Analysis of Recycling of Asphalt Shingles in Pavement Mixes from a Life Cycle Perspective

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Final Report

Prepared for:
U.S. Environmental Protection Agency, Region 8
Resource Conservation and Recovery Program
Industrial Materials Recycling
1595 Wynkoop Street
Denver, CO 80202-1129

Prepared by:
Booz | Allen | Hamilton
121 South Tejon Street, Suite 900
Colorado Springs, CO 80903

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For more information about this report, please contact:

Kendra A. Morrison
Environmental Scientist
U.S. Environmental Protection Agency Region 8
1595 Wynkoop Street
Denver, CO 80202
morrison.kendra@epa.gov

DISCLAIMER

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Acronyms

BEES	Building for Environmental and Economic Sustainability
BTU	British thermal unit
CDOT	Colorado Department of Transportation
CO	Carbon monoxide
CO_2e	Carbon dioxide equivalents
EPA	Environmental Protection Agency
F	Fahrenheit
GHG	Greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions and Energy Use in Transportation
GWP	Global warming potential
Hg	Mercury
H&M	Heating & mixing
HMA	Hot mix asphalt
lb	Pound
LCA	Life cycle assessment
NH_3	Ammonia
NOx	Nitrogen oxides
NREL	National Renewable Energy Laboratory
PM	Particulate matter
Pb	Lead
PCAS	Post-consumer asphalt shingles
RAP	Reclaimed asphalt pavement
RAS	Recycled asphalt shingles
SOx	Sulfur oxides
U.S.	United States
U.S. LCI	U.S. Life Cycle Inventory Database
VOC	Volatile organic chemicals / compounds
VSI	Vertical shaft impact
WaRM	Waste Reduction Model
WMA	Warm mix asphalt

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Executive Summary

Asphalt roofing shingles constitute nearly two-thirds of the roofing market for both new homes and roof replacements. Annually, new or replacement roof installation generates an estimated seven to ten million tons of shingle tear-off waste and installation scrap. More than sixty manufacturing plants across the United States (U.S.) generate another 750 thousand to one million tons of manufacturing shingle scrap. Landfilling this scrap material when it contains valuable material is both an economic and environmental issue. However, asphalt roofing shingles have excellent recycling potential because they are plentiful in the construction and demolition waste stream; they are mostly generated separately from other wastes and, hence, easy to isolate; and recycling technology and end markets are available. One potential use of the recycled shingles is in the production of asphalt pavement, where use of the recycled material can yield cost savings and potentially even enhance roadway performance.

The goal of this assessment is to compare limited environmental inventory and impacts of seven asphalt mixes with various percentages of reclaimed asphalt and recycled shingles to a baseline of virgin asphalt. The inventory and impacts cover avoided landfill impacts, global warming potential (GWP), and criteria and other air pollutants on a cradle-to-gate basis.[1] Energy consumption and resource depletion are considered for select stages in the life cycle.

While this study does quantify greenhouse gas (GHG) emissions on a common basis – their GWP – it should not be considered a full life cycle assessment (LCA). The study does not attempt to compile a full inventory list from which to determine all environmental impacts. Instead, by assessing a limited number of inventory items for parts of the life cycle, it serves as a first study that may guide future work.

Figure ES-1 illustrates the life cycle GHG emissions in pounds carbon dioxide equivalents per short ton of asphalt (lbs CO_2e/short ton). The GHG emissions vary with the distance the asphalt is transported. The aggregate and mixing chamber (heating & mixing) emissions stay relatively consistent across the various asphalt mixes with major contributions — while emissions from petroleum refining for the binder is reduced as the higher concentrations of secondary binder from recycled materials are introduced.

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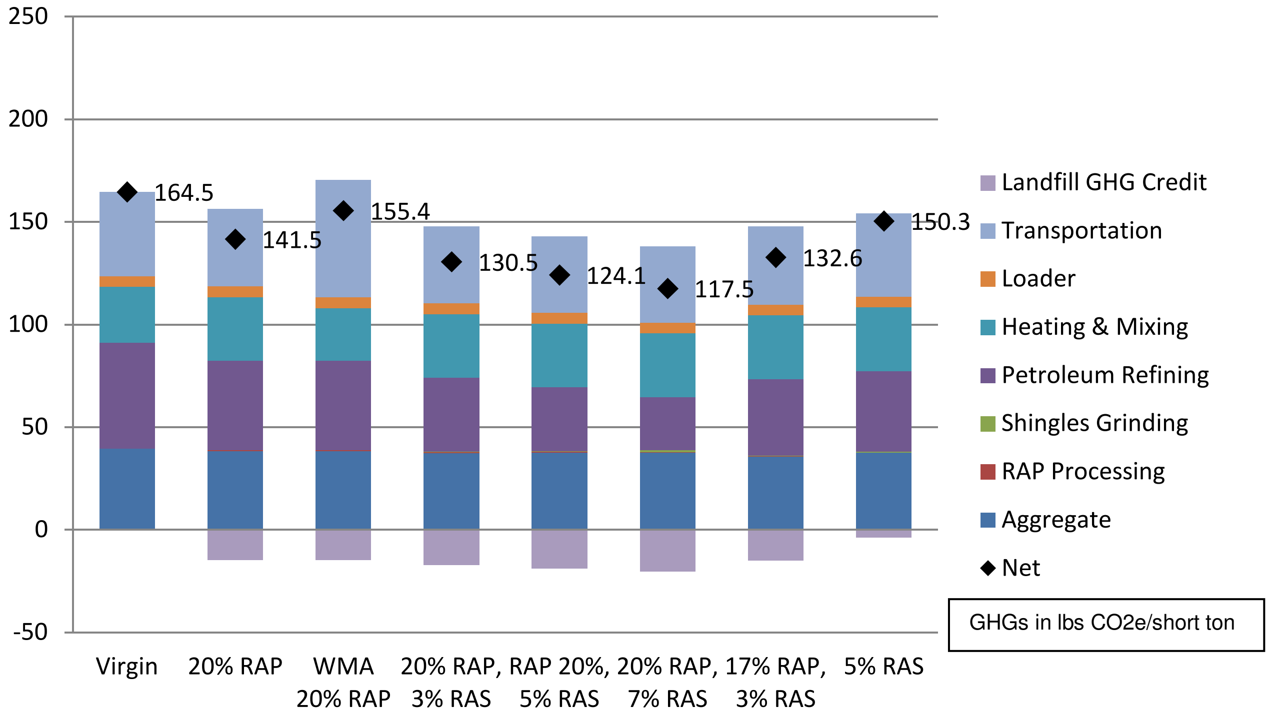
[1] Global warming is an average increase in the temperature of the atmosphere near the earth's surface and in the troposphere, which can contribute to changes in global climate patterns. It can occur from a variety of causes, both natural and human induced. Global warming is influenced mainly by emissions of greenhouse gases such as carbon dioxide (CO_2), methane, nitrous oxide (N_2O), and fluorinated gases. Carbon dioxide equivalent (CO_2e) is a measure used to compare the emissions from various greenhouse gases based upon their GWP. The emission of a greenhouse gas is multiplied by its GWP to calculate the equivalent level of CO_2 emissions.

Figure ES-1: Greenhouse Gas Emissions, No Allocation



Because the incoming transportation of aggregates and the final transportation are roughly equal in most of the cases considered here, shortening the distance traveled for either step can have a significant impact on the total GHG emissions (i.e. reduction). The warm mix asphalt (WMA) case has considered a longer final transportation distance (60 miles rather than 30 miles), and the increased emissions can be seen in the results.

There are environmental benefits to the use of recycled asphalt shingles in asphalt production for use in road construction. The greatest GHG emission reductions come from the largest percentage inclusion of both reclaimed asphalt pavement and recycled shingles.

1 Introduction

Asphalt roofing shingles constitute nearly two-thirds of the roofing market for both new homes and roof replacements. Annually, new or replacement roof installation generates an estimated seven to ten million tons of shingle tear-off waste and installation scrap. More than sixty manufacturing plants across the U.S. generate another 750 thousand to one million tons of manufacturing shingle scrap. Landfilling this scrap material when it contains valuable material is both an economic and environmental issue. However, asphalt roofing shingles have excellent recycling potential because they are plentiful in the construction and demolition waste stream; they are mostly generated separately from other wastes and, hence, easy to isolate; and recycling technology and end markets are available. One potential use of the recycled shingles is in the production of asphalt pavement, where use of the recycled material can yield cost savings and potentially even enhance roadway performance.

Asphalt shingle recycling has been identified as possessing a market potential greater than most other components of construction and demolition materials. The potential markets for waste asphalt shingle recycling include use in mixtures for asphalt pavements such as hot mix asphalt (HMA), warm mix asphalt (WMA), and cold asphalt patching; use in roadways as dust control for rural roads (e.g., as temporary roads and driveways); and as a fuel stock for cement kilns. Asphalt shingle recycling not only reduces the requirement for the virgin materials that the shingles are replacing such as binder and aggregate in the asphalt pavement market, but also reduces the use of landfill space.[2] Shingle recycling may also reduce the emission of potentially hazardous components associated with the mining, production, and transport of virgin materials used in the manufacture of binder and aggregates.[3] This analysis looks at the use of the waste shingles in pavement to provide information in support of the Roof to Roads Colorado program and growing regional interests. It is a first look using a more holistic approach at the use of specific recycled materials in the road construction industry.

To assess the environmental benefits of utilizing post-consumer asphalt shingles (PCAS) in pavement production, it is important to be able to measure variations between different mix designs, materials, and required energy inputs. One method for doing so is life cycle assessment, or LCA.[4] LCA is a quantitative accounting of the cumulative environmental impacts of a product or process across all stages of the life cycle. LCA provides a more accurate picture of the true environmental trade-offs in product and process selection.[5]

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[2] Products that only contain materials taken directly from the environment are considered virgin. This does not include materials recovered from a previous use. A final product may contain both virgin and recovered materials.

[3] Townsend, T., Powell, J., and C. Xu (2007). *Environmental Issues Associated with Asphalt Shingle Recycling*. Prepared for the Construction Materials Recycling Association. Innovative Waste Consulting Services, LLC, Gainesville, FL. Retrieved from http://www.shinglerecycling.org/

[4] International Standards Organization (2006). *ISO 14040 - Environmental management - Life cycle assessment - Principles and framework*.

