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Life Cycle Assessment of Asphalt Binder, Warm Mix Asphalt Additives, and Bonded Concrete Overlay of Asphalt for California Conditions

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Life Cycle Assessment of Asphalt Binder, Warm Mix Asphalt Additives, and Bonded Concrete Overlay of Asphalt for California Conditions

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16. ABSTRACT
The UCPRC is updating and expanding the life cycle inventories (LCIs) that are available for materials, pavements, and practices being used in or introduced to California for use in the project-level design software, *eLCAP*, and in the Caltrans pavement management system, *PaveM*. This report presents the results of developing LCI for use in life cycle assessment (LCA) for three types of materials or pavement structures being used in California: (1) asphalt binder regionalized to California from a national average, (2) warm mix asphalt (WMA) technologies, and (3) bonded concrete overlay of asphalt (BCOA). These LCIs fill important gaps because asphalt binder environmental product declarations (EPDs) will not be available for several years and very few WMA EPDs are available. The results of the binder LCI showed that California has a typical asphalt binder global warming (GW) of 0.456 kgCO_2 eq/kg of binder compared to Petroleum Administration for Defense District (PADD) 5 (western states) at 0.487 and the US/Canada average from the Asphalt Institute (AI) LCA study, which was 0.637. This difference is due to the percentage of heavy Canadian oil sands in the crude oil slates in the AI LCA study compared to PADD 5 and California. In the AI study, the heavy oil imported from Canada is 53% of crude input, 18% in PADD 5, and 3% in California. The results of the main study and of the sensitivity analysis suggest that asphalt binder GW should be considered to be a distribution of values rather than a single value, or, if a single value is used, it should be understood that there can be considerable variability around it. WMA is considered a potential means for reducing energy consumption and emissions during the material and construction stages of asphalt concrete by allowing for the lowering of mixing temperatures in the asphalt plant. WMA can also be used with the same mixing temperatures to allow for compaction at lower temperatures at the construction site, which does not reduce energy and emissions from mixing but can result in better compaction and longer pavement life. When WMA is used to reduce the mixing temperature to the lowest recommended temperature, the net reductions in GW range between approximately 2% and 5%, except for one WMA additive where the reduction in mixing temperature resulted in a net GW increase of 14%. It was found that the material stage can be considered the hot spot due to high environmental impacts and high energy consumption compared with the transportation and construction stages, as expected.

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Lea, J., Harvey, J., Saboori, A., and Butt, A.A. 2022. *eLCAP: A Web Application for Environmental Life Cycle Assessment for Pavements* (Technical Memorandum: UCPRC-TM-2018-04). Davis and Berkeley, CA: University of California Pavement Research Center.

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The UCPRC laboratory is accredited by AASHTO re:source and CCRL for the laboratory testing discussed in this report.

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PROJECT OBJECTIVES

This report was produced over two projects, PPRC Project 4.66 and PPRC Project 4.80, that shared a common objective: update life cycle assessment with new material inventories. This report partly completes that objective by providing new inventories of asphalt binder, warm mix asphalt additives, and bonded concrete overlay of asphalt that are modeled for the California region.

EXECUTIVE SUMMARY

Sustainability cannot be addressed without consideration of the environmental impacts of the systems, products, activities, and processes that support quality of life. The life cycle assessment (LCA) methodology, which identifies and quantifies the energy use, materials consumption, and emissions (land, air, water), can be used for environmental analysis for a life cycle perspective of a system. The UCPRC has been collecting data for different pavement materials, construction processes, transport methods, energy sources, and other variables important for California to give Caltrans the capability to perform LCAs for decision support for project-level design, network analysis for pavement management, benchmarking and reporting, and policy evaluation (e.g., specifications and directives).

The UCPRC earlier developed life cycle inventories (LCIs) for a range of commonly used infrastructure materials and construction activities for Caltrans. The UCPRC continues to update California-specific LCIs and develop new ones for the materials and processes that were not covered earlier. Once the LCIs have been reviewed, they are uploaded into the *environmental Life Cycle Assessment of Pavement* (*eLCAP*) tool, which was also developed for Caltrans. The three newly developed LCIs covered in this research report are the following:

(1) Asphalt binder regionalized to California from a national average
(2) Warm mix asphalt (WMA) technologies
(3) Bonded concrete overlay of asphalt (BCOA) (now called concrete overlays of asphalt [COA])

These new inventories fill important gaps in the current LCI in the Caltrans project-level LCA program, *eLCAP*, and in the LCA models in the Caltrans pavement management system, *PaveM*. As of February 2023, environmental product declarations (EPDs) are not available for asphalt binders except for the United States/Canada national average LCA currently being used across North America and they are not expected to be available until 2025 at the soonest. As of the same date, there are only a handful of EPDs available for warm mix products. BCOAs are growing in use in California, and an LCI framework and the example provided in this report will aid in decision-making regarding use of this pavement rehabilitation strategy.

Chapters 2, 3, and 4 of this report provide the details of the LCI for California asphalt binder, warm mix technologies, and BCOA, respectively. Chapter 5 provides a summary and conclusions. A brief summary of each chapter follows.

Asphalt Binder

Several pavement studies have used databases and LCA for evaluating the environmental impacts of an asphalt binder in pavements. The Eurobitume LCIs (first published in 2012) were pioneering works that have been used extensively in LCA. Eurobitume used a fictional refinery with characteristics from several refineries in northern Europe and a representative average crude oil slate. The following LCA models of petroleum refineries for North America have also used an average crude oil slate for all refinery products: the thinkstep refinery model in the *GaBi* software (2016 version reviewed for this report), the Petroleum Refinery Life Cycle Inventory Model (PRELIM v1.1, 2016), and the National Renewable Energy Laboratory's US Life Cycle Inventory (USLCI).

In 2014, Yang evaluated average crude oil slates for different Petroleum Administration for Defense Districts (PADDs) in the United States when evaluating the impacts of materials extraction for different crude sources used for all refinery products in each PADD. The United States was divided into five PADDs to help organize fuel distribution during World War II, and the West Coast is PADD 5, which includes California along with six other western states. The PADDs help users of petroleum data from the Energy Information Administration (EIA) evaluate regional petroleum product supplies as well as analyze patterns of crude oil and petroleum product movements throughout the nation.

The 2019 Asphalt Institute (AI) LCA for North American (United States and Canada) asphalt binders used data for the refineries that produce asphalt and that were willing to participate in the data collection effort. The LCA is therefore based on the crude oil slate representative of those refineries. The participating refineries provided data for the LCA that reflected when the refineries were producing asphalt as opposed to other times when they were not producing asphalt. The average crude oil slate in the 2019 AI LCA, which is the only value used in the current version of the National Asphalt Pavement Association's Emerald Eco-Label EPD program, is heavily weighted toward use of crude from oil sands from the Canada (primarily Alberta and also Saskatchewan). California is not connected to the Canadian oil sands by pipeline, and only one pipeline—the Trans Mountain pipeline to Vancouver, British Columbia—connects the Canadian oil sands to the sea, providing the possibility of maritime transport to California.

The average crude oil slate used in the AI LCA was thought by the UCPRC to not be representative of crude used in PADD 5 or California and that a study was needed to produce a more representative regionalization of the AI LCA to better calculate asphalt binder environmental impacts in California for use in pavement LCA. The goal of this LCI study is to quantify the environmental impacts from the production of the asphalt binder used in California. This study focuses on the LCA of the asphalt binder production in PADD 5 and California in 2017 and 2018, and a comparison with the AI study LCA was also performed. The declared unit defined for this study is the production of 1 kg of asphalt binder.

