled materials, with BMD offering a performance-based mix design framework that does not compromise pavement performance. To ensure competitiveness in a low bid environment, economic incentives such as tax credits, rebates, and project level incentives can help offset the increased cost of capital improvements and the differential cost of other low carbon technologies.

Significant research and implementation efforts will be needed to achieve more ambitious GHG emission reductions in support of the U.S. goal of reaching net zero GHG emissions in the U.S. economy by 2050. The following areas were identified as key priorities for research and implementation:

- Reduction in upstream emissions associated with asphalt binder production, particularly with respect to emissions during extraction of Canadian oil sands;
- The potential use of carbon-sequestering bio-based asphalt binders and binder extenders;
- The potential use of carbon-sequestering synthetic aggregates;
- Development and deployment of alternative fuels for trucking and other material transport activities;
- Use of alternative energy sources for asphalt mixture production, including low carbon biofuels and electrification of process heating equipment; and
- Reducing burner fuel consumption through development and deployment of half-warm mix asphalt and CCPR technologies.

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APPENDIX A
ASSUMPTIONS AND DATA INPUTS FOR GHG EMISSION CALCULATIONS

General Approach

GHG emissions were calculated with openLCA software using the LCA model developed by Mukherjee (2021).

The input data and methodology for calculating GHG emissions in this study are generally consistent with the Product Category Rules (PCR) for Asphalt Mixtures (NAPA, 2022) to maintain consistency with the emissions reported in EPDs for asphalt mixtures. However, there are some deviations from the PCR requirements due to limitations related to data availability:

- Many of the data inputs such as fuel consumption, electricity consumption, and transportation distances are estimated based on extrapolation from industry surveys conducted by NAPA and government agencies. In contrast, the PCR for Asphalt Mixtures requires these parameters to be directly collected as primary data.
- With the exception of modified asphalt binders, the upstream emissions (A1) associated with manufacturing mix additives and binder additives are not accounted for.
- The downstream emissions (A3) associated with transporting and processing off-spec materials and waste generated during asphalt plant operations (e.g., startup and shutdown waste) are not accounted for.
- The operational emissions (A3) associated with transporting portable asphalt plants are not accounted for.

Raw Material Inputs (A1)

An average mix design was developed for each year, with the mix design comprised of five components: virgin aggregates, neat asphalt binder, modified asphalt binder, RAP, and RAS. The average mix designs were derived from a combination of the annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage (NAPA's IS-138 series of reports e.g., Williams et al., 2020) and the Asphalt Institute's (AI's) annual Asphalt Usage Survey for the United States and Canada (Asphalt Instutute, 2011-2020). Raw data inputs to the mix design calculations are provided in Table A-1. Average mix design compositions for each year are provided in Table A-2. Calculation methodologies are explained below.

The mix design percentage for each component represents the reported or calculated consumption of that component divided by total mix production. For example, in 2019, 421.9 million tons of mix were produced in the U.S. and 921,000 tons of RAS were consumed, yielding an average RAS composition of 0.22% (Williams et al., 2020).

For each year, the virgin aggregate content for the average mix design was calculated using Equation 1:

$$MC_{Agg} = 100 - (BC_{Neat} + BC_{Mod} + MC_{RAP} + MC_{RAS})$$

where MC_{Agg} is the virgin aggregate content, BC_{Neat} is the neat asphalt binder content, BC_{Mod} is the modified asphalt binder content, MC_{RAP} is the RAP content, and MC_{RAS} is the RAS content, all expressed as percentages of total mix by weight.

Table A-1. Material quantities used to calculate average mix design compositions, 2009-2019.