[5] U.S. Environmental Protection Agency (2006). *Life Cycle Assessment: Principles and Practice*. EPA/600/R-06/060. Retrieved from http://www.epa.gov/nrmrl/std/lca/lca.html

> According to ISO 14040, there are four phases in a LCA study:
>
> a) goal and scope definition,
> b) inventory analysis,
> c) impact assessment, and
> d) interpretation.
>
> The goal and scope, including the system boundary and level of detail, of an LCA depends on the subject and the purpose of the study. Goal definition and scoping establish the context in which the assessment is to be made and identify the boundaries and environmental effects to be reviewed for the assessment. Product systems are subdivided into a set of unit processes (see Figure 1) in a flow diagram. Unit processes link together to form a life cycle picture of the system within the defined boundaries.
>
> The life cycle inventory (LCI) analysis provides a compilation and quantification of inputs (raw materials and energy consumed) and outputs (emissions and other releases to the environment) for a given system throughout its life cycle. It is an inventory of these data.
>
> The life cycle impact assessment phase (LCIA) evaluates the potential environmental impacts associated with the inputs and outputs identified in the LCI.
>
> The last phase of LCA is interpretation, or the systematic technique to evaluate the results of the LCI and the LCIA.

While this study does quantify greenhouse gas (GHG) emissions on a common basis – their global warming potential (GWP) in carbon dioxide equivalents – it should not be considered a full LCA. The study does not attempt to compile a full inventory list nor assess all environmental impacts. Instead, by assessing a limited number of inventory items for parts of the life cycle it serves as a first study that may guide future work. For ease of communication, this report will often refer to the analysis as an LCA. More information on these limitations is described in the following section.

2 General Information

This section covers the Goal and Scope of the analysis, as well as the functional unit, boundaries and scenarios covered by the analysis.

2.1 Goal

The goal of this assessment is to compare limited environmental inventory and impacts of seven asphalt mixes with various percentages of reclaimed asphalt and recycled shingles (Table 1) to a baseline of virgin asphalt. The inventory and impacts cover avoided landfill impacts, global warming potential, and criteria and other air pollutants on a cradle-to-gate basis. Energy consumption and resource depletion are considered for select stages in the life cycle. Further, asbestos contained as a fire-retardant in shingles has been raised as an environmental and a health concern, so asbestos information is provided as well. As asphalt production technology has evolved, methods have been developed to reuse materials that would have otherwise been considered waste, as well as new processes that reduce costs and energy consumption. Three of those methods currently being used or experimented with are: (1) recycling asphalt pavement materials after the useful life of the road (processing the pavement and using it in a new mix); (2)

using asphalt shingles in place of portions of the virgin binder and aggregate ingredients; (3) and reducing plant temperatures required for mixing in combination with the use of WMA technologies and recycled pavement.

This study captures how these asphalt production scenarios are being used, or may be used, in the Environmental Protection Agency's (EPA) Region 8 (Colorado, Montana, North Dakota, South Dakota, Utah, and Wyoming). It is important to note this study assumes all asphalt mixes are able to perform under the road conditions for which they are designed. No consideration was given in this project to how these variations might alter the required maintenance or lifetime of a specific mixture. However, some literature suggests that the addition of recycled asphalt shingles (RAS) to asphalt pavement mix increases the pavement's resistance to wear and moisture while decreasing deformation of the pavement and cracking from thermal changes and fatigue.[6] The incorporation of any information regarding the potential changes to performance has been identified as a future research need.

This assessment focuses on the production and transportation of asphalt for road paving within EPA Region 8 states. Colorado and South Dakota contacts provided the most comprehensive shingle recycling data; however, the other states within the Region indicated their interest in shingle recycling opportunities. Those asphalt plants already collecting and using PCAS may alter their energy requirements and emissions as their manufacturing processes change. For instance, not all plants currently own grinding machinery, so they hire a company to come onsite to perform that task.[7] For WMA, data were collected from Colorado and North Dakota. The type of WMA processing occurring in the plants interviewed does not represent all of the potential technologies which might be used to recycle asphalt shingles. The use of water is the type of WMA technology assessed for this study.

2.2 Functional Unit

The functional unit is the production of one short ton of asphalt transported to a road construction site. All results are reported with respect to the functional unit. For a frame of reference on this functional unit and the results presented in this report, it takes approximately 387 tons of asphalt to pave one 12-foot wide lane, with a one-inch thickness, for one mile. In other words, one ton of asphalt will pave the same width and depth road for a length of 13.6 feet. The total amount of material used is the same for all of the mix designs.

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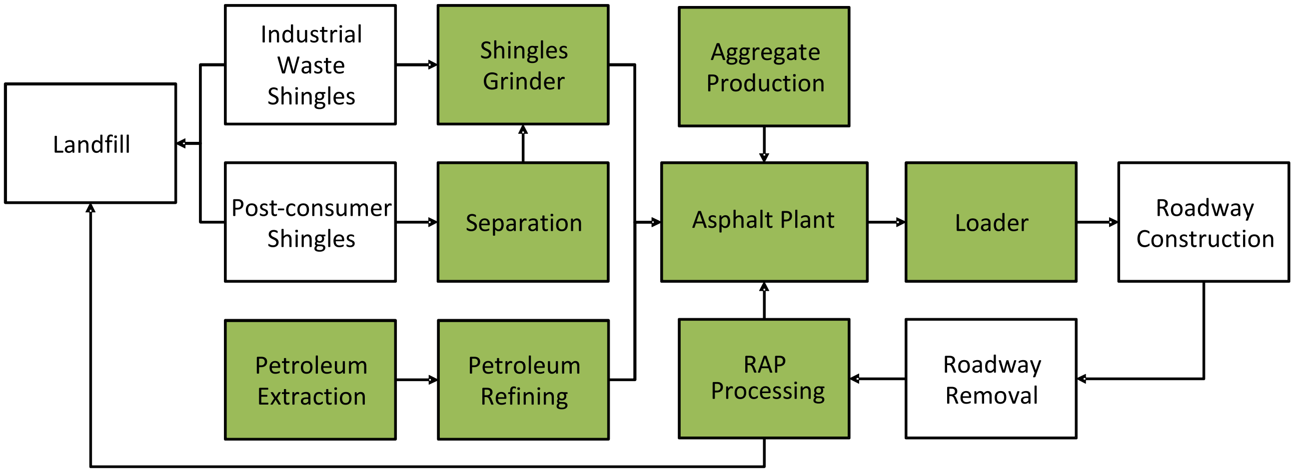
[6] NAHB Research Center (1998). *From Roofs to Roads…Recycling Asphalt Roofing Shingles into Paving Materials.* NAHB Research Center. Upper Marlboro, MD. Accessed June 27, 2011. Retrieved from http://www.epa.gov/wastes/conserve/rrr/imr/cdm/pubs/roof_br.pdf

[7] If a plant were to install grinding equipment within their facility it would increase their direct energy use but not necessarily the total amount of energy used in the system.

2.3 Scope

The scope of an LCA determines what portions of the system are examined within effort and resource constraints. Figure 1 represents the production streams for asphalt, including the potential options of using reclaimed asphalt pavement (RAP) and RAS as aggregate and binder substitutes, respectively. The shaded boxes represent steps that were considered and included in this study. The white boxes were accepted as parts of the pathway, but are not included in this study and will be addressed later in the text.

Figure 1: System Boundaries



Virgin asphalt pavement for road construction consists of three primary components: aggregate of various sizes, binder, and possible additives such as lime. The life cycle of asphalt cement, or binder, starts with the extraction of crude oil, and includes transportation and refining processes. Data for aggregate and crushing and sizing sand was incorporated, and transportation of the aggregate is included. A small amount of lime is used as a stabilizer and to mitigate against moisture damage in the asphalt and therefore its production is also included.

For the RAS and RAP used in asphalt mixes, this study assumes all upstream production emissions to be related to the products' initial useful life cycle. As part of a sensitivity analysis for RAS, the upstream emissions are allocated between the shingles and the asphalt (allocation is further explained in Section 2.5.1). Because this study does not include the end of life, no assumptions are made regarding further recycling of materials coming from the shingles. Recycled asphalt shingles fall into two categories: industrial manufacturing waste and tear-offs from roofing projects. Industrial manufacturing waste comes straight from the shingles manufacturing process. When manufacturing a batch of shingles, a portion of undesirable product is generated until the precise specifications and color are reached. The materials produced before specifications are reached are considered waste and would otherwise be landfilled. This is considered clean waste and can be ground and included in the mix without additional steps. Tear-off waste is generated primarily by residential housing roof replacements. Additional components, such as nails, tar or felt paper backing, and other types of deconstruction debris, may be transported with the shingles to the asphalt facility. These contaminants must be removed before the shingles are ground up for use in the asphalt mix. The transportation for the RAS and RAP are included for comparison to that of virgin materials (see Section 2.4 for more information).

The endpoint for this study occurs when the asphalt has been transported to the construction site. This point takes into consideration the fact that WMA has the ability to be transported greater distances than HMA and still achieve compaction. The physical activities associated with laying, maintaining, and removing of the pavements, as well as the emissions from those activities, are assumed to be similar across all scenarios and therefore are not included in the boundaries of this analysis. Thus, this study's results are most useful for comparing recycled asphalt paving options, and not as a full inventory of the process from roofs to roads.

2.4 Process Description

In general, asphalt is made through the following processes. The binder, typically bitumen obtained from an oil refinery or manufacturer, is a carefully refined residue from the distillation process of crude oil. Additional ingredients (primarily aggregates) are added to the binder at the asphalt mixing facility to create a desired asphalt design. Ingredients are typically stockpiled or stored at the facility until ready for use. Typical aggregates range from one and one half inch rocks to fine aggregates such as vertical shaft impact (VSI) sand. Data provided by suppliers indicated that VSI sand, present in shingles, is used for a portion of the aggregate. The varying sized aggregates are key factors in the finished pavement's strength and integrity. Some asphalt ingredients may require additional processing before use. For instance, RAP is generally milled off of a road and stockpiled or processed into finer grade material before being added to the mixture process. Most Colorado companies use a counter-flow drum mixer for the production of asphalt. Aggregates are added to and heated in the drum mixing chamber, where the heat is transferred to the RAP and RAS, and mixed with the virgin binder. After the mixture is consistent throughout, it is either transferred to storage bins or silos that are heated, or into trucks for transport to a paving site. Once at the paving site, the asphalt is placed and compacted with a roller.