The cradle-to-gate approach used includes the material extraction and production stages as well as the transportation of the materials up to the point of leaving the gate of the refinery. Due to the lack of other sources of information, it was assumed that the refineries and terminals of the current study and those in the AI study were similar and the AI study's data were used for the following processes: refining of crude oil into asphalt, transport to a terminal, and the final blending process. The *GaBi* software, developed by thinkstep and now distributed by Sphera, was used to create the asphalt binder models. The secondary LCI data for the background system were extracted from the 2019 *GaBi* LCI database. Because the most recent and most complete data that were obtained from most of the sources were from 2017, that year was considered the reference year, and TRACI 2.1 impact calculations were used. Three sources of oil are used in California to make asphalt: from California wells; from other US wells, nearly all from Alaska; and from other countries. Where there were no data for a country, data for extraction impacts were used from countries with similar production types.

The results showed that California has the lowest global warming (GW) at 0.456 $kgCO_2$ eq/kg of binder compared to PADD 5 at 0.487 and the United States/Canada average from the AI LCA study, which was 0.637. This difference is due to the percentage of heavy Canadian oil sands in the crude oil slates in the AI LCA study compared to PADD 5 and California. The heavy oil imported from Canada is 53% of crude input in the AI LCA study, 18% in PADD 5, and 3% in California. It should be noted that the AI LCA study used the Intergovernmental Panel on Climate Change (IPCC) *Fifth Assessment Report* (*IPCC AR5*) from 2014, while the TRACI 2.1 impact indicator system uses earlier climate change modeling that is in *IPCC AR 4* from 2007.

Sensitivity analysis considered using the US average domestic crude oil slate versus the California/Alaska domestic crude oil slate typical for California, which resulted in a further 12% reduction in GW. The results of the main study and of the sensitivity analysis suggest that asphalt binder GW should be considered to be a distribution of values rather than a single value, or, if a single value is used, it should be understood that there can be considerable variability around it.

Warm Mix Asphalt Additives

Warm mix asphalt (WMA) is considered a potential means for reducing energy consumption and emissions during the material and construction stages of asphalt concrete by allowing for lowering mixing temperatures in the asphalt plant. WMA can also be used with the same mixing temperatures to allow for compaction at lower temperatures at the construction site, which does not reduce energy and emissions from mixing but can result in better compaction and longer pavement life. Lowered mixing temperatures result in less emissions at the construction site as well as the plant, producing better conditions for workers and neighbors. According to previous UCPRC research, the use of warm mix asphalt additives (WMAAs) in asphalt mixes, especially in asphalt rubber projects, should be encouraged. Studies conducted in European countries and the United States have indicated the possibility of reductions in the asphalt concrete mixing and placement temperatures and of potentially related emissions.

Several studies have been conducted globally to assess the environmental impacts of WMA. However, many unanswered questions remain pertaining to the environmental benefits of WMA. In this study, the life cycle environmental impacts of different types of WMA containing different WMAAs were evaluated and compared with conventional hot mix aspahtl (HMA). No study was found in the literature, until June 2021, on the environmental impacts of some WMA technologies used in California. Therefore, the UCPRC took the initiative to develop estimated LCI datasets for different WMAAs. Because there are no definitive ingredient lists and proportions, this study used the best available knowledge and created proxies. There were also no EPDs for WMA until one was produced by Ingevity in December 2021.

This study aims to quantify the potential environmental impacts that occur during the material production stage of WMA. Thus, the scope of the study is from cradle to gate, including the materials extraction to transportation to plants and all the processes conducted in the plant to prepare the final mix. A comparative attributional LCA approach is adopted where life cycle environmental impacts from the production of WMA using different WMAAs are compared with the conventional HMA. The asphalt mix designs are mainly reflecting California-specific mix designs. The declared unit for this study is 1 kg of WMA.

The chemical components of the WMAAs were obtained from safety data sheets (SDSs, previously called material safety data sheets) and online published materials. UC Davis researcher Dr. Peter Green, an environmental chemistry expert, was consulted about the additives that did not have enough information available online and for the final chemical components. The WMAAs considered in the current study include the following:

- Additive Technologies
  - Evotherm DAT (A1), chemical surfactant technology, referred to as Evotherm in this report
  - Rediset LQ, chemical surfactant technology referred to as Rediset in this report
  - Cecabase RT, chemical surfactant technology, referred to as Cecabase in this report
  - Advera, chemical water foaming technology, referred to as Advera in this report
  - Sasobit, organic wax technology, referred to as Sasobit in this report
  - SonneWarmix, organic wax technology, referred to as SonneWarmix in this report
- Water Injection Technologies
  - Astec Double Barrel Green, water injection technology, referred to as Astec in this report
  - Gencor Ultrafoam GX2, water injection technology, referred to as Gencor in this report

This study used the *GaBi* software to develop models for different asphalt mixes. Different non-rubberized and rubberized asphalt concrete mix designs were considered based on a UCPRC research report that evaluated the mix properties and performance under accelerated pavement testing of the WMA technologies shown above. The California asphalt binder analysis from Chapter 2, which considered the US average domestic crude in the crude oil slate, was used for the calculations in this chapter. Natural gas use was estimated based on the recommended reduction in mixing temperature for each WMAA. The life cycle impact assessment (LCIA) results reveal that the combination of WMA mixing temperature, the chemical components of the WMA technologies, and the dosage of additives in the mix are the three main factors influencing the final environmental emissions.

As expected, use of the WMA technology as a means to reduce mixing temperature (Group C in tables in Chapter 3) can reduce GW due to the reduced natural gas consumption during production of the WMA at a reduced temperature. Whether or not there is a reduction and the size of the reduction depend on the relative effects of the three factors listed previously: temperature reduction, WMAA chemistry and production, and WMAA dosage. When the WMAA is used as a compaction and transportation aid without reducing the mixing temperature (Group B in tables in Chapter 3), there is not reduction in GW from mix production and construction, though there may be a life cycle GW reduction if better compaction and sufficiently longer life are achieved from the WMAA to compensate for its use. The calculated percent changes in each impact category in the WMA group were compared with conventional HMA and also done for conventional rubberized hot mix asphalt (RHMA) and RHMA with WMAA. The results showed that compared with HMA, use of WMA at the same mixing temperature as a compaction and transportation aid results in changes in GW of less than 1%, except for Rediset, which increases the GW by more than 17%. When the WMA is used to reduce the mixing temperature to the lowest recommended temperature, the net reductions in GW range between approximately 2% and 5%, except for Rediset where the reduction in mixing temperature results in a net increase of GW of 14%.

Bonded Concrete Overlay on Asphalt

BCOA is a rehabilitation alternative that consists of placing a hydraulic cement concrete overlay on existing asphalt pavement. It should be noted that more recent terminology in California is concrete overlay on asphalt (COA). This study is mainly focused on thin BCOA, where the overlay is 100 to 175 mm (4 to 7 in.) thick. BCOA with an overlay thickness of 50 to 100 mm (2 to 4 in), typically referred to as ultrathin, is primarily used in urban areas with light traffic. While the technology for thin BCOA has been used on highways and conventional roads in several US states as well as in other countries for at least 20 years, the use of thin BCOA has been very limited in California. BCOA has been evaluated under accelerated trafficking conducted with the Heavy Vehicle Simulator (HVS) by UCPRC for Caltrans with positive results. Caltrans decided to move forward and built a pilot thin BCOA project on State Route 113 (SR 113) in Woodland in District 3 and another on State Route 247

(SR 247) in San Bernardino County in District 8. The experimental data presented in this study come from the Woodland thin BCOA construction project.

The goal of this study is to quantify the potential environmental impacts due to the material and construction stages of thin BCOA. The UCPRC has developed LCA models for different life cycle stages of a pavement using California-specific data and produced an LCI database for Caltrans, which is being used in the *eLCAP* software. This database is mainly used to develop LCIs and LCIAs of BCOA pavements. The portland cement concrete (PCC) mix designs of thi study include PCC Type III used for the HVS test sections with 4 hours opening time (OT), PCC Type II/V used for the Woodland project with 24 hours OT, and the normal strength PCC Type II/V used by Caltrans with 10 days OT as well as RHMA mix design used in the pavement layers of the project. The PCCs with 4 hours and 24 hours OT were designed to provide 450 psi (3 MPa) flexural strength (the Caltrans requirement for opening the lane to traffic) after 24 hours, while the PCC with 10 days OT was designed to provide 650 psi (4.5 MPa) flexural strength at 10 days.