Parameter	Total Quantity, million tons										
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Mix Production[1]	358.4	359.9	366.0	360.3	350.7	352.0	364.9	374.9	379.4	389.3	421.9
Asphalt Binder Use, Neat[2]	N/A	12.3	11.0	12.6	12.6	13.0	13.5	14.3	13.7	14.3	15.3
Asphalt Binder Use, Modified[2]	N/A	2.1	2.1	2.1	1.9	2.0	2.2	2.4	2.7	2.6	2.7
RAP Use[1]	56.1	62.1	66.7	68.3	67.8	71.9	74.2	76.9	76.2	82.2	89.2
RAS Use[1]	0.7	1.1	1.2	1.9	1.6	2.0	1.9	1.4	0.9	1.1	0.9

[1] From IS-138 series of reports (e.g., Williams et al., 2020).
[2] From Asphalt Institute (2011-2020).

Table A-2. Average mix design composition for asphalt mixtures produced in the United States, 2009-2019.

Parameter	Average Mix Design Composition										
	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Asphalt Binder Content, Neat (BC_{Neat})	3.69%	3.60%	3.49%	3.49%	3.58%	3.69%	3.69%	3.80%	3.60%	3.69%	3.63%
Asphalt Binder Content, Modified (BC_{Mod})	0.62%	0.60%	0.67%	0.58%	0.55%	0.57%	0.59%	0.65%	0.71%	0.68%	0.65%
RAP Content, Average (MC_{RAP})	15.65%	17.26%	18.23%	18.96%	19.33%	20.42%	20.33%	20.51%	20.08%	21.11%	21.14%
RAS Content, Average (MC_{RAS})	0.20%	0.31%	0.33%	0.52%	0.47%	0.56%	0.53%	0.37%	0.25%	0.27%	0.22%
Aggregate Content, Average (MC_{Agg})	79.84%	78.23%	77.30%	76.45%	76.06%	74.75%	74.85%	74.66%	75.35%	74.25%	74.36%

NAPA's IS-138 series of reports provide annualized total mix production, RAP use, and RAS use for all years, allowing MC_{RAP} and MC_{RAS} to be easily calculated for the entire time series. AI's Annual Asphalt Usage Survey provides the neat and modified paving asphalt binder consumption for the years 2010-2012. Because the AI survey reports provide reported asphalt usage data without estimating total asphalt binder consumption, a reasonableness check was established to ensure data quality. For the reasonableness check, the total asphalt binder content was calculated according to Equation 2:

$$BC_{Total} = BC_{Neat} + BC_{Mod} + BC_{RAP} + BC_{RAS}$$

Where BC_{Total} is the total asphalt binder content in the mix, BC_{RAP} is the recycled asphalt binder content from RAP, and BC_{RAS} is the recycled asphalt binder content from RAS, all expressed as percentages of total mix by weight. We assume that RAP has a 5% binder content and RAS has a 20% binder content. BC_{RAP} and BC_{RAS} were calculated by multiplying these binder contents by MC_{RAP} and MC_{RAS}, respectively.

A minimum value of 5% was established for the total asphalt binder content reasonableness check. The total asphalt binder content exceeded the reasonableness check for all years except 2010 and 2011 (Figure A-1). This suggests that neat and modified asphalt binder usage may have been under-reported for 2010 and 2011.

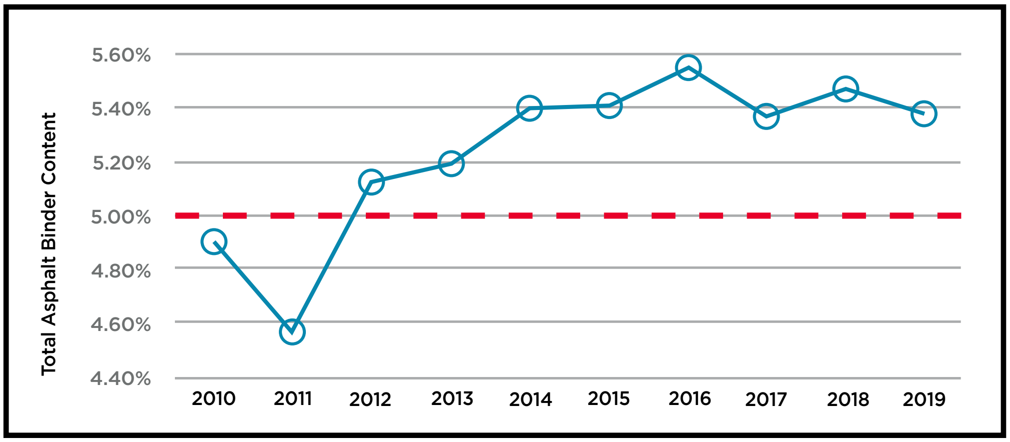

Figure A-1. Total asphalt binder content based on reported use of neat and modified asphalt binder and estimated use of RAP and RAS (see Equation 2).