The utilization of RAP allows for a decrease in the required amount of virgin aggregate. Additionally, as RAP is heated, the binder in the RAP is released and a portion of it is used with the addition of new materials to replace a portion of the raw or new binder. Recycling asphalt pavement thereby saves landfill space and reduces greenhouse gas emissions associated with landfilling. It also reduces the upstream impacts from aggregate processing (mining and sizing) and transportation since virgin aggregate travels farther distances than recycled aggregate, with distances increasing based on regional availability.[8] In a parallel comparison, asphalt shingles contain the asphalt cement binder that can be used in asphalt pavement after the shingles are sent through a grinding process. The roofing asphalt is typically conditioned (i.e. oxidized) and therefore a higher (stiffer) grade of binder.[9] Utilizing ground-up shingle scrap from shingle-manufacturing waste and roofing/re-roofing activities in asphalt mixes was first attempted in the

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[8] Reiner, M. (2007). *Technology, Environment, Resource and Policy Assessment of Sustainable Concrete in Urban Infrastructure.* University of Colorado Denver.

[9] Athena Sustainable Materials Institute (2001). *A Life Cycle Inventory for Road and Roofing Asphalt*. Prepared by Franklin Associates, Ltd., Ottawa. Retrieved from http://calculatelca.com/wp-content/themes/athena/images/LCA%20Reports/Road_And_Roofing_Asphalt.pdf

early 1990s. Asphalt shingles typically contain between 19 and 36 percent asphalt cement,[10] while RAP typically contains between three (3) and seven (7) percent asphalt cement by weight.[11] Based on discussions with industry suppliers, it is assumed that the RAP contains four (4) percent binder and RAS contains 24.3 percent by weight.

Asphalt mixtures are produced at a variety of temperatures: hot, cold, and warm. Each is useful for different types of paving. Asphalt mixtures with only virgin components are not commonly utilized in Region 8, primarily because of the cost benefit of utilizing recycled and reclaimed asphalt materials. HMA and WMA are primarily used to pave roads, while cold mixes are used to temporarily patch overlays and small sections of roads. WMA allows the producers of asphalt pavement material to lower the temperatures at which the material is mixed and placed on the road. These temperature reductions have the benefits of cutting fuel consumption, decreasing the production of GHG emissions, allowing for longer transportation distances, and extending the paving season. The extended paving season is a notable benefit in the cold weather climates of Region 8.

WMA has been produced in the United States since 2004, when the National Asphalt Pavement Association introduced the technology from Europe. The original goal of utilizing WMA was to create durable asphalt equal to or better than HMA, while lowering emissions. The greatest benefit to the asphalt pavement industry in the U.S. from WMA has been as a compaction aid in order to achieve density as a superior performing pavement.[12] Thus, WMA has a longer window for placement and compaction than HMA; as well as has reduced emissions and lower excess heat emissions from the cooling asphalt due to the smaller temperature differential.[13] WMA is generally made from the same types of binder and aggregates as HMA, but there may also be the addition of chemicals or additives to help with the coating of the aggregate at lower temperatures. The addition of chemicals and other additives are not accounted for in this study. According to a supplier in EPA Region 8, the most common technology they use is the addition of water into the hot asphalt binder before it is mixed with the aggregate. Water is added to the binder and inside the mixing chamber, foam is created, which improves the even-coating of the aggregates. Among the suppliers interviewed for this study, only a select few are not seeing the full 40-50 degree F temperature reductions touted by some proponents.

Despite some initial concerns about long term performance, the suppliers generally like working with WMA, and WMA is performing well at test sections at the National Center for Asphalt

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[10] Townsend, T., Powell, J., and C. Xu (2007). *Environmental Issues Associated with Asphalt Shingle Recycling*. Prepared for the Construction Materials Recycling Association. Innovative Waste Consulting Services, LLC, Gainesville, FL. Retrieved from http://www.shinglerecycling.org/

[11] Federal Highway Administration and Recycled Materials Resource Center. User Guidelines for Waste and Byproduct Materials in Pavement Construction. FHWA-RD-97-148. Accessed April 8, 2013. Retrieved from http://www.fhwa.dot.gov/publications/research/infrastructure/structures/97148/rap131.cfm.

[12] National Asphalt Pavement Association. Written correspondence with Dr. Howard Marks and Dr. Audrey Copeland. September 20, 2012.

[13] Moore, W. (2007). "Warm-Mix Asphalt (WMA) Potentially Can Provide Important Benefits for Paving Contractors, Reduce Fuel Costs, and Diminish Green-House Gases.*" Construction Equipment*. Accessed June 27, 2011. Retrieved from http://www.constructionequipment.com/warm-mix-asphalt-wma-potentially-can-provide-important-benefits-paving-contractors-reduce-fuel-costs

Technology and in projects across the country.[14,15] The lower temperature associated with WMA allows for mixtures to be transported longer distances and adds flexibility by extending the paving season. Also, as WMA pavement reaches the end of its life cycle, it has the same ability to be used as RAP in a new asphalt mix.

A number of sources are available for more information regarding asphalt manufacturing, warm mix asphalt, and the use of recovered materials. The National Asphalt Pavement Association publishes a textbook titled *Hot Mix Asphalt Materials, Mixture Design & Construction* (2009). Resources such as Krivit (2007), Aschenbrener *et al.* (2011), and Townsend *et al.* (2007) may also be helpful.

2.5 Scenarios

Table 1 provides the eight unique systems or mixture scenarios, seven for HMA and one for WMA, assessed in this study. These scenarios come from 2010 and 2011 mix designs provided by manufacturers. All of the 20% RAP and the virgin mix designs are from the 2010 paving season while the remaining two mix designs (scenarios 7 and 8) are from the 2011 paving season. The HMA scenarios include a virgin mix, a 20% RAP mix, four RAS and RAP mixes, and one mix with just RAS. The WMA scenario has the same 20% RAP mix design with an adjustment to the energy requirements.

Table 1: Study Scenarios

Scenario	Type of Mix	Design Mix	Referred To As
1	HMA	Virgin Materials	Virgin
2	HMA	Hot Mixed Reclaimed Asphalt Pavement (20%)	20% RAP
3	WMA	Warm Mixed Reclaimed Asphalt Pavement (20%)	WMA 20% RAP
4	HMA	20% Reclaimed Asphalt Pavement and 3% Recycled Asphalt Shingles	20% RAP-3% RAS
5	HMA	20% Reclaimed Asphalt Pavement and 5% Recycled Asphalt Shingles	20% RAP-5% RAS
6	HMA	20% Reclaimed Asphalt Pavement and 7% Recycled Asphalt Shingles	20% RAP-7% RAS
7	HMA	17% Reclaimed Asphalt Pavement and 3% Recycled Asphalt Shingles	17% RAP-3% RAS
8	HMA	5% Recycled Asphalt Shingles	5% RAS

The virgin mix is a baseline to which all of the other scenarios will be compared. Without this, it would be difficult to determine the potential overall reduction in environmental impact of the other scenarios. Currently, the combination of HMA and RAP is the most commonly used asphalt mix. While RAP can be added in as 10 to 80 percent of the mass of the asphalt, most states set a cap at 15 to 20 percent before a change in binder grade is required, and some states allow up to 30

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[14] National Center for Asphalt Technology at Auburn University. Warm-mix and RAP: A Winning Combination. Accessed December 17, 2012. Retrieved from http://ncat.us/newsroom/wma-rap-combo.html

[15] Aschenbrener, T *et al.* (2011). *Three-Year Evaluation of the Colorado Department of Transportation's Warm-Mix Asphalt Experimental Feature on I-70 in Silverthorne, Colorado*. National Center for Asphalt Technology. Accessed December 17, 2012. Retrieved from http://ncat.us/files/reports/2011/rep11-02.pdf

percent RAP.[16] The asphalt binder in the RAP has chemically changed over the time of the asphalt's life. When adding in large quantities of the RAP, these changes in the recycled asphalt binder make it hard for it to mix and create a homogenous compound with the virgin binder. By lacking a homogenous compound for the binder, the asphalt pavement may have performance issues later in its life.[17] The ground-up pavement has two primary benefits: (1) it reduces the virgin aggregate needed in the asphalt, and (2) when it is heated, usable binder remains such that it reduces the amount of virgin binder needed. Most states allowing the use of RAS in asphalt are capping it at five (5) percent. Another option is limiting the concentration of recycled asphalt binder as the Colorado Department of Transportation does in its newly modified Section 401, which sets the limit of recycled asphalt binder at no more than 30 percent.[18] The following scenarios meet that specification: Virgin, 20% RAP, WMA 20% RAP, 17% RAP-3% RAS, and 5% RAS. The 20% RAP-3% RAS mix is only a fraction above (0.03% by mass) the recycled content value so it may be usable under different recycled asphalt binder concentration assumptions. Currently, not all municipalities in Colorado have adopted this specification for their roads. As part of this, the 20% RAP-5% RAS and 20% RAP-7% RAS scenarios have been included to show what overall environmental impact reductions could be created should the state specification be modified in future years.

2.5.1 Allocation

When materials from one product system are recycled at the end of their life into a second product system it is possible to divide the upstream emissions between the two. This is similar to, but distinct from, co-product allocation.[19] Only the steps in the life cycle that are necessary for both systems are shared (e.g., none of the energy for making a roofing shingle out of the raw materials is allocated to asphalt pavement). Recycling allocation is an alternative to the cut-off-method, where system boundaries are drawn such that recovered materials come with no burdens other than collection and processing.[20] The cut-off-method is the primary approach used in this study.

In order to determine how sensitive the results are to the choice of post-consumer modeling methods, emissions for the following materials and processes are apportioned equally between the shingles and the asphalt pavement:

- Cradle-to-gate production of materials used in shingles;
- Transportation of recovered shingles to a grinding facility;
- Processing recovered shingles for use in asphalt pavement;
- GHG emission credit for avoided landfill disposal.