It was found that the material stage can be considered the hot spot due to high environmental impacts and high energy consumption compared with the transportation and construction stages, as expected. Improvement of the concrete material impacts while maintaining at least the same functionality (time to traffic opening, material properties related to durability) will likely result in the most significant improvement in environmental impacts and energy use.

The transportation stage is of secondary importance to the materials, meaning that methods of shortening the haul distance for aggregate or reusing aggregate sources would be an approach to reduce the transportation impacts. The assumed distances between the stone quarries to the asphalt and concrete plants and other hauling distances are included in the analysis, with longer distances leading to higher environmental impacts. The thickness of the surface layer is an important factor affecting environmental impacts and energy consumption in the material stage.

The second influential criterion is the additional RHMA layer under the surface rigid layer, resulting in significant increases in the environmental impacts and primary energy demand. The results show an increase of 8% to 13% in GW, photochemical ozone creation (POCP), PM2.5, and renewable primary energy demand. The use of the RHMA base is warranted for environmental reasons if increases in performance life occur because of its use. The difference in the concrete mix designs is another notable factor that causes emissions and energy consumption changes. Mix designs intended to produce faster strength gains to be able to open to traffic sooner are more carbon intensive. The HVS PCC Type III mix with 4 hours OT has the highest environmental impacts and energy consumption, followed by the PCC Type II/V mix designs.

Conclusions and Recommendations for Future Work

The main goal of the three studies presented in this report was to contribute to an up-to-date and regionally representative LCI database for transportation infrastructure. Literature reviews, surveying of local contractors and their practices, review of Caltrans data and interviews, and calculations using databases such as *GaBi* and *EcoInvent* were used to collect the data. The existing UCPRC LCI, which is a comprehensive pavement dataset developed and calibrated for California, was also used and included a comprehensive list of materials, sources of energy, transport modes, and pavement surface treatments. The three developed LCIs and the three case studies that are covered in this report are the following:

(1) Asphalt binder, regionalized to California using the AI 2019 North American (United States and Canada) LCI and information regarding crude oil sources refined in California
(2) Warm mix asphalt (WMA) technologies, estimated using proxy data for the chemical components and their quantities taken from SDSs, because of the lack of other information such as EPDs regarding WMAAs
(3) BCOA (now called concrete overlays of asphalt [COA]), a new type of pavement for California

In each of these cases the best available information at the time of development of this report (2019 to 2022) were used. Sensitivity analyses for important variables were performed identifying how changes in those variables affect the environmental and resource use impact indicators.

The primary finding from the asphalt binder study is that asphalt binder produced using typical crude oil slates used in California refineries results in a significantly lower GW and other impacts than the crude oil slate used for the 2019 AI continental average LCA. This regionalized asphalt binder LCI can be used in California pavement LCAs, while remaining cognizant of the assumptions and limitations of this study. The primary finding from the WMA study is that the different WMAAs can have important differences in the impacts they cause in the asphalt mix impact indicators, in the range of 2% to 5% for the WMAA considered, when used to reduce mixing and compaction temperature and that those impacts are driven by the combination of the chemistry of the WMAA and the range of mixing temperatures that can be used when the WMAA is added. The range of temperatures includes no reduction in temperature when the WMAA is used as a compaction aid to extend the time available for compaction and transport to the maximum reduction possible with the WMAA resulting in less natural gas use and the same compaction time and transport distance that occurs for HMA. The primary finding from the BCOA sensitivity analysis is that the concrete mix designs developed for different times to opening of the concrete to traffic have a significant effect on environmental impact indicators, particularly GW, as does the design choice of including a RHMA base or only milling the existing asphalt surface.

Regarding recommendations for future work, the LCI database and models from these studies should be regularly reviewed and updated. This is necessary due to ongoing advancements in material production technologies, construction practices, energy sources, and data collection methods. Additionally, new materials and elements such as roads, bridges, rails, and culverts, which currently lack data inventories in California, need to be included. An important advancement to help improve the quality of the data is to collect more primary data (directly measured) instead of secondary data (collected from other sources, estimated or assumed) from local material production plants and contractors. These studies were performed between 2019 and 2022. While they provide important information and fill data gaps of that time, some of their findings need to be updated.

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LIST OF ABBREVIATIONS

AI	Asphalt Institute
BCOA	Bonded concrete overlay of asphalt
CBD	Center for Biological Diversity
CEC	California Energy Commission
COA	Concrete overlays of asphalt
EIA	Energy Information Administration
EOR	Enhanced oil recovery
EPD	Environmental product declaration
GWP	Global warming potential
GW	Global warming
HMA	Hot mix asphalt
HMDA	Hexamethylenediamine
HVS	Heavy Vehicle Simulator
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
NACEI	North American Cooperation on Energy Information
NASEO	National Association of State Energy Officials
NEB	National Energy Board
ODP	Ozone depletion potential
OT	Opening time
PADD	Petroleum Administration for Defense Districts
PCC	Portland cement concrete
PED	Primary energy demand
PED-NR	Nonrenewable primary energy demand
POCP	Photochemical ozone creation potential
PRELIM	Petroleum Refinery Life Cycle Inventory Model
RAP	Reclaimed asphalt pavement
RAS	Reclaimed asphalt shingles
RHMA	Rubberized hot mix asphalt
RWMA	Rubberized warm mix asphalt

SCO	Synthetic crude oil
SDS	Safety data sheet
UCPRC	University of California Pavement Research Center
WMA	Warm mix asphalt
WMAA	Warm mix asphalt additive

SI* (MODERN METRIC) CONVERSION FACTORS				
APPROXIMATE CONVERSIONS TO SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
in.	inches	25.40	millimeters	mm
ft.	feet	0.3048	meters	m
yd.	yards	0.9144	meters	m
mi.	miles	1.609	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.09290	square meters	m^2
yd^2	square yards	0.8361	square meters	m^2
ac.	acres	0.4047	hectares	ha
mi^2	square miles	2.590	square kilometers	km^2
		VOLUME		
fl. oz.	fluid ounces	29.57	milliliters	mL
gal.	gallons	3.785	liters	L
ft^3	cubic feet	0.02832	cubic meters	m^3
yd^3	cubic yards	0.7646	cubic meters	m^3
		MASS		
oz.	ounces	28.35	grams	g
lb.	pounds	0.4536	kilograms	kg
T	short tons (2000 pounds)	0.9072	metric tons	t
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	(F-32)/1.8	Celsius	°C
		FORCE and PRESSURE or STRESS		
lbf	pound-force	4.448	newtons	N
lbf/in^2	pound-force per square inch	6.895	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
Symbol	**When You Know**	**Multiply By**	**To Find**	**Symbol**
		LENGTH		
mm	millimeters	0.03937	inches	in.
m	meters	3.281	feet	ft.
m	meters	1.094	yards	yd.
km	kilometers	0.6214	miles	mi.
		AREA		
mm^2	square millimeters	0.001550	square inches	in^2
m^2	square meters	10.76	square feet	ft^2
m^2	square meters	1.196	square yards	yd^2
ha	hectares	2.471	acres	ac.
km^2	square kilometers	0.3861	square miles	mi^2
		VOLUME		
mL	milliliters	0.03381	fluid ounces	fl. oz.
L	liters	0.2642	gallons	gal.
m^3	cubic meters	35.31	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.03527	ounces	oz.
kg	kilograms	2.205	pounds	lb.
t	metric tons	1.102	short tons (2000 pounds)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C + 32	Fahrenheit	°F
		FORCE and PRESSURE or STRESS		
N	newtons	0.2248	pound-force	lbf
kPa	kilopascals	0.1450	pound-force per square inch	lbf/in^2

*SI is the abbreviation for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised April 2021)

1 INTRODUCTION

Sustainability cannot be addressed without consideration of the environmental impacts of the systems, products, activities, and processes that support quality of life. The life cycle assessment (LCA) methodology—which identifies and quantifies energy use, materials consumption, and emissions (land, air, water)—can be used for environmental analysis for a life cycle perspective of a system. The University of California Pavement Research Center (UCPRC) and the California Department of Transportation (Caltrans) developed a Roadway LCA Roadmap for California, a living document that gets updated every three years. Caltrans's vision is to be able to quantitatively assess the social, economic, and environmental impacts of transportation infrastructure. The UCPRC has been collecting data for different pavement materials, construction processes, transport methods, energy sources, and other variables important for California to give Caltrans the capability to perform LCAs for decision support for project-level design, network analysis for pavement management, benchmarking and reporting, and policy evaluation (e.g., specifications and directives).