For the years 2012-2019, BC_{Neat} and BC_{Mod} were calculated directly using the neat and modified asphalt binder usage data from AI's Annual Asphalt Usage Survey reports.

For 2010 and 2011, the virgin asphalt binder content was calculated according to Equation 3:

$$BC_{Virgin,n} = BC_{Total,2012} - BC_{RAP,n} - BC_{RAS,n}$$

Where $BC_{Virgin,n}$ is the virgin asphalt binder content for year n, $BC_{Total,2012}$ is the total asphalt binder content for 2012, $BC_{RAP,n}$ is the recycled asphalt binder content from RAP for year n, and $BC_{RAS,n}$ is the recycled asphalt binder content from RAS for year n, all expressed as percentages of total mix by weight. BC_{Neat} and BC_{Mod} were then calculated for 2010 and 2011 by multiplying $BC_{Virgin,n}$ by the relative percentage of neat and modified asphalt binder usage reported for each of these years. This approach assumes that the total asphalt binder content in 2010 and 2011 was equal to the total asphalt binder content in 2012. It also assumes there was no bias in the apparent under-reporting of neat and modified asphalt binder in 2010 and 2011.

For 2009, BC_{Neat} and BC_{Mod} were calculated using the same method as 2010 and 2011, except the relative percentages of neat and modified asphalt for 2010 were applied. This was necessary because the AI Annual Asphalt Usage Survey Reports did not provide data for 2009.

This approach assumes that the total asphalt binder content in 2009 was equal to the total asphalt binder content in 2012. It also assumes the relative percentages of neat and modified asphalt binder usage in 2009 were equal to the values reported for 2010.

Modified asphalt binder was assumed to be modified using 3.5% SBS, which is the most conservative (the highest emissions intensity) of the three modified asphalt binder datasets provided by Asphalt Institute (2019). The upstream impacts associated with manufacturing and transporting other mix additives and binder additives are not accounted for in this study due to a lack of available estimates regarding the types and quantities of additives used on a national basis.

Transportation (A2 and C2)

Average transportation distances are provided in Table A-3. All material transportation was assumed to be via truck. The average transport distances reported by Mukherjee (2016) were used for aggregates and asphalt binder. The RAP transport distance was broken down into two components based on the LCA cut-off method using data collected in an industry survey (Shacat, 2022). End-of-life RAP transport (C2) is the distance from the paving jobsite to the initial stockpile or processing location. Processed RAP transport (A2) is the weighted average distance from the initial stockpile or processing location to the asphalt plant.

The RAS transport distance was assumed to be 50 miles per Mukherjee (2016). This conservative estimate accounts for transport that occurs during the A2 stage (from the processing location to the asphalt plant). NAPA intends to refine this estimate through an industry survey in 2022.

Mix Production Energy Consumption (A3)

The Manufacturing Energy Consumption Survey (MECS), jointly conducted by the U.S. Energy Information Administration (EIA) and the U.S. Census Bureau, was used to estimate the average blend of fuels consumed by asphalt plants. The average blend of fuels consumed (Table A-4) for the years 2010, 2014, and 2018 was calculated using the Energy Consumption as a Fuel data reported in Tables 3.2 and 3.5 of EIA (2013, 2017, and 2021b) for the Asphalt Pavement Mixture and Block sector (NAICS Code 324121). The average blend of fuels was interpolated for the intermediate years (2011-2013 and 2015-2017) and held constant for 2009 and 2019 (e.g., the 2010 average blend of fuels was also used for 2009).