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[16] U.S. Department of Transportation, Federal Highway Administration (2011). *Reclaimed Asphalt Pavement in Asphalt Mixtures: State of the Practice*. Retrieved from http://www.fhwa.dot.gov/publications/research/infrastructure/pavements/11021/11021.pdf

[17] Al-Quadi, I., M. Elseifi, and S. Carpenter (2007). "Reclaimed Asphalt Pavement – A Literature Review." Illinois Center for Transportation. Accessed May 18, 2011. Retrieved from http://ict.illinois.edu/publications/report%20files/FHWA-ICT-07-001.pdf

[18] Colorado Department of Transportation. Revision of Section 401 Reclaimed Asphalt Shingles. April 26, 2012.

[19] Co-product allocation of environmental impacts is necessary when a process produces more than one valuable product and involves apportioning the impacts between those products. Recycling allocation apportions energy, materials, and emissions between different systems when materials are reused.

[20] For a more complete discussion of postconsumer recycling see Section 3.4.3 of Sauer, 2012.

No allocation of RAP is done because the asphalt pavement end of life is not considered in this study. In this study, it is noted in the text where allocation has been applied to provide an alternative set of results.

3 Inventory Data Collection

Primary data collection was accomplished by interviewing multiple suppliers of recycled shingle asphalt, augmented with publicly available facility environmental inventory data.[21] Suppliers from Colorado, North Dakota, South Dakota, and Montana were successfully contacted for information. Suppliers in Colorado and South Dakota are currently using shingles or plan to use shingles in their asphalt mixes. Additional suppliers in Colorado and North Dakota placing WMA also provided information.

The information collected from suppliers was directly related to the products being produced. Requests were made for all energy inputs, including the type(s) of energy being utilized, because each type of energy has different upstream combustion and emissions profiles. Energy usage was also collected for each piece of machinery, as applicable.

In addition to the data collected from suppliers, upstream profiles were collected from publicly available life cycle inventory databases. These upstream profiles are used in combination with combustion profiles for the production of ingredients in the asphalt. The primary energy sources consumed are diesel, binder, natural gas, and electricity. Unit process data for petroleum refining, fuel extraction and combustion, limestone, lime, and truck transportation were obtained from the National Renewable Energy Laboratory's U.S. Life Cycle Inventory Database (U.S. LCI).[22] Electricity was assumed to be a mix of generation representative of the U.S. mix.[23] Uncertainty is introduced when selecting a more regionally specific generation profile.[24]

All boiler and industrial equipment profiles were obtained from the U.S. LCI Database. The profiles contain emission factors on the basis of fuel use taken from EPA's AP-42, *Compilation of Air Pollutant Emission Factors,* and represent either external or internal combustion sources. Boiler processes are used in the model whenever heating is involved and industrial equipment processes are used for steps such as crushing and grinding. In this study, natural gas is used as a heating fuel and diesel is used for processing and loading.

Sand and aggregate profiles were taken from the Building for Environmental and Economic Sustainability (BEES) database.[25] These profiles contain information on the energy needed to produce course and fine aggregate, but the information is not matched to specific size ranges.

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[21] Primary data is directly tracked or measured and can include purchasing records and production amounts.

[22] National Renewable Energy Laboratory. U.S. Life Cycle Inventory Database. Department of Energy. Website updated September 24, 2010. Accessed February 15, 2011. Retrieved from http://www.nrel.gov/lci/database/

[23] Ibid

[24] Weber, C. L., Jaramillo, P., Marriott, J., and C. Samaras (2010). "Life Cycle Assessment and Grid Electricity: What Do We Know and What Can We Know*?" Environmental Science & Technology*, 44(6): 1895-1901.

[25] National Institute of Standards and Technology, Building and Fire Research Laboratory (2007). BEES: Building for Environmental and Economic Sustainability, Version 4.0e.

Energy values, using both diesel and electricity, were assumed to be the same as the profile for the aggregate production for “Generic Concrete Products with Portland Cement.”

The option of a credit has been added because some of the ingredient materials are being diverted from the landfill. EPA’s Waste Reduction Model (WaRM) calculates and totals GHG emissions of baseline and alternative waste management practices based on a life cycle approach.[26] The model assigns GHG emissions to different materials that are disposed of in a landfill, recycled, composted, or combusted. It displays the difference in emissions if the material is diverted from its initially planned disposition, like a landfill, to an alternative one. The database will also depict GHG emissions reduced if the materials do not have to be initially produced. The tool includes both asphalt concrete (i.e. asphalt) and asphalt shingles. An assumption was made that these materials initially would have been landfill-bound, but they are now being diverted through recycling in order to obtain the GHG emissions avoided for this credit.

It is assumed that asphalt and aggregate are transported in a Class 8 single-unit truck. Data on the emissions per ton-mile are taken from the U.S. LCI Database. As the transportation of different materials will have different masses, all emissions were determined on a per ton-mile basis. It is assumed for the transportation of the asphalt to the construction site that the dump truck travels a distance of 30 miles. Virgin aggregate is assumed to travel 36 miles and recycled materials nine (9) miles.[27]

4 Life Cycle Inventory

A proprietary set of asphalt mix designs were obtained from one of the suppliers. They provided aggregate mixes for the Virgin, 20% RAP, 20% RAP-3% RAS, 20% RAP-5% RAS, 20% RAP-7% RAS, 17% RAP-3% RAS, and 5% RAS. In all mixes, 5% of the weight of the inputs was binder. The amount of virgin binder decreases as the RAP and RAS are used as substitutes. Shingles are assumed to be 24.3 percent asphalt while the remainder is sand, fiberglass fibers, and other materials. The percentage of RAS included in the batch was multiplied by the percent binder in the shingles, to determine the estimated reduction of additional asphalt cement to the mixture. The RAP creates a reduction of 0.8 percent additional binder when used as 20 percent of the weight of the mix design with a concentration of four (4) percent binder, a value provided by the supplier of the mix designs. The actual binder concentration in both the RAP and the RAS is likely to vary according to what is collected for recycling. This variable should be considered when calculating the binder reduction in other scenarios.

A spreadsheet was developed which examines each stage of production and then sums the values for the overall emissions of the mix design. The aggregate, sand, and lime production values are summed and considered to be the “Aggregate Production” value. The individual processing steps for RAP and RAS have been defined separately, since they are used variably depending on the mix. All mixes require binder from the petroleum refinery, have the aggregates heated using

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[26] U.S. Environmental Protection Agency (2010). Waste Reduction Model. Accessed February 15, 2011. Retrieved from http://www.epa.gov/climatechange/wycd/waste/calculators/Warm_home.html

[27] Reiner, M. (2007). *Technology, Environment, Resource and Policy Assessment of Sustainable Concrete in Urban Infrastructure*. University of Colorado Denver.

natural gas, and are mixed in a drum plant. Transportation is variable based on the assumed distance the material is traveling.

5 Inventory and Impact Assessment Results

The following sections look at different emissions and impacts separately. Asbestos content, energy consumption, resource depletion, avoided landfill impacts, greenhouse gases, and criteria and other air pollutants are discussed. *The impacts reported here are not the results of a full impact assessment as dictated by the LCA method.* There were data gaps in the primary data collection that may skew the results of employing an impact assessment indicator tool such as EPA's Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts (TRACI). This can be seen in Figure 6, which shows many of the criteria air emissions coming from petroleum refining – a secondary process in this study's data collection. A more complete inventory from the primary processes of this study could result in a complete and robust impact assessment.

5.1 Asbestos

Asbestos is addressed here due to legacy concerns regarding the inclusion of asbestos as a fire-retardant in roofing materials. However, asbestos was not quantified as part of our inventory. Historically, asbestos was used in some shingles and roofing products. According to the U.S. Geological Survey (USGS) and the Asbestos Information Association/North America, asbestos is not used in the production of asphalt shingles today, and was phased out as a material used in shingles in the early 1980s. The shingle manufacturers have reported to the Construction & Demolition Recycling Association that they phased out the use of asbestos in shingles in the mid-1970s.[28] According to the USGS, asbestos is still imported and utilized in roofing products, but the total imported has declined over time.[29] The roofing products that still utilize asbestos include roof coatings, cements, and mastics. Some types of other asphalt roofing products, such as roll roofing, adhesives, paints, or waterproofing compounds may contain asbestos. Therefore, it's possible to find asbestos-containing material on a roof, particularly when roofing is built-up (layered) or because the accompanying materials contain it. If these materials are to enter a recycling center for grinding, the asbestos content may be hazardous to workers.

Analytical results for over 27,000 asphalt shingle samples collected at various facilities in the U.S. indicated that approximately 1.5% of all samples contained enough asbestos to be considered asbestos-containing material.[30] Asbestos-containing material is defined by EPA's National Emission Standards for Hazardous Air Pollutants (NESHAP) as any material containing more than one (1) percent asbestos, which is determined by using polarized light microscopy. Many of the asbestos detections from the samples were caused by other materials, such as mastic, that were attached to the asphalt shingles. For roofs sampled in Colorado, asbestos detections have been nearly congruent with the national average, and when found, have not been found in the shingles

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[28] Construction & Demolition Recycling Association. Written correspondence with William Turley. August 6, 2012.