The UCPRC earlier developed life cycle inventories (LCIs) for several infrastructure materials and construction activities for Caltrans *(1,2)*. The UCPRC continues to update California-specific LCIs and develop new ones for the materials and processes that were not covered earlier. Once the LCIs have been reviewed, they are uploaded into the *environmental Life Cycle Assessment of Pavement* (*eLCAP*) tool, which was also developed for Caltrans *(3)*.

The three newly developed LCIs covered in this research report are the following:

(1) Asphalt binder regionalized to California from a national average
(2) Warm mix asphalt (WMA) technologies
(3) Bonded concrete overlay of asphalt (BCOA)

These new inventories fill important gaps in the current LCI in the Caltrans project-level LCA program *eLCAP* and in the LCA models in the Caltrans pavement management system (*PaveM*). It is expected that these LCIs will be included in *eLCAP* after outside critical review is completed, until and unless better LCIs become available from industry. As of June 2024, environmental product declarations (EPDs) are not available for asphalt binders except for the United States/Canada, where the national average LCA of asphalt binder is currently being used across North America, and they are not expected to be available until 2025 at the soonest. As of the same date, there are only a handful of EPDs available for warm mix products. Bonded concrete overlays of asphalt (now called concrete overlays of asphalt [COA]) are growing in use in California, and an

LCI framework and the example provided in this report will aid in decision-making regarding using of this pavement rehabilitation strategy.

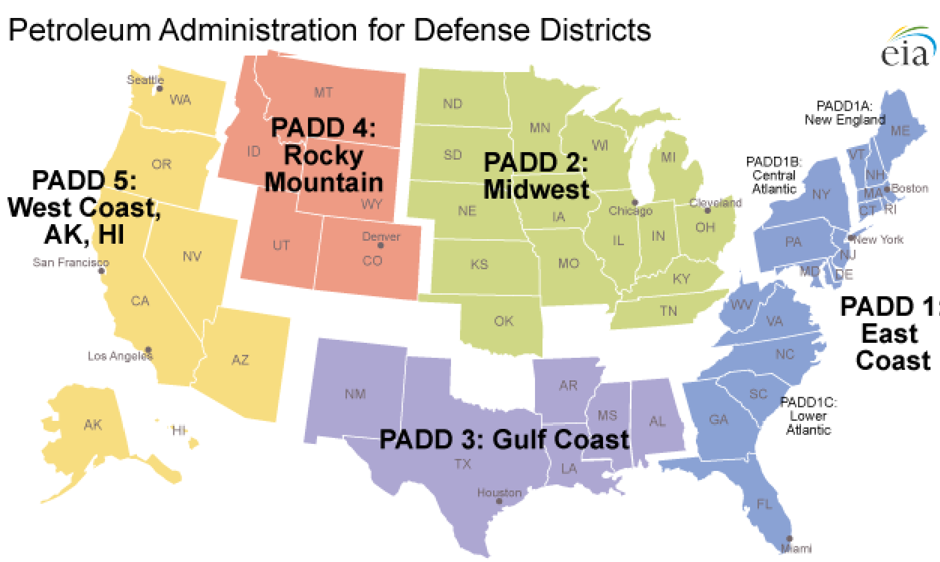
Chapters 2, 3, and 4 of this report provide the details of the LCI for California asphalt binder, warm mix technologies, and bonded concrete overlay of asphalt (BCOA), respectively. Chapter 5 provides a summary and conclusions. The intended audience for the results of the LCI studies in Chapters 2, 3, and 4 are local governments, pavement researchers and practitioners, and pavement designers performing LCAs for pavements in California and as example LCIs for other materials and in other locations.

2 ASPHALT BINDER

2.1 Introduction

Several pavement studies have used databases and LCA for evaluating the environmental impacts of an asphalt binder in pavements. The Eurobitume LCIs were pioneering works that have been used extensively in LCA *(4)*. Eurobitume used a fictional refinery with characteristics from several refineries in northern Europe and a representative average crude oil slate. The following LCA models of petroleum refineries for North America have also used an average crude oil slate for all refinery products: the thinkstep refinery model in the *GaBi* software *(5)*, the Petroleum Refinery Life Cycle Inventory Model (PRELIM) *(6)*, and the National Renewable Energy Laboratory's US Life Cycle Inventory (USLCI) *(7)*.

Yang evaluated average crude oil slates for different Petroleum Administration for Defense Districts (PADDs) in the United States when evaluating the impacts of materials extraction for different crude sources used for all refinery products in each PADD *(8)*. Figure 2.1 shows that the United States was divided into five PADDs to help organize fuel distribution during World War II: East Coast (PADD 1), Midwest (PADD 2), Gulf Coast (PADD 3), Rocky Mountain (PADD 4), and West Coast (PADD 5). California is included in PADD 5 along with six other western states. The PADDs help users of petroleum data from the US Energy Information Administration (EIA) evaluate regional petroleum product supplies as well as analyze patterns of crude oil and petroleum product movements throughout the nation *(9)*.



Source: US Energy Information Administration (2020) *(9)*.

Figure 2.1: Petroleum Administration for Defense Districts (PADDs) in the United States.

The 2019 Asphalt Institute (AI) LCA for North American (United States and Canada) asphalt binders used data for the refineries that produce asphalt and that were willing to participate in the data collection effort *(10)*. The LCA, which is the only value used in the current version of the National Asphalt Pavement Association's Emerald Eco-Label EPD program, is therefore based on the crude oil slate representative of those refineries. The participating refineries provided data for the LCA that reflected when the refineries were producing asphalt as opposed to other times when they were not producing asphalt.

The average crude oil slate in the AI LCA is heavily weighted toward use of crude from oil sands from Canada (primarily Alberta and also Saskatchewan). California is not connected to the Canadian oil sands by pipeline, and only one pipeline—the Trans Mountain pipeline to Vancouver, British Columbia—connects the Canadian oil sands to the sea, providing the possibility of maritime transport to California. Canadian oil sands are classified as heavy, meaning that they contain more bitumen used to make asphalt than lighter constituents that are used to make transportation fuels. They are also classified as sour, meaning that they are high in sulfur, requiring sulfur extraction to make transportation fuels. The average crude oil slate used in the AI LCA was thought by the UCPRC to not be representative of crude used in PADD 5, where California is located. It was also expected that there are large differences between California and the other states in PADD 5 and that a study was needed to produce a more representative regionalization of the AI LCA to better calculate asphalt binder environmental impacts in California for use in pavement LCA.

No study on the environmental impacts of asphalt binder has been performed previously for California. Thus, the UCPRC set out to develop an LCI dataset of asphalt binders by using data from PADD 5 and to further narrow that to the refineries in California. The following discussion describes the framework that was developed to model asphalt binder production inventory data and environmental impacts for PADD 5 and California. Data sources and supporting methodologies with assumptions are also discussed in detail in the following sections.

It should be noted that the Trans Mountain pipeline is being expanded to increase its capacity from 300,000 barrels per day (bpd) to 890,000 bpd, with construction originally scheduled to be completed in 2022 and the likely first shipping of oil through it late in the first quarter of 2024 *(11)*. It is not certain how much the pipeline expansion will change the crude oil slates used by California refineries in the future. Future updates to this report will likely be warranted, until the asphalt industry produces EPDs covering the binders used in California, as the economics of California asphalt production and importation of crude used to produce asphalt change.