The MECS dataset provides a good estimate for the relative percentage of fuels consumed during asphalt mix production. However, it's not a reliable source for total fuel consumption because it significantly underestimates the number of asphalt plants in the U.S., which leads to an underestimate of the total fuel consumption (see discussion in Appendix B). Also, mix production is not collected in the MECS dataset, complicating efforts to estimate and benchmark mix production energy intensity. Instead, the average fuel consumption of 0.289 MMBtu/ton reported by Mukherjee (2016) was used. This value was multiplied by the total annual mix production to quantify the total annual fuel consumption (Table A-5). Estimates of total annual mix production were provided by NAPA's IS-138 series of reports, the annual Asphalt Pavement Industry Survey on Recycled Materials and Warm-Mix Asphalt Usage (e.g., Williams et al., 2020). The average blend of fuels for each year (Table A-4) was then multiplied by the total fuel consumption for the respective year to calculate the total quantity of each fuel (in thermal units) consumed per year (Table A-5).

Annual fuel consumption for asphalt mix production in the United States was then converted from thermal units to physical units, as reported in Table A-6. Conversion factors are provided in Table A-7. Table A-6 also reports annual electricity consumption based on the average electricity consumption of 3.32 kWh/ton reported by Mukherjee (2016). The electricity region was set to the national average rather than defining a regional balancing authority.

It should be noted that although energy efficiency measures and use of WMA technologies at asphalt plants have reduced energy intensities during the period 2009-2019, there is insufficient data to quantify this effect on a national level. For example, although the MECS survey is collected every four years, the dataset does not include a key parameter (mix production) that would be required to calculate the energy intensity of mix production. In contrast, the industry-wide LCA conducted by Mukherjee (2016) provides an estimate for average energy intensity, but this is only for a snapshot in time.

Table A-3. Average transportation distances.

Material	Distance	Units	Reference
Aggregates	21.5	ton-miles/ton	Mukherjee (2016)
Asphalt Binder	3.9	ton-miles/ton	Mukherjee (2016)
RAP – Jobsite to Processing Site (C2)	33	ton-miles/ton	Shacat (2022)
RAP – Processing Site to Plant (A2)	7.2	ton-miles/ton	Shacat (2022)
RAS – Processing Site to Plant (A2)	50	ton-miles/ton	Mukherjee (2016)

Table A-4. Average blend of fuels consumed by the U.S. asphalt mix production industry.[1]

Parameter	Units	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Residual Fuel Oil	% of Fuel	4.9%	4.9%	4.6%	4.3%	4.0%	3.7%	3.2%	2.7%	2.2%	1.7%	1.7%
Diesel Fuel	% of Fuel	19.7%	19.7%	17.1%	14.5%	11.9%	9.3%	10.3%	11.4%	12.5%	13.6%	13.6%
Natural Gas	% of Fuel	63.9%	63.9%	67.4%	70.9%	74.3%	77.8%	75.7%	73.6%	71.6%	69.5%	69.5%
Propane (HGL)[2]	% of Fuel	1.6%	1.6%	1.7%	1.7%	1.8%	1.9%	2.7%	3.5%	4.3%	5.1%	5.1%
Used Oil[3]	% of Fuel	9.8%	9.8%	9.2%	8.6%	8.0%	7.4%	8.1%	8.8%	9.5%	10.2%	10.2%

[1] Data for 2010, 2014, and 2018 are derived from EIA (2013), EIA (2017), and EIA (2021b), respectively. Relative fuel consumption percentages are interpolated for intermediate years (e.g., 2011-2013) and held constant for 2009 and 2019 (e.g., 2010 values were used for 2009). Percentages for individual years may not total 100 due to rounding.

[2] HGL is hydrocarbon gas liquids. This parameter may include other fuels such as ethane, ethylene, propylene, butane, and butylene. This parameter is assumed to be propane for this study.

[3] Used oil includes other fuels and waste oils (e.g., biodiesel and used cooking oil) not otherwise quantified in EIA (2013, 2017, and 2021b).