[29] U.S. Geological Survey (2011). Mineral Commodity Summaries. Accessed August 15, 2011. Retrieved from http://minerals.usgs.gov/minerals/pubs/commodity/asbestos/mcs-2011-asbes.pdf

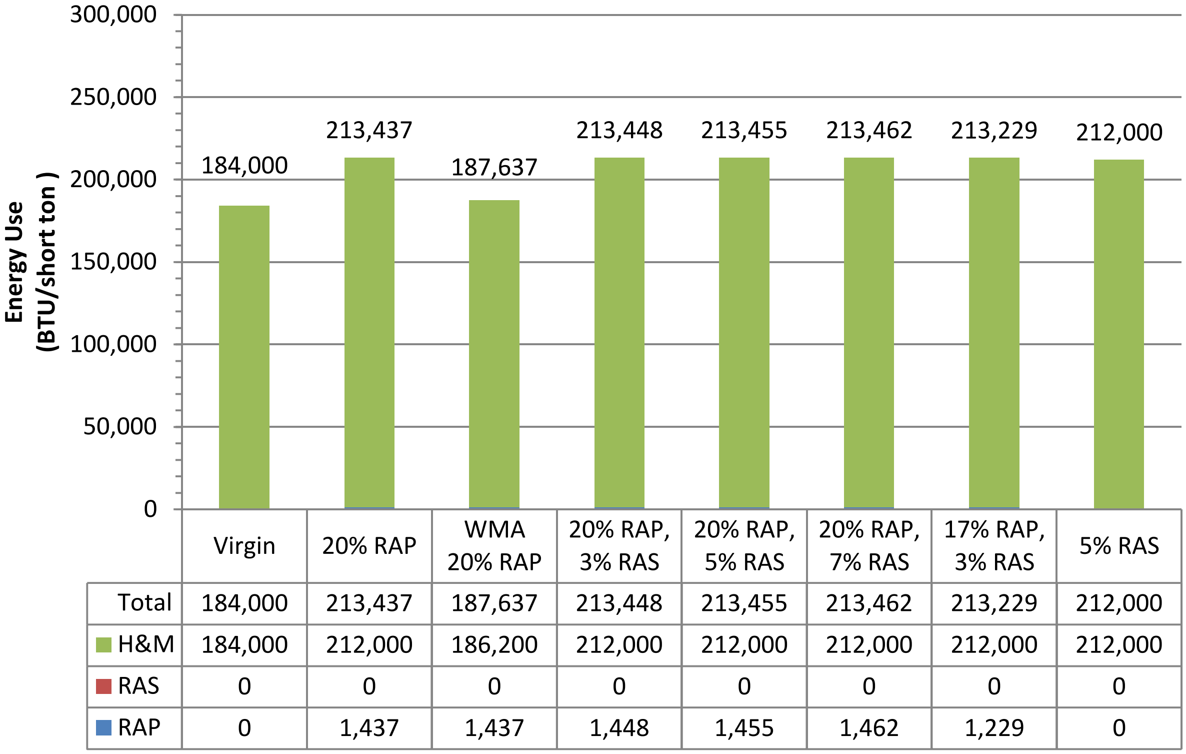
[30] Construction & Demolition Recycling Association. Shinglerecycling.org. Accessed August 15, 2011. Retrieved from http://www.shinglerecycling.org/content/asbestos-asphalt-shingles

themselves, but the accompanying roofing materials. Few detections of asbestos may be specific to the region as storms that cause damage to the roofs are common and therefore the average life of roofs is shorter than in other areas of the country. Also, in cases where roofing companies are testing for asbestos from shingles intended for recycling, roofers are sorting out asbestos-containing material for disposal so that it does not reach the production facility. Currently, asbestos testing practices in Region 8 include sampling roofs and/or loads, and visual screening along with sampling pre-processed shingles and finished ground product. The Colorado Department of Transportation's standard specification requires a minimum of three tests for asbestos every 1000 tons of processed RAS material. So, while asbestos should be considered when recycling asphalt shingles because of its known health hazards, it is not scaled and reported as part of the life cycle inventory here.

5.2 Energy Use

Only energy consumed during the preparation of recovered materials and inside the asphalt processing plant is considered in this study. This energy use represents data collected directly from manufacturers, and is not representative of the entire life cycle. Thus, the differences in combustion, which occur at the plant when the ingredients are mixed together, are the focus for quantifying the effects of RAP, WMA, and RAS on energy consumption among the eight different mixtures. The RAS and RAP values represent the energy demands for processing.

Figure 2: Energy Consumption During Select Life Cycle Stages



	Virgin	20% RAP	WMA 20% RAP	20% RAP, 3% RAS	20% RAP, 5% RAS	20% RAP, 7% RAS	17% RAP, 3% RAS	5% RAS
Total	184,000	213,437	187,637	213,448	213,455	213,462	213,229	212,000
🟩 H&M	184,000	212,000	186,200	212,000	212,000	212,000	212,000	212,000
🟥 RAS	0	0	0	0	0	0	0	0
🟦 RAP	0	1,437	1,437	1,448	1,455	1,462	1,229	0

The drying, heating and mixing (H&M) of the aggregate dominates the processes at the manufacturing facility. The use of RAP with WMA provides an approximate 12 percent energy reduction compared to the HMA 20% RAP counterpart. Greater potential reductions are likely if states will allow asphalt production facilities to lower temperatures for mixing the WMA. However, because this is still considered a relatively new technology, the maximum energy reductions cannot yet be portrayed.

5.3 Resource Depletion

As economic, natural resource scarcity, and environmental compliance pressures increase, most industries are seeking ways to make their processes more efficient. The petroleum refining industry is no different. Bitumen, used as the binder in asphalt, is essentially a byproduct of the petroleum refining process, one which has historically been utilized as a valuable component of other products and has not been wasted. However, from the refining industry's perspective, asphalt has a much lower value than other refinery products, and processes are designed to extract as much high-value product as possible.[31] As this shift to higher value products occurs, less binder is available for use in pavement production.

The oil embargo of the 1970s also drastically reduced the oil available for petroleum refining. It was then that pavement recycling was initiated, based on the discovery that asphalt cement binder was still viable after its initial useful life. The asphalt paving industry later began to use shingles in an effort to replace expensive virgin asphalt cement and aggregate. Due to the combination of RAP and RAS being used as a substitute for binder, this study assumed no change in petroleum resource depletion (i.e., there is no reduction of crude oil extraction directly related to the binder production).[32]

As the deposits in closest proximity to asphalt plants are extracted, the transportation distances for the aggregate increase and ultimately increase the overall emissions. Transportation accounts for a quarter of the GHG emissions created during asphalt production, regardless of the mixture scenario. By decreasing the quantity of virgin aggregate that is transported over these increasing distances, reductions in the overall emissions will be made. Table 2 shows the quantities of aggregate from the virgin extraction and the recycling centers. Beyond the use of RAP and RAS as a binder replacement, consideration may be given to other recycled materials that could potentially create an adequate virgin aggregate substitute.

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[31] U.S. Energy Information Agency (2012). U.S. Refinery Yield of Asphalt and Road Oil. Accessed December 12, 2012. Retrieved from http://www.eia.gov/dnav/pet/hist/LeafHandler.ashx?n=PET&s=MAPRYUS3&f=A

[32] Using a value of 24.3 percent asphalt in shingles, 4.9 pounds of petroleum are no longer needed for each 1 percent of RAS included in a ton of asphalt cement. This can be used as an upper boundary when considering reduction in resource depletion.

Table 2: Quantities of Virgin and Recycled Aggregates

Scenario	Virgin Quantity (lb/short ton)	Recycled Quantity (lb/short ton)
Virgin	1,881	-
20% RAP	1,514	383
WMA 20% RAP	1,514	383
20% RAP-3% RAS	1,467	444
20% RAP-5% RAS	1,436	485
20% RAP-7% RAS	1,404	527
17% RAP-3% RAS	1,523	386
5% RAS	1,809	96

5.4 Avoided Landfill Impacts and Greenhouse Gas Credit

Because virgin asphalt is considered to be the baseline of this comparison, a credit is applied for the materials that are recycled and avoid landfill disposal. Asphalt materials do not biodegrade in a landfill, so no emissions of methane are associated with the materials themselves in a landfill.[33] However, greenhouse gas emissions are emitted during transportation to the landfill and the operation (i.e. equipment use) of the landfill itself. Avoiding the landfill means a reduction in these greenhouse gases.[34] The mass and volume reductions achieved by recycling the RAP and RAS are provided in Table 3.

Table 3: Landfill Impacts – Mass and Volume Reductions from Recycling RAS and RAP

Scenario	Mass Avoided (lbs/short ton)	Volume Avoided (cubic yards/short ton)
Virgin	0	0
20% RAP	383	0.28
WMA 20% RAP	383	0.28
20% RAP-3% RAS	444	0.42
20% RAP-5% RAS	485	0.52
20% RAP-7% RAS	527	0.62
17% RAP-3% RAS	386	0.38
5% RAS	96	0.23

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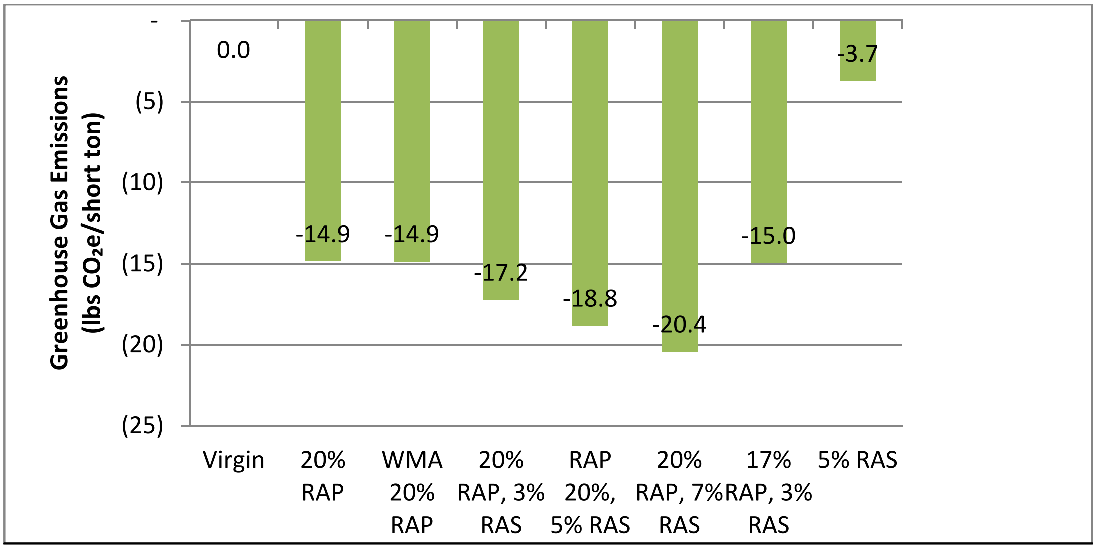
[33] According to the WaRM documentation, 82 percent of residential shingles use a fiberglass felt backing. The WaRM model does not address shingles that may contain organic material.

[34] U.S. Environmental Protection Agency. Waste Reduction Model (WaRM). Version 12, February 2012.