2.2 Goal and Scope of California Asphalt Binder LCI Study

The goal of this LCI study is to quantify the environmental impacts from the production of the asphalt binder used in California. This study focuses on the LCA of the asphalt binder production in PADD 5 and California in 2017 and 2018. Additionally, a comparison with the AI study LCA was also performed *(10)*. This study provides an example framework for regionalizing national asphalt binder inventories from national averages.

2.2.1 *Declared Unit*

A declared unit is typically used instead of a functional unit when the application and function of the product are uncertain. A declared or defined unit is used for pavement materials such as asphalt binder and aggregate to define mass, volume, area, or length in pavement design and construction *(12)*. The declared unit defined for this study is the production of 1 kg of asphalt binder, also referred to as "bitumen" in the European research literature.

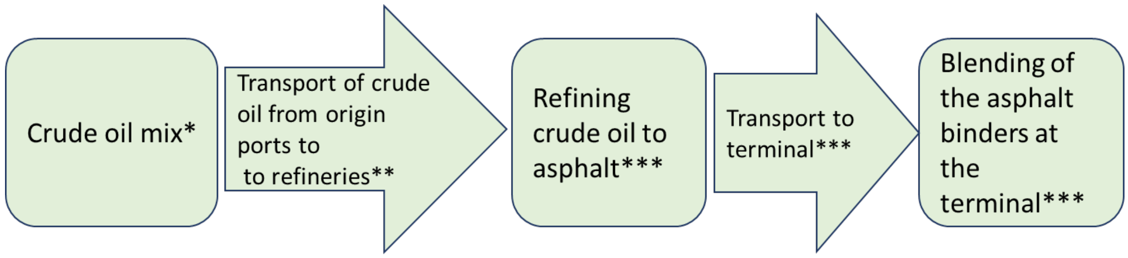
2.2.2 *System Boundary*

The cradle-to-gate approach used for this study includes the material extraction and production stages as well as the transportation of the materials up to the point of leaving the gate of the refinery. This study covers the complete supply chain for asphalt binder for PADD 5 and California presented in a previous UCPRC study *(13)*, including the following processes shown in Figure 2.2:

- Extraction of crude oil from all sources in the crude oil slate
- Transport of crude oil from origin port to the destination port and refineries
- Refining of crude oil into asphalt, transport to the terminal, and final blending of the asphalt binders

In the crude oil slate model, all known transport processes—including ocean freighter, barge, rail, truck, and pipeline transport of bulk commodities—are included.[1]

[1] *GaBi* process dataset available at gabi-6-lci-documentation.gabi-software.com/xml-data/processes/f3e83b9f-8ebc-4e83-a13c-d061ae537a32.xml.

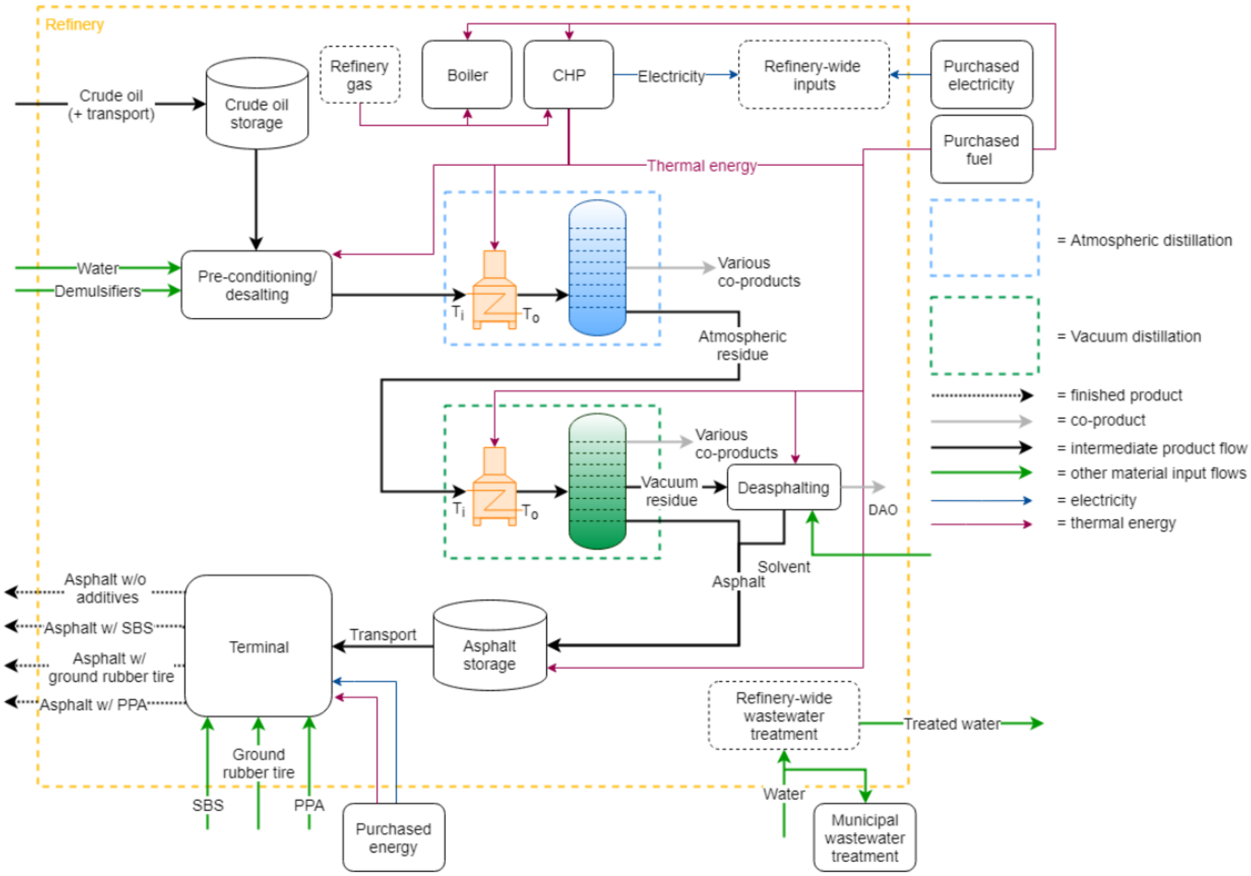


Notes:
* Crude oil slate: Modeled based on crude oil slate of *GaBi* software.
** Transportation of crude oil from origin port to the destination port and refineries: Modeled in *GaBi* based on data collected from the US Energy Information Administration (EIA), California Energy Commission (CEC), National Energy Board (NEB), *Oil Sands Magazine*, *Oil & Gas Journal*, North American Cooperation on Energy Information (NACEI), Enerdata, National Association of State Energy Officials (NASEO), and the Government of Canada.
*** Refining of crude oil into asphalt, transport to the terminal, and final blending of the asphalt binders: Used Asphalt Institute (AI) study model and data.

Figure 2.2: System boundary of asphalt binder covered in this study.

In the AI LCA of asphalt binder study, the main reference for this current study, inventories were supplied by 12 AI member refineries and 11 terminals from four companies in North America *(8)*. Due to the lack of other sources of information, it was assumed that the refineries and terminals of the current study and the AI study were similar. The AI study's data were used for the following processes: refining of crude oil into asphalt, transport to a terminal, and the final blending process.

The system boundary of the AI LCA study includes "raw material sourcing and extraction, transportation to refineries, refining of crude oil into asphalt, transport to the terminal, and final blending of the asphalt binders at the terminal." Only processes at the refinery associated with asphalt production were included in the AI refinery system boundary, shown in Figure 2.3, and processes for producing other products after extraction of asphalt from the crude were not included.



Note: DAO: deasphalted oil.

Source: Wildnauer et al. *(10)*.

Figure 2.3: Asphalt Institute cradle-to-gate system boundary.

2.2.3 *Product System*

This section covers the cradle-to-gate processes of the production of asphalt binder.