Table A-5. Annual fuel consumption for U.S. asphalt mix production, 2009-2019, thermal units.

Parameter	Units	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Mix Production[1]	million tons	358.4	359.9	366.0	360.3	350.7	352.0	364.9	374.9	379.4	389.3	421.9
Total Fuel Consumption[2]	trillion Btu	103.6	104.0	105.8	104.1	101.3	101.7	105.5	108.3	109.6	112.5	121.9
Residual Fuel Oil[3]	trillion Btu	5.1	5.1	4.9	4.5	4.1	3.8	3.4	2.9	2.4	1.9	2.1
Diesel Fuel[3]	trillion Btu	20.4	20.5	18.1	15.1	12.0	9.4	10.9	12.4	13.7	15.3	16.5
Natural Gas[3]	trillion Btu	66.2	66.5	71.3	73.8	75.3	79.1	79.8	79.8	78.5	78.2	84.7
Propane (HGL)[3]	trillion Btu	1.7	1.7	1.8	1.8	1.8	1.9	2.8	3.8	4.7	5.7	6.2
Used Oil[3]	trillion Btu	10.2	10.2	9.8	9.0	8.1	7.5	8.5	9.5	10.4	11.4	12.4

[1] Mix production estimates are from NAPA's IS-138 series of reports (e.g., Williams et al., 2020).

[2] Total Fuel Consumption is based on an assumption of 0.289 MMBtu/ton per Mukherjee (2016).

[3] Fuel quantities are calculated by multiplying Total Fuel Consumption by the relative percentage of fuel reported in Table A-4. Values reported here may vary slightly due to rounding.

Table A-6. Annual electricity and fuel consumption for U.S. asphalt mix production, 2009-2019, physical units.[1]

Parameter	Units	2009	2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Electricity[1]	million kWh	1,190	1,195	1,215	1,196	1,164	1,169	1,212	1,245	1,260	1,292	1,401
Residual Fuel Oil	million gal	34.0	34.2	32.6	30.0	27.1	25.2	22.6	19.5	16.1	12.7	13.8
Diesel Fuel	million gal	148.3	148.8	131.3	109.6	87.5	68.5	79.3	89.9	99.6	111.0	120.3
Natural Gas	million MCF	63.7	64.0	68.6	71.0	72.5	76.2	76.8	76.8	75.5	75.2	81.5
Propane (HGL)	million gal	19.7	19.8	20.8	21.1	21.2	21.9	32.6	43.6	54.5	66.4	72.0
Used Oil	million gal	71.3	71.6	68.3	62.8	56.9	52.8	59.8	66.7	72.8	80.1	86.8

[1] Electricity consumption is based on an assumption of 3.32 kWh/ton per Mukherjee (2016).

Table A-7. Conversion factors for fuel consumption calculations. From EIA (2018).

Parameter	Value	Units
Residual Fuel Oil	6.287	million Btu/bbl
Diesel Fuel	5.773	million Btu/bbl
Natural Gas	1.039	million Btu/MCF
Propane (HGL)	0.0861	million Btu/gal
Used Oil	6	million Btu/bbl
Volume Conversion	42	gal/bbl

APPENDIX B
DATA QUALITY CONSIDERATIONS

Total Mix Production and Recycled Material Contents

The estimates of total mix production and recycled material contents provided in NAPA's IS-138 series are based on relatively large datasets, with the number of plants that participate in each annual survey ranging from 1,027 to 1,328. Geographical representativeness is good, with nearly all 50 states represented in most years. Other measures of representativeness include the relative percentages of the number of asphalt plants and total mix production covered in the IS-138 series.