Figure 3: Greenhouse Gas Credit for Avoided Landfill, No Allocation



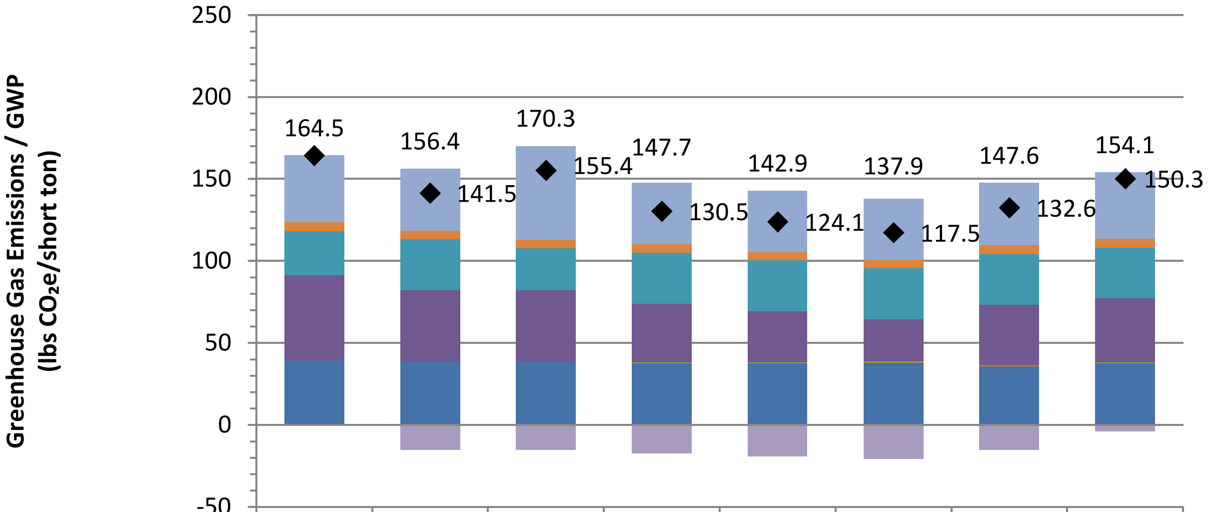
The GHG values for this credit are shown in Figure 3. Note that since this study quantifies both an avoided landfill volume and an associated greenhouse gas credit associated with that volume reduction, care must be taken if the results are fed into an impact assessment tool to not double count the greenhouse gas credit.

If half of the credit from diverting RAS is allocated to the original shingles, the overall savings for this stage of the life cycle decreases. The change in total results is limited by the small amount of RAS included in the asphalt – more of the credit comes from keeping RAP out of a landfill. In the cases with 5% RAS, the credit decreases by approximately 2 pounds CO_2e per short ton.

5.5 Greenhouse Gases

When examining the life cycle GHG emissions attributed to the various mix designs, there is a three (3) percent reduction in GHG emissions when switching from the 20% RAP to the WMA 20% RAP assuming a 30 mile final product transport distance. However, since GHG emissions vary with the distance the asphalt is transported, when the feasible transport distance for the WMA is doubled from 30 miles to 60 miles, the WMA 20% RAP GHG emissions are nine (9) percent higher. Figure 4 illustrates these life cycle GHG emissions, or the global warming potential (GWP). The aggregate and mixing chamber GHG emission values stay relatively consistent across the board with major contributions — while GHG emissions from petroleum refining for the binder are reduced as the higher concentrations of secondary binder are introduced. (Note: The shingle and RAP processing emissions are difficult to discern due to the scale of the graph in this report. Variances in pavement processing and shingle grinding emissions are generally small compared to the overall results.) The inclusion of the landfill greenhouse gas emissions credit results in a somewhat larger reduction. The global warming impacts in carbon dioxide equivalents are calculated using IPCC 2007 100-year GWPs of 25 for methane and 298 for nitrous oxides.

Figure 4: Greenhouse Gas Emissions, No Allocation



	Virgin	20% RAP	WMA 20% RAP	20% RAP, 3% RAS	RAP 20%, 5% RAS	20% RAP, 7% RAS	17% RAP, 3% RAS	5% RAS
Subtotal	164.5	156.4	170.3	147.7	142.9	137.9	147.6	154.1
■ Landfill GHG Credit	-	(14.87)	(14.87)	(17.24)	(18.83)	(20.44)	(14.97)	(3.73)
■ Transportation	41.0	37.8	57.1	37.3	37.2	37.0	38.0	40.4
■ Loader	5.3	5.3	5.3	5.3	5.3	5.3	5.3	5.3
■ Heating & Mixing	27.0	31.0	25.7	31.0	31.0	31.0	31.0	31.0
■ Petroleum Refining	51.8	43.5	43.5	35.9	30.9	25.9	37.2	39.2
■ Shingles Grinding	0.0	0.0	0.0	0.3	0.6	0.8	0.3	0.6
■ RAP Processing	0.0	0.3	0.3	0.3	0.3	0.3	0.3	0.0
■ Aggregate	39.5	38.5	38.5	37.5	37.6	37.6	35.6	37.6
◆ Net	164.5	141.5	155.4	130.5	124.1	117.5	132.6	150.3

Petroleum refining is the largest source of GHG emissions when no recovered materials are used, with aggregate production and all transportation steps each contributing to approximately a quarter (~25%) of the total. As the amount of recovered content increases, the emissions from petroleum refining decrease, leaving it equal to or slightly less than transportation and aggregate production in most cases. Around 70 percent of GHG emissions related to aggregates are actually from lime production, which releases CO_2 during production.

Because the incoming transportation of aggregates and the final transportation are roughly equal in most of the cases considered here, shortening the distance traveled for either step can have a significant impact on the total GHG emissions. The WMA case has considered a longer final transportation distance (60 miles rather than 30), and the increased emissions can be seen in the results.

The following table shows the reductions in greenhouse gas emissions for each scenario from the baseline of virgin asphalt in both lbs CO2e/short ton and percentage values.

Table 4: Change in Greenhouse Gas Emissions by Scenario

Change (lbs CO_2e/short ton)	20% RAP	WMA 20% RAP	20% RAP, 3% RAS	20% RAP, 5% RAS	20% RAP, 7% RAS	17% RAP, 3% RAS	5% RAS
With no Landfill Credit	-8.1	5.8	-16.8	-21.6	-26.6	-16.9	-10.4
	-5%	4%	-10%	-13%	-16%	-10%	-6%
With Landfill Credit	-23.0	-9.1	-34.0	-40.4	-47.0	-31.9	-14.2
	-14%	-6%	-21%	-25%	-29%	-19%	-9%

Table 4 shows that the greatest reductions in greenhouse gas emissions come from the largest percentage inclusion of both RAP and RAS, at 16 percent without the avoided landfill credit and 29 percent with the landfill credit. All scenarios except the WMA show a reduction in GHG emissions with or without the landfill credit, but larger margins when the avoided landfill emissions are included.

GHG emissions assigned to the system increase up to five (5) percent when allocation is performed between the shingles and the asphalt pavement. This is for the case with 7% RAS content, and the reduction scales linearly. The increases are due to the reduction in landfill gas GHG credit and emissions associated with material production.

5.6 Criteria and Other Air Emissions

Criteria air pollutants consist of six common air pollutants found in the U.S. that the EPA regulates under the Clean Air Act with human health and environmental standards, called the National Ambient Air Quality Standards (NAAQS). Criteria air pollutants consist of particulate matter (PM), ground-level ozone, carbon monoxide (CO), sulfur dioxide (SO_2), nitrogen oxides (NO_x), and lead (Pb). Volatile organic chemicals (VOC) are included here to represent ozone since they are a precursor for ozone formation, and ozone is not emitted directly into air. Sulfur oxides (SO_x) are represented here and include SO_2. In addition, mercury (Hg) and ammonia (NH_3) emissions are quantified.

The relative magnitude of criteria air pollutants follows a similar trend as the GHG emissions, as seen in Figure 5**.** This correlation is because most of the emissions take place during fuel combustion. Carbon monoxide is the largest emission by mass, followed by sulfur oxides, nitrogen oxides, and particulate matter.[35]

Figure 6 shows the results for the 20% RAP-5% RAS mix, with the breakdown of emissions for each life cycle stage. Aggregate production accounts for almost all lead, mercury, and PM emissions. The lead and mercury are from coal combustion during lime production, and the PM is from process emissions. Petroleum refining accounts for most of the remaining emission releases. Combustion processes in asphalt plants and transportation account for just over a third of SO_x and NO_x emissions, respectively.

Because petroleum refining is a significant source of air emissions in the system, allocating some of the burdens from materials used in shingles increases the amount of these emissions assigned

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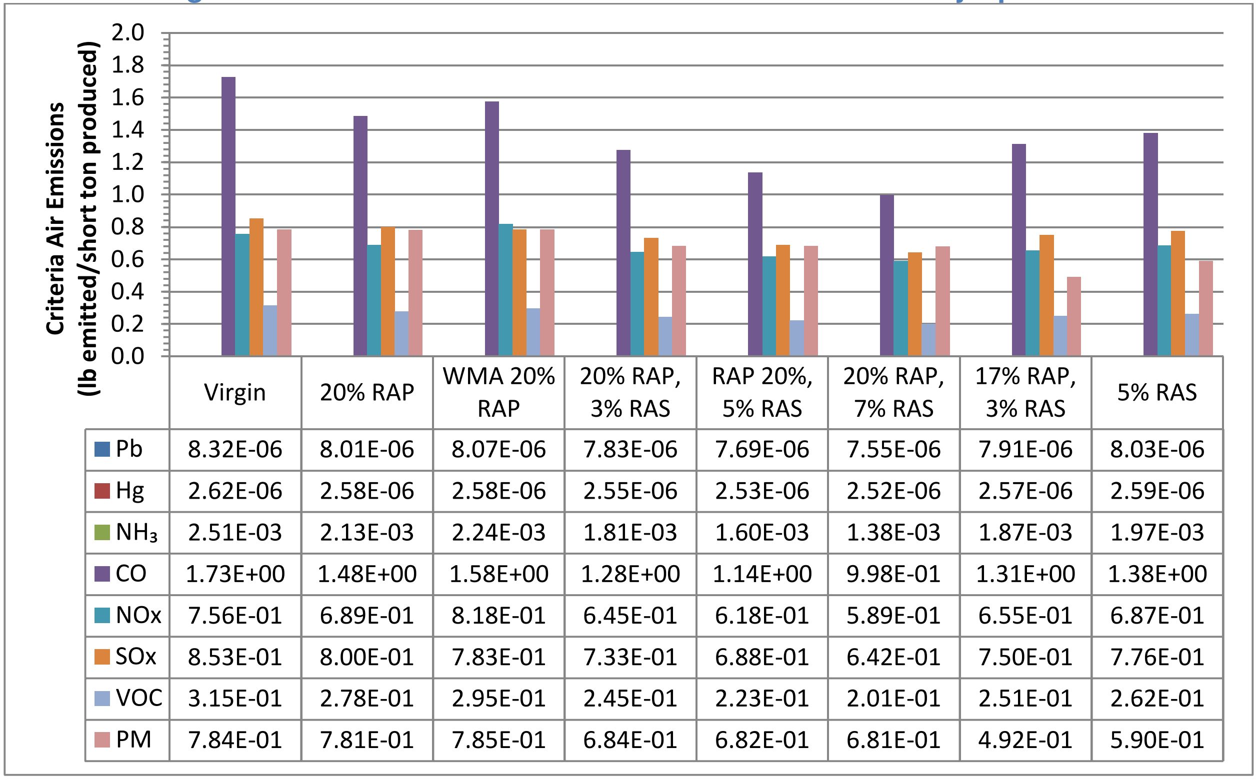
[35] This reflects the mass of emissions released in each of the systems studied, and does not reflect potential impacts.