2.2.3.1 Crude Oil Types and Qualities

Asphalt binder production starts with the extraction of crude oil followed by delivery to the refinery. In this study, crude oil is modeled based on the crude oil slate dataset available in *GaBi* that covers the entire supply chain of crude oil starting with the extraction of crude oil and delivery to the refinery. Crude oil slate extraction, as reported in the *GaBi* dataset documentation, includes well drilling, crude oil production and processing, long-distance transport, and the regional distribution to the final consumer. Losses occurring during transportation via pipeline or vessel are also included in *GaBi (4)*.

The most important technologies used for crude oil extraction—such as conventional production (primary, secondary, tertiary) and unconventional production (oil sands, oil shale), which include parameters such as energy consumption, transport distances, and crude oil processing technologies—are independently considered for each crude oil production country in the *GaBi* dataset, shown in Figure 2.4. In the crude oil slate model, all known transport processes—including ocean freighter and barge transport as well as rail, truck, and pipeline transport of bulk commodities—are included.

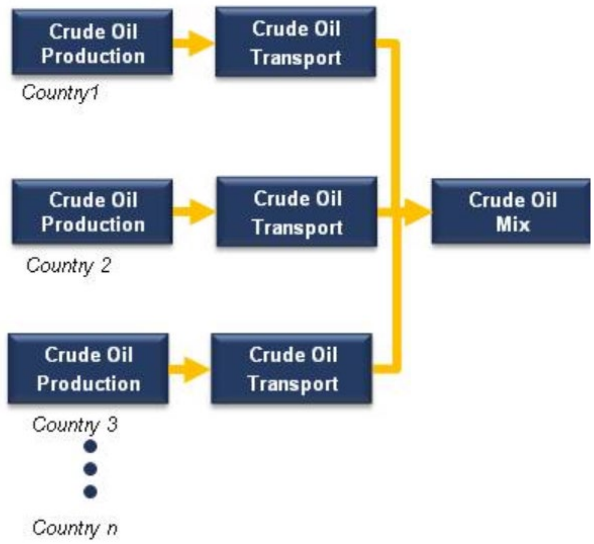
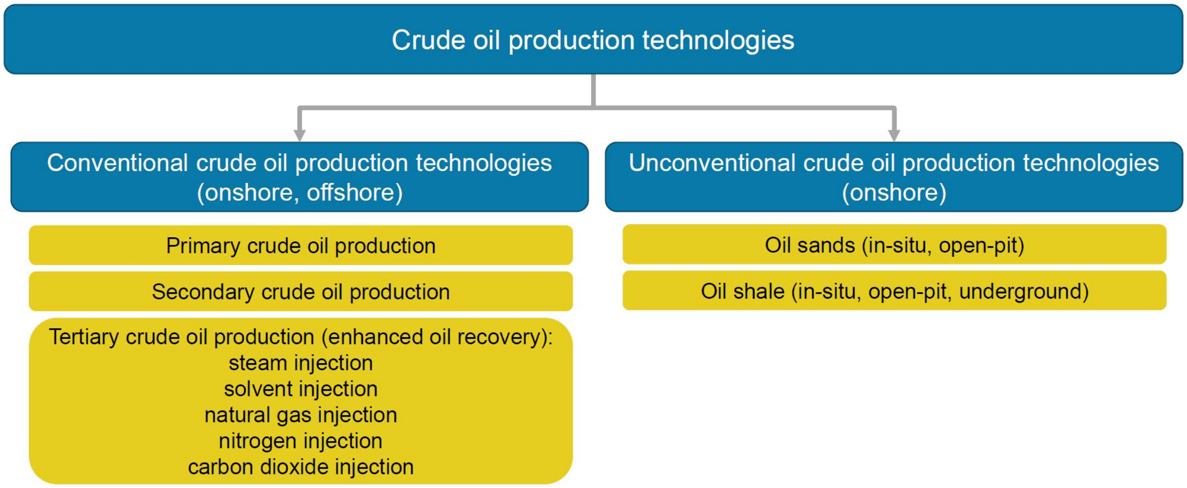


Figure 2.4: Typical pictogram of crude oil slate extraction.

There are two classifications of crude oil: conventional and unconventional. There are three conventional crude oil development and production technologies in US oil reservoirs called primary, secondary, and tertiary, shown in Figure 2.5. During primary recovery, about 10% of a reservoir's original oil in place is produced and the natural pressure of the reservoir combined with artificial lift techniques (such as pumps) brings the oil to the surface. For secondary technology, about 20% to 40% of a reservoir's original oil in place is produced by extending a field's productive life through the injection of gas or water to displace the oil and drive it to a production wellbore. For tertiary or enhanced oil recovery (EOR) technology, which is the most popular technique in the United States, more than 30% and up to 60% of a reservoir's original oil in place is brought to the surface. EOR usually uses three major technologies: thermal recovery, gas injection, and chemical injection *(14)*.

Unconventional production requires techniques and technologies to increase or enable oil and natural gas production beyond what might occur using conventional production techniques. Unconventional crude oil production includes extracting hydrocarbons from oil sands and oil shale by various techniques *(15,16)*.



Source: Schuller, Hengstler, and Thellier (2019) *(17)*.

Figure 2.5: Crude oil production technologies.

To compare the quality of different crude oils, sulfur content and density are two of the most important attributes. The EIA defines crude oil with less than 1% sulfur as "sweet" and crude oil with more than 1% sulfur as "sour" *(18)*. The American Petroleum Institute (API) gravity method, which is an inverse of the petroleum liquid's density relative to water, is used to classify different crude types. API gravity is commonly grouped as heavy, medium, or light. Crude oil from conventional extraction with an API gravity less than or equal to 25 is defined as heavy crude oil, and any crude oil with an API gravity greater than 25 is classified as medium or light crude oil, shown in Figure 2.6 *(18)*.

Conventional Oil
Light (API > 30)
Medium (25 < API ≤ 30)
Heavy (API ≤ 25)

Figure 2.6: Crude oil types from different conventional extraction methods.

Unconventional oil has a different set of definitions that do not correspond to the API gravities previously described and shown on the left side of Figure 2.5. Canadian oil sand typically has an API of 8 to 10. One type of oil sand can be classified as bitumen which is too viscous to flow through a pipeline. If the bitumen is diluted with lighter hydrocarbons to lower its viscosity, it is called diluted bitumen or "dilbit." Upgrading is a process by which bitumen is transformed into light/sweet synthetic crude oil (SCO) by fractionation and chemical treatment, removing virtually all traces of sulfur and heavy metals. About one-third of Alberta's bitumen is upgraded into

SCO before being sold to downstream refineries. "Synbit" is a mixture of synthetic crude and bitumen, typically a 50/50 blend *(19)*.

Table 2.1 shows data from the AI LCA study that compares the percent of crude oil of each gravity category in crude oil slates with the crude oil slates in different regions. The same information for California is also shown in the table from data from the EIA *(9)*. In 2018, California refineries received 31.1% of their crude from California wells, 11.4% from Alaska, and 57.5% from foreign sources. Top foreign sources that year were Saudi Arabia, Ecuador, and Iraq. Foreign sources of crude are increasing because California and Alaska oil fields are aging. Many of California's fields have been developed for a century and the Alaskan fields for a half century. California crude oil production in 2018 breaks down into the following API gravity categories: 68% of crude oil is heavy, 24% is medium, and the remaining 8% is light. Although the crude oil slate used by California's refineries resembles that of the AI LCA study in terms of gravity, less than 2% of that crude oil slate is imported from Canada *(22)*.

Table 2.1: Gravity of Crude Oil Slates from Different Sources in 2017

Type of Crude Oil Slate	Gravity of Crude Oil (% by mass)				
	Asphalt Institute[a]	North American Average[a]	US Average[b]	PADD 5[b]	California[b]
Heavy and Medium (API ≤ 30)	90	65	39	40	92
Light (API > 30)	10	35	61	60	8

[a] *Source:* Wildnauer et al. (2019) *(10)*.
[b] *Source:* US Energy Information Administration (2020) *(9)*.