There are various estimates for the number of asphalt plants in the United States. The U.S. Environmental Protection Agency (EPA) estimated that there were 3,600 asphalt plants in 1996 (U.S. EPA, 2000). In contrast, the U.S. Census Bureau estimated a total of 1,324 establishments in 2012 with a primary North American Industrial Classification System (NAICS) code of 324121, Asphalt Pavement Mixture and Block Manufacturing (U.S. Census Bureau, 2021). The Census Bureau likely underestimates the number of asphalt plants since it is organized by primary NAICS code; asphalt plants that are co-located with other operations may be categorized under other NAICS codes. Another estimate of the number of asphalt plants can be calculated by dividing the total annual asphalt mix production by the average annual mix production per plant reported in NAPA's IS-138 series, which suggests a range of 2,700 to 3,000 asphalt plants.

Virgin Asphalt Binder Consumption

Quantities for neat and modified asphalt binder consumption are based on voluntary participation in AI's Annual Asphalt Usage Survey. The annual survey reports publish asphalt sales at the retail level as reported by terminals and refineries. The reports are unaudited and unverified. They do not estimate asphalt binder use, suggesting that actual asphalt binder usage might be higher than reported. For the 2014 usage report, AI's member manufacturers and first sellers represented approximately 92% of the asphalt and road oil supply reported by the EIA. Therefore, any variance between reported usage and actual usage of asphalt binder is likely to be within about 10%. This variance was only evaluated for 2014.

Despite the potential under-reporting of actual asphalt binder usage, AI indicated that the paving asphalt binder usage is likely over-reported, since the reported values include asphalt binder that is subsequently converted to asphalt emulsion by customers. Additionally, the modified asphalt binder usage is likely under-reported, since some of the neat asphalt binder is subsequently modified by customers. These uncertainties have not been quantified. (M. Buncher, personal communication, February 25, 2022)

In addition to the uncertainties associated with the reported values of neat and modified asphalt binder consumption, the actual type and quantity of modifiers used is unknown. The assumption that 3.5% SBS is representative of all modified binders was selected because it's the most conservative (highest GHG emissions) of the modified asphalt binder products reported by Asphalt Institute (2019).

Transportation of Raw Materials

The average transportation distances reported by Mukherjee (2016) for aggregates and asphalt binder are based on sample sizes of 15 and 19 plants, respectively. With such a small sample size, these estimates are subject to large uncertainties.

The average transportation distances reported by Shacat (2022) for RAP are based on an industry survey representing 124 companies and 756 asphalt plants. Confidence in the RAP transport distances is high.

Energy Intensity of Asphalt Mix Production

Mukherjee (2016) reported an average energy intensity of 289,000 Btu/ton of mix produced with a 95% confidence interval of ±52,000 Btu/ton based on a survey of approximately 50 asphalt plants. A separate analysis by Miller (2020) of user data entered in the Emerald Eco-Label environmental product declaration (EPD) software for 43 asphalt plants indicated an average energy intensity of 290,000 ±74,000 Btu/ton. Given the consistency of average mix production energy intensities from two independent datasets, confidence in the estimate used for this study is high.

Blend of Fuels Consumed for Asphalt Mix Production

The blend of fuels consumed for asphalt mix production is based on data reported in the EIA's Manufacturing Energy Consumption Survey (MECS), which includes relative standard errors for all parameters that are generally below 5%. However, the MECS data suggest a total population size for the number of U.S. asphalt plants in 2010, 2014, and 2018 of 1,338, 1,285, and 1,289, respectively (EIA, 2013, 2017, and 2021b). This is less than half the number of estimated U.S. asphalt plants. It's unknown whether or to what extent any bias in the MECS data would affect the blend of fuels consumed for asphalt mix production used in this analysis. Thus, the uncertainty for these values is unquantifiable.

Additives

Asphalt mixtures and asphalt binders often include small quantities of additives to improve pavement performance or provide other desirable qualities, such as enhancing workability during paving operations. With the exception of asphalt modifiers, additives are not accounted for in this study. Additive quantities are typically less than 1% of the mix by weight, and many mixes do not include any additives. There are no publicly available estimates of the quantity of additives used in the U.S. asphalt pavement industry. There is also relatively little publicly available information on the carbon footprint of most asphalt additives. Information regarding the upstream GHG emissions associated with asphalt additives remains an important data gap for informed decision-making (Shacat et al., 2022).