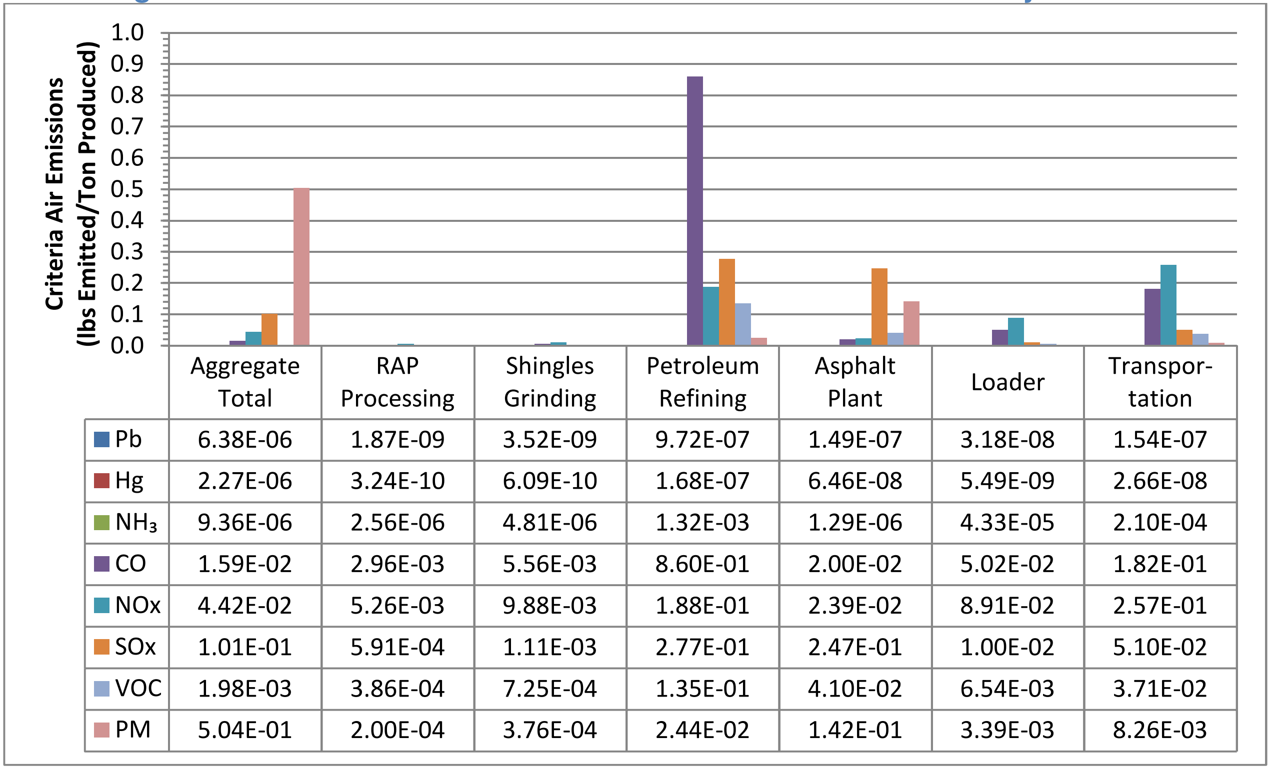
to asphalt pavement. In the case of 7% RAS, the allocation increases the calculated ammonia emissions by 22 percent, and the CO emissions by 20 percent.

Figure 5: Criteria Air Pollutant and Other Air Emissions by Species



	Virgin	20% RAP	WMA 20% RAP	20% RAP, 3% RAS	RAP 20%, 5% RAS	20% RAP, 7% RAS	17% RAP, 3% RAS	5% RAS
Pb	8.32E-06	8.01E-06	8.07E-06	7.83E-06	7.69E-06	7.55E-06	7.91E-06	8.03E-06
Hg	2.62E-06	2.58E-06	2.58E-06	2.55E-06	2.53E-06	2.52E-06	2.57E-06	2.59E-06
NH_3	2.51E-03	2.13E-03	2.24E-03	1.81E-03	1.60E-03	1.38E-03	1.87E-03	1.97E-03
CO	1.73E+00	1.48E+00	1.58E+00	1.28E+00	1.14E+00	9.98E-01	1.31E+00	1.38E+00
NOx	7.56E-01	6.89E-01	8.18E-01	6.45E-01	6.18E-01	5.89E-01	6.55E-01	6.87E-01
SOx	8.53E-01	8.00E-01	7.83E-01	7.33E-01	6.88E-01	6.42E-01	7.50E-01	7.76E-01
VOC	3.15E-01	2.78E-01	2.95E-01	2.45E-01	2.23E-01	2.01E-01	2.51E-01	2.62E-01
PM	7.84E-01	7.81E-01	7.85E-01	6.84E-01	6.82E-01	6.81E-01	4.92E-01	5.90E-01

Figure 6: 20% RAP-5% RAS Criteria Air and Other Air Pollutants by Process



	Aggregate Total	RAP Processing	Shingles Grinding	Petroleum Refining	Asphalt Plant	Loader	Transpor-tation
Pb	6.38E-06	1.87E-09	3.52E-09	9.72E-07	1.49E-07	3.18E-08	1.54E-07
Hg	2.27E-06	3.24E-10	6.09E-10	1.68E-07	6.46E-08	5.49E-09	2.66E-08
NH_3	9.36E-06	2.56E-06	4.81E-06	1.32E-03	1.29E-06	4.33E-05	2.10E-04
CO	1.59E-02	2.96E-03	5.56E-03	8.60E-01	2.00E-02	5.02E-02	1.82E-01
NOx	4.42E-02	5.26E-03	9.88E-03	1.88E-01	2.39E-02	8.91E-02	2.57E-01
SOx	1.01E-01	5.91E-04	1.11E-03	2.77E-01	2.47E-01	1.00E-02	5.10E-02
VOC	1.98E-03	3.86E-04	7.25E-04	1.35E-01	4.10E-02	6.54E-03	3.71E-02
PM	5.04E-01	2.00E-04	3.76E-04	2.44E-02	1.42E-01	3.39E-03	8.26E-03

6 Market Information

When considering substituting materials with recycled products, it is important to determine what the maximum impact may be, based on some limiting factor. Colorado is the only state where data were available for current use of RAS in the HMA. The Colorado Department of Transportation (CDOT) expected to place 820,000 tons of asphalt in the state during the 2011 paving year.[36] In 2010, 101,550 tons of RAS asphalt were placed into city and commercial projects, and one CDOT project, by two companies in Colorado.[37,38] In Colorado, the shingles tear-off quantity is estimated to be 240,000 tons per year,[39] most of which are ending up in landfills.

CDOT revised its Standard Specifications for Road and Bridge Construction with a standard special provision on April 26, 2012, for RAS. RAS will be allowed in HMA up to a maximum of five (5) percent of the total weight of the mix provided all specifications for HMA are met. The total binder replaced by RAS, RAP, or both shall not exceed 30% of the effective binder content of either the mix design or the produced mix.[40]

Even though the reduction in GHG emissions is small relative to other practices – such as reducing fuel consumption in vehicles – with greater reduction potential, recycling these materials provides an option for GHG mitigation. However, given other environmental and economic benefits, the reduction is not expected to be the driver to encourage this practice.

7 Conclusions

There are environmental benefits to the use of recycled asphalt shingles in asphalt production for use in road construction. The addition of RAS to pavement mixes containing RAP helps further increase environmental reductions relative to the baseline of using virgin asphalt. Figure 7 shows a decrease in greenhouse gases when the percentage of RAS is increased with the RAP content being held at 20 percent. Other emissions considered follow a similar reduction trend.

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[36] Zufall, J. Written Correspondence with James Zufall, Colorado Department of Transportation. April 28, 2011.

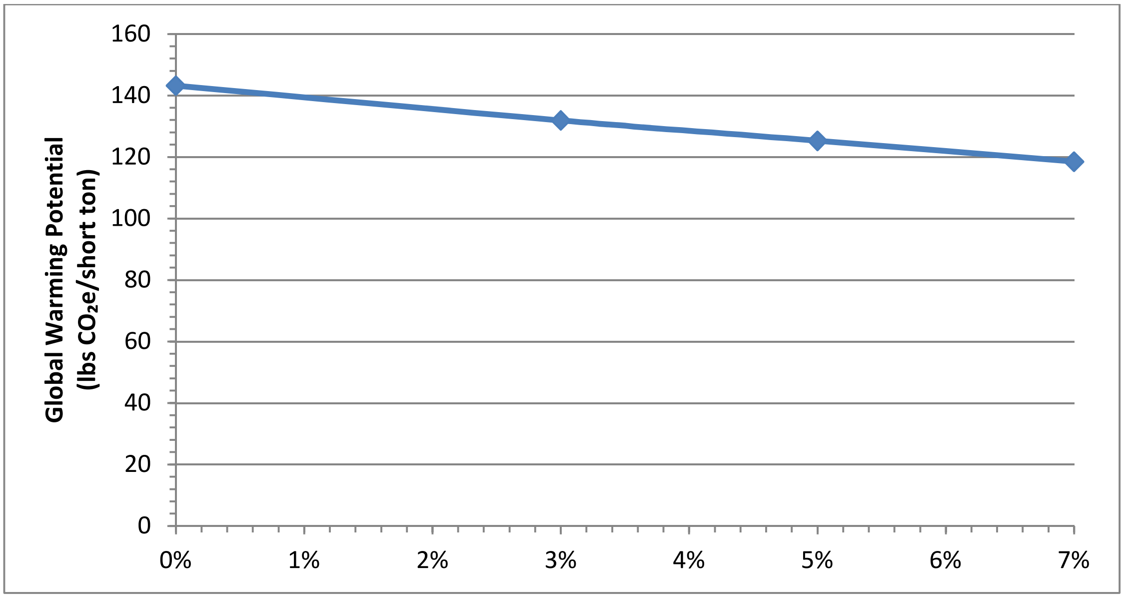
[37] Stillmunkes, G. Written Correspondence with Gary Stillmunkes, Asphalt Specialties Co., Inc. April 20, 2011.