2.2.3.2 Refinery

The following discussion reviews the methodology and assumptions used in the AI LCA study. Process-specific electricity, thermal energy, water usage, and emissions were the preferred data in the AI LCA study, but they were unavailable at the process level in the AI study. Therefore, researchers collected refinery-level data for sitewide consumption of electricity, thermal energy, and direct emissions.

The allocation method considered in the AI LCA study included electricity allocated based on the total mass of the coproducts, the sensible heat allocation method for thermal energy, and total thermal energy use allocation based on direct emissions from refinery processes (i.e., fuel combustion). The mass allocation method was considered for crude oil extraction and transportation. This current study assumed the same allocation method.

In the AI LCA study, the thermal energy input was calculated using the following equation:

$$Thermal\ energy\ needed = \frac{C * \Delta T}{\eta} + L$$

Where,

C = heat capacity (J/K)

ΔT = temperature difference between crude oil input and asphalt run down (K)

η = efficiency of heating system (unitless)

L = losses (J)

It should be noted that each refinery considered in the AI LCA study was modeled individually based on its own data and then combined to create the production-weighted average.

2.2.3.3 Asphalt Binder Production

Crude oil is the raw material that is extracted from the ground and transported to crude oil refineries—mainly through ports and pipelines, though rail is used by some refineries. At the refinery, the crude oil is partially heated and mixed with water to dissolve the salts (a process called desalting) followed by the separation and removal of the water from the crude oil. The desalted crude oil is further heated in the atmospheric distillation unit where fractional distillation takes place. All products lighter than heavy gas oil are vaporized and captured outside the unit. The resulting atmospheric residue then enters the vacuum distillation unit where the residue is heated and distilled under a vacuum. Gas oils and diesel are vaporized in the vacuum distillation unit, and asphalt, a remaining hot liquid, is left at the bottom of the vacuum distillation tower. Before the asphalt goes to the asphalt rundown line and asphalt storage, it passes through heat exchangers in conjunction with other refinery feeds in the crude and vacuum distillation units to return heat energy in the asphalt to the process *(10,12*). This complete process is presented in Figure 2.3.

The data in the AI LCA study indicates that approximately 93% of the nonrenewable energy consumption and 63% of the global warming (GW) from the production of asphalt binder comes from the crude oil slate extraction *(10)*. In this study, the production of asphalt binder focused on crude oil production and transportation in PADD 5 and California and assumed the same impacts of asphalt binder refineries and terminals. Of the 12 refineries in the AI LCA study, two are in California and one is in Washington State. Because crude oil extraction and transportation are heavily dependent on the crude oil source, expected differences in the crude oil slates used in California compared with PADD 5 and the rest of the United States are expected to result in large differences in nonrenewable energy use, GW, and other environmental impacts of asphalt binder production.

2.3 Life Cycle Inventory and Life Cycle Impact Assessment

2.3.1 *Life Cycle Inventory*

To develop an LCI of asphalt binder for PADD 5 and California, this study considered all components of the material stage: crude oil slate extraction (i.e., well drilling, exploration, production, and processing; long-distance transport; and regional distribution to the port of the crude oil source), transportation of crude oil from the origin port to the destination port and refineries, refining of crude oil into asphalt, transport of asphalt to the terminal, and final blending of the asphalt binders. As previously discussed, production of asphalt binder in this study focused on crude oil slate and transportation in PADD 5 and California and assumed the same impacts of asphalt binder refineries and terminals as the AI LCA study. As crude oil sources vary significantly among different regions, the current study collects data for crude oil in PADD 5 and California, specifically.

The framework developed in this study is mainly based on available crude oil slate data updated by the EIA and CEC *(9,20)*. The procedure developed can be used to calculate more precisely the environmental impacts of asphalt binder production for other parts of the United States and can be compared with the averaged data in the AI LCA study. The model can also be updated and adjusted in the future as trends change.

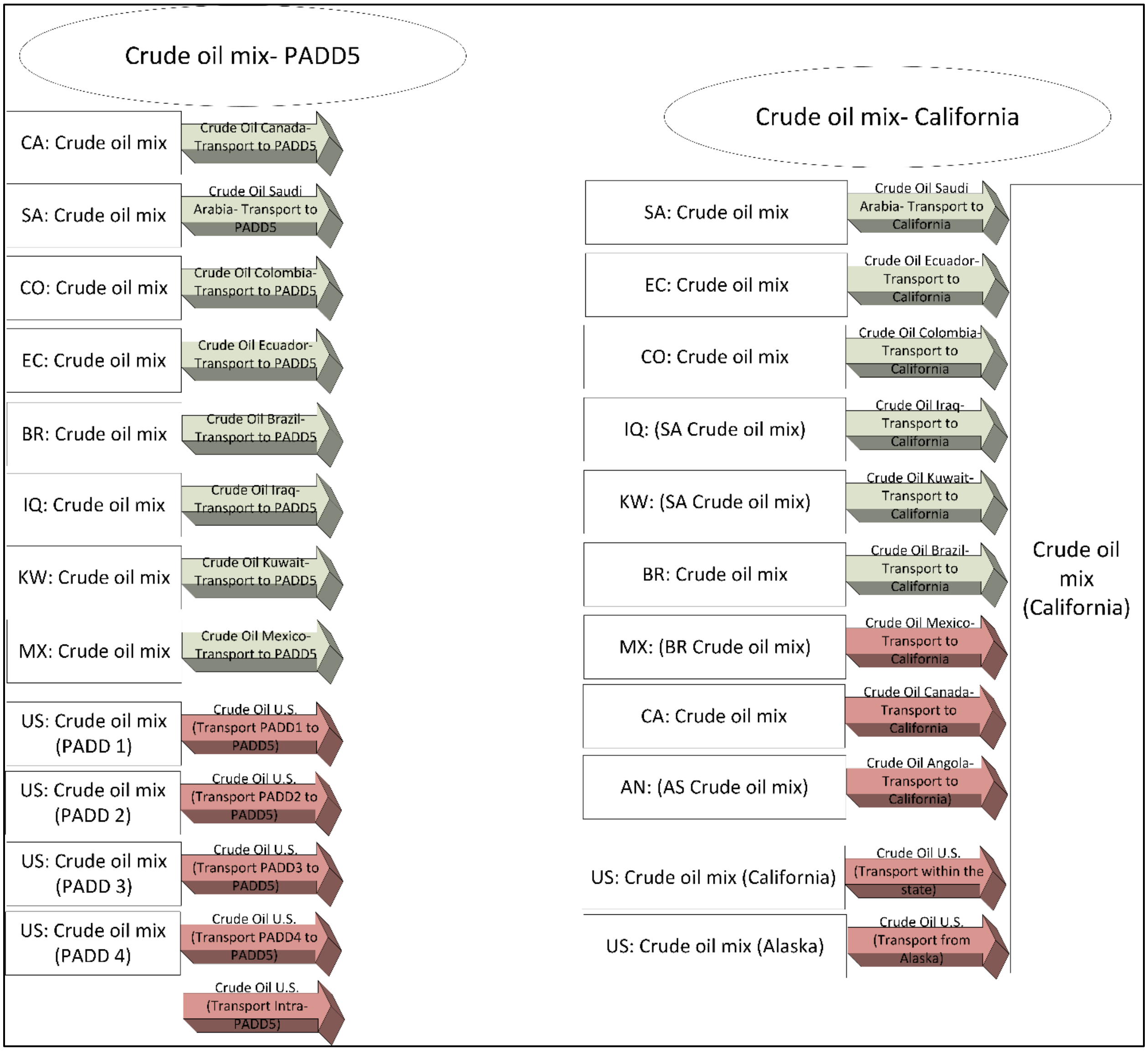
2.3.1.1 Data Sources and Software

As previously discussed, the crude oil slate data used specifically for the production of the PADD 5 and California asphalt binders were mainly collected from the following sources: the US Energy Information Administration (EIA) *(9,21)*, California Energy Commission (CEC) *(22,23)*, National Association of State Energy Officials (NASEO) *(24)*, Enerdata *(25)*, *Oil Sands Magazine (26–28)*, *Oil & Gas Journal (29)*, Congressional Research Service *(30)*, North American Cooperation on Energy Information (NACEI) *(31)*, and the Government of Canada *(32,33)*.