[38] Welch, J. Written Correspondence with Jarrett Welch, Brannan Sand & Gravel Co. April 20, 2011.

[39] Asphalt Recovery Specialists, Inc. "Product/Service Information Brochure."

[40] Colorado Department of Transportation (2012). Revision of Section 401 Reclaimed Asphalt Shingles. April 26, 2012.

Figure 7: Decreasing GWP as RAS Content Increases



When examining GHG emissions by mixture scenario, the greatest reductions come from the largest percentage inclusion of both RAP and RAS (the 20% RAP-7% RAP mix). For the two mixes containing RAS that meet CDOT's specification, 17% RAP-3% RAS and 5% RAS, 31.9 lbs CO2e/short ton and 14.2 lbs CO2e/short ton of greenhouse gases are mitigated (with the landfill credit), respectively (Table 4).

One place for potential improvements in the asphalt life cycle would be improved efficiency within the asphalt plant itself. The asphalt plant is responsible for roughly 21 percent of the gross GHG emissions in recycled HMA cases and, at the lowest, 16 percent in the virgin case and 15 percent in the WMA case. Most of the interviewed manufacturers stated they were utilizing natural gas to power their mixing chambers, with the capability of using other fuel types, if necessary. Potential emissions from mixing chambers utilizing natural gas are lower than those using most other fuel types.

The petroleum refinery is the largest source of most criteria and other non-GHG air emissions. Increasing the amount of recovered binder from the use of recycled materials can help to reduce those emissions. Aggregate production is the primary PM emission source, so increasing the use of recovered aggregate (both from RAP and RAS) can help reduce particulate emissions.

Transportation distances for aggregate to the asphalt plant and the heated asphalt to the job site are both highly sensitive variables that can have large impacts on the total life cycle emissions. Increasing the transportation distance for WMA from 30 to 60 miles raises the GHG emissions for transportation by 51 percent compared to the equivalent HMA case. The change is 19 pounds CO_2e per short ton of asphalt, which is over 10 percent of the emissions considered in this study.

For the cases considered in this paper, the use of WMA with 20% RAP results in a 12 percent reduction in energy used at the asphalt plant compared to the 20% RAP in HMA case. This results in lower GHG emissions for that stage of the life cycle. The reduction can be more than offset, however, by the increased transportation distance possible with WMA.

Larger reductions in impacts are seen when RAP is included over solely using RAS. The addition of RAP reduces the amount of virgin aggregate required which must be transported over a longer distance. Combining RAP and RAS diverts even larger volumes of materials away from landfills.

7.1 Sensitivity to Lifetime

The energy and associated life cycle emissions associated with placement and maintenance are not included in this study. If the overall lifetime of the asphalt pavement changes with the amount of recovered material used, these may become important. As a point of reference, the BEES database shows that the amount of energy used for placement may be approximately 60 percent of the energy used for heating aggregate and mixing the asphalt. The energy requirement for resurfacing, which may be needed every 15 years, is a third of placement. However, the information from BEES is for generic concrete products with Portland cement and asphalt pavement needs resurfaced more frequently than concrete pavement, so the energy requirement may be higher. These processes use diesel fuel and may have significant impacts on the total air emissions for each asphalt mix.

8 Potential Areas for Additional Research

This study is only an initial, limited life cycle inventory and impact assessment. There is a need for a more complete life cycle assessment from the use of recycled shingles and asphalt pavement in asphalt road construction to help identify other potential environmental impacts. The inclusion of other impact categories from life cycle inventories, such as ecosystem quality and human health, would help quantify the overall benefits. This study was scoped such that water impacts (consumption and discharges) and ambient air quality (air within the manufacturing plants and immediately at the construction site) have been omitted except where secondary sources of data are available. The use and the quality of returned water is important and should be added to a future scope. Additionally, the ambient air quality may provide different positive and negative aspects to different production methods.

Information on the actual emissions of asbestos, if any, from the grinding of shingles was unavailable for this study. If such data becomes available through future research, this information could be incorporated into an update of the study.

This study assumed that physical activities associated with placing, maintaining, and removing the pavements, as well as the emissions from those activities, were similar across all scenarios. Differences in design and construction practices could be accounted for in future expansion of this study. Further analysis could be done to incorporate the use phase by considering pavement performance and roadway maintenance. Some literature suggests that the addition of RAS to HMA increases the pavement's resistance to wear and moisture while decreasing deformation of the pavement and cracking from thermal changes and fatigue.[41] The National Cooperative Highway Research Program of the Transportation Research Board will be evaluating the performance of asphalt mixtures incorporating WMA technologies and RAS, with and without RAP, and developing a design and evaluation procedure for acceptable performance starting in June

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[41] NAHB Research Center (1998). "From Roofs to Roads…Recycling Asphalt Roofing Shingles into Paving Materials." NAHB Research Center. Upper Marlboro, MD. Accessed June 27, 2011. Retrieved from http://www.epa.gov/wastes/conserve/imr/cdm/pubs/roof_br.pdf

2013.[42] This research, as well as existing projects and research from other groups, such as Colorado State University and the National Center for Asphalt Technology at Auburn University, could provide valuable information on local and national pavement performance.

Some researchers are developing a new approach to recycling asphalt shingles. This approach involves grinding shingles to a smaller size and using a wet process to blend ground shingles with the binder prior to mixing with the aggregates, versus dry blending shingles with the aggregates before the asphalt binder is added to the batch.[43] The wet process offers the potential for better blending control, and may offer performance benefits which could be considered if this new approach is an option that may be used for pavement production in the future.

Warm mix asphalt use is rapidly growing in the U.S. There are 47 states with specifications for use, and 25 to 30 percent of the total asphalt mix produced in the country is now done with WMA, versus only about five (5) percent in 2009.[44] As the use of WMA grows in EPA Region 8 and the rest of the U.S., the benefits from lowering temperatures for mixing and placing asphalt could reduce energy consumption and emissions at the asphalt plant. However, as the asphalt is able to be transported further distances, life cycle greenhouse gas emissions will increase from the transport and can more than offset the energy and emission savings at the plant. More than 29 different technologies exist for WMA currently.[45] These technologies use water, water-bearing minerals, chemicals, waxes, oils, organic additives, or a combination of technologies. Further analysis could be conducted to account for changes to potential life cycle environmental impacts when different WMA technologies are used to produce asphalt with RAS, and asphalt with RAS and RAP. This study could also be improved by looking at upstream energy consumption when accounting for full life cycle inventory and impacts.

An additional study on aggregate and its production could add significant relevant detail to this study. All data on aggregate production utilized in this study was generic and/or from secondary sources, and was not developed specifically for each type of aggregate used in asphalt. Some aggregate producers have noted that a streamlined approach to processing aggregates is proving to be beneficial in lowering production cost and related environmental reductions. Collecting primary data on the production of aggregate used in asphalt would increase the quality of the data already available, and would add value to the comparison between virgin and recycled aggregates. Additional recycled aggregates not considered in this study could also be incorporated.

There are various types of unconventional asphalt. Some states are experimenting with the addition of ground up tires to increase mix design strength since tires are petroleum based products. This would also divert more waste away from landfills and reduce virgin aggregate requirements.

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[42] Transportation Research Board of the National Academies, National Cooperative Highway Research Program. Written correspondence with Dr. Ed Harrigan regarding NCHRP Project 09-55, Recycled Asphalt Shingles in Asphalt Mixtures with Warm Mix Asphalt Technologies. April 9, 2013.

[43] Mostafa, E. (2012). Recycling of Asphalt Shingles in Asphalt Pavements – a New Approach. *C&D World*, May/June. Retrieved from www.cdrecycling.org

[44] Federal Highway Administration Resource Center. Telephone correspondence with Steve Mueller. November 19, 2012.

[45] Ibid.

Additional analysis of the economic and environmental factors driving the use of RAS will help to clarify the maximum potential environmental benefits that can be derived from using recovered shingles in asphalt. The asphalt industry is ever-changing and evolving. It has been successfully innovating ways to recycle binder and aggregate ingredients from other products into its own, thus reducing its need for virgin resources. As shingle recycling processes mature and become more established in Region 8, it is anticipated that more asphalt producers will utilize this recycled feedstock in their mixes.

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Appendix A – Key Assumptions

All asphalt mixes are able to perform under the road conditions for which they are designed.
All upstream production emissions for RAS and RAP are related to the products' initial useful life cycle.
The physical activities associated with placing, maintaining, and removing of the pavements, as well as the emissions from those activities, are assumed to be similar across all scenarios.
Energy consumption and environmental releases associated with sand and aggregate production are not discerned according to size, and are assumed to be the same as for aggregate production for generic concrete products with Portland cement (BEES database).
Asphalt and aggregates are transported in a Class 8 single-unit truck.
Virgin aggregate is assumed to be transported 36 miles, while recycled materials are assumed to be transported 9 miles.
Transportation to the construction site is assumed to be 30 miles for all asphalt mixes except WMA 20% RAP, which is assumed to be transported 60 miles.
RAP contains 4% binder and RAS contains 24.3% binder by weight.
All mixes require binder from the petroleum refiners, have the aggregates heated using natural gas, and are mixed in a drum plant.
There is no change in petroleum resource depletion because there is no reduction of crude oil extraction directly related to the binder production.