The *GaBi* software, developed by thinkstep and now distributed by Sphera, was used to create the asphalt binder models. The secondary LCI data for the background system were extracted from the 2019 *GaBi* LCI database *(5)*. Because the most recent and most complete data that were obtained from most of the sources was from 2017, that year was considered the reference year.

2.3.1.2 Crude Oil Slate Calculations

Crude oil slate data and the data for the transportation of crude oil from the origin port to the destination port and to refineries were collected from the previously discussed data resources. Figure 2.7 depicts the process diagram of crude oil for PADD 5 and California.



Note: US = United States, CA = Canada, SA = Saudi Arabia, CO = Colombia, EC = Ecuador, BR = Brazil, IQ = Iraq, KW = Kuwait, MX = Mexico, AN = Angola.

Figure 2.7: Crude oil slate process diagram for PADD 5 and California.

The foreign and domestic crude oil sources supplied to PADD 5 were determined based on EIA data from 2017 *(9)*. Only the countries that contributed more than 5% of PADD 5's crude oil imports were considered in the calculations, and the percentages of those source contributing less than 5% were assigned to those countries with contributions of more than 5% with similar crude sources (light, medium, heavy and sulfur content) and production methods. Major countries that export their crude oil to PADD 5 include Saudi Arabia, Canada, Ecuador, Colombia, and Brazil. The percentage of heavy, medium, and light oil for comparison was not available for some countries shown in Table 2.2. Countries that did not have crude oil data available were substituted with countries that have similar extraction and transportation and crude oil quality based on the EIA data. For instance, the crude oil slate of Saudi Arabia, which includes five types from heavy to super light, was used as a substitution for Iraq and Kuwait's crude oil slates based on regional similarities and because the Iraqi and Kuwaiti crudes are in between Arabian heavy and extra light in terms of average API gravity and sulfur content similarity *(9,20)*. Mexico's crude oil slate was substituted with Brazil's crude oil slate based on the similarity of the crude's API gravity, offshore production, and geographical locations, though the sulfur contents differ *(9,20)*. The production from smaller producers of oil for PADD 5 (shown as Crude Oil from Other Countries) was prorated across the assumed suppliers. Table 2.2 shows the crude oil imports to PADD 5 reported by the EIA, and the study's calculated percentages, which also considered data from the California Energy Commission.

Table 2.2: PADD 5 Crude Oil Imports from Foreign Countries in 2017

Crude Oil Country of Origin	**EIA Percentage (by mass) (%)**	**Calculated PADD 5 Percentage with Smaller Sources Added with Assumed Similar Production and Crude (by mass)[a] (%)**
Saudi Arabia (SA)	25	40 = 25 + 3 + 3 + (18*(25 + 3 + 3)/82)
Canada (CA)	18	22 = 18 + (18 * (18/82))
Ecuador (EC)	15	18 = 15 + (18*(15/82))
Colombia (CO)	10	12 = 10 + (18*(10/82))
Iraq (IQ)	4	—
Kuwait (KW)	4	—
Brazil (BR)	3	7 = 3 + 3 + (18*((3 + 3)/82))
Mexico (MX)	3	—
Other Countries	18	—
All Foreign Countries	100	100

[a] Example calculation: Brazil's calculated percentage = 3% from Brazil + 3% from Mexico (similar crude and production) + the prorated portion of the Other Countries percentage (18%*(3%+3%)/82%)) = 7%.

Source: US Energy Information Administration (2020) *(9)*.

The domestic crude oil resources used in PADD 5 include PADD 5 field production crude oil (Intra-PADD) in addition to the crude oil coming from other PADDs to PADD 5. Table 2.3 depicts the amount of foreign and domestic crude oil resources refined in the United States and in PADD 5.

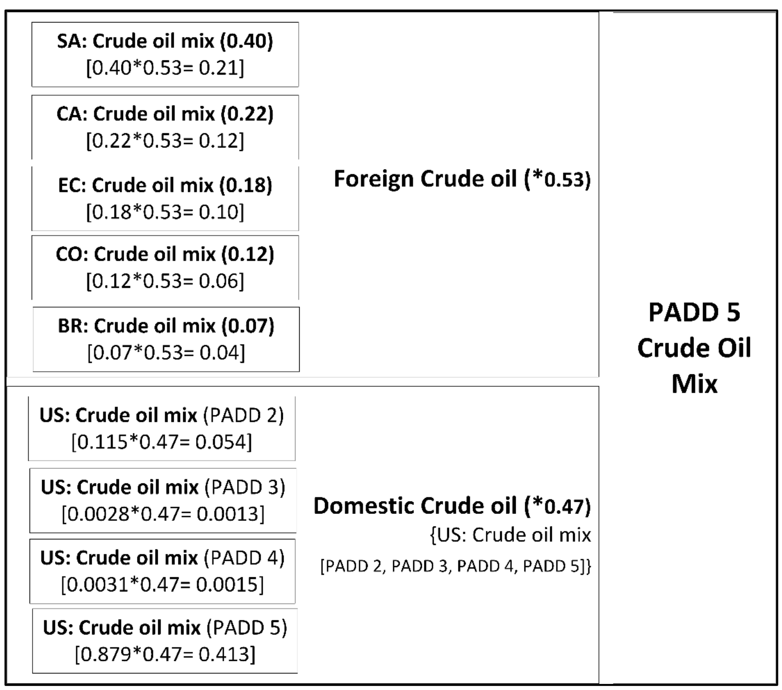
Table 2.3: Foreign and Domestic Crude Oil Resources Refined in the United States and PADD 5 in 2017

Crude Oil Resources Used	US (million barrels)	US (percentage by mass) (%)	PADD 5 (million barrels)	PADD 5 (percentage by mass) (%)
Domestic[a]	3,413.4	54	410.2	47
Foreign	2,908.6	46	462.6	53

[a] Produced within the United States.

Source: US Energy Administration (2020) *(9)*.

As previously dicussed, there are two main sources of crude oil refined in PADD 5: (1) 47% is domestic (PADD 2, PADD 3, PADD 4, and Intra-PADD 5) and (2) 53% is foreign (imported from foreign countries into PADD 5). To estimate the sources of the domestic crude oil slate brought into and refined in PADD 5 (PADD 2, PADD 3, PADD 4, and Intra-PADD 5), the US average crude oil slate data are multiplied by 47% (domestic crude oil resources used in Table 2.3) and the portion of the foreign crude oil brought into PADD 5 from each foreign country (Table 2.2) is multiplied by 53% (foreign crude oil resources used in Table 2.3). The impacts of the US average crude oil slate, as a national average for domestic crude oil sources, were derived from *GaBi.* The impacts of the crude oil slate for each foreign country were also taken from the *GaBi* database. The crude oil slate and its impacts on PADD 5 were calculated by adding these figures. This calculation process is shown in Figure 2.8.



Source: US Energy Administration (2020) *(9)*.

Figure 2.8. PADD 5 crude oil slate calculations using 2017 data.

The crude oil slate calculations performed to estimate a California average mix are similar to the ones done for PADD 5. All inventories were extracted from EIA and CEC information for 2017 *(9,20)*. The calculated percentages based on the assumptions discussed in Section 2.2.3 for crude oil imports are shown in Table 2.4. Table 2.5 shows domestic and foreign crude oil percentages for the United States, PADD 5, and California. It should be noted that domestic crude oil for California is defined as crude oil slate in California, plus crude oil brought into California from inside the United States (nearly all from Alaska, which is in PADD 5, since there are no pipelines connecting California to the other 48 continental states). The same substitutions made for PADD 5 for crudes from Iraq, Kuwait, and Mexico and crudes from other countries were also made for California. Figure 2.9 shows the process diagram for the California crude oil calculations.

Table 2.4: Assumed California Crude Oil Imports from Foreign Countries in 2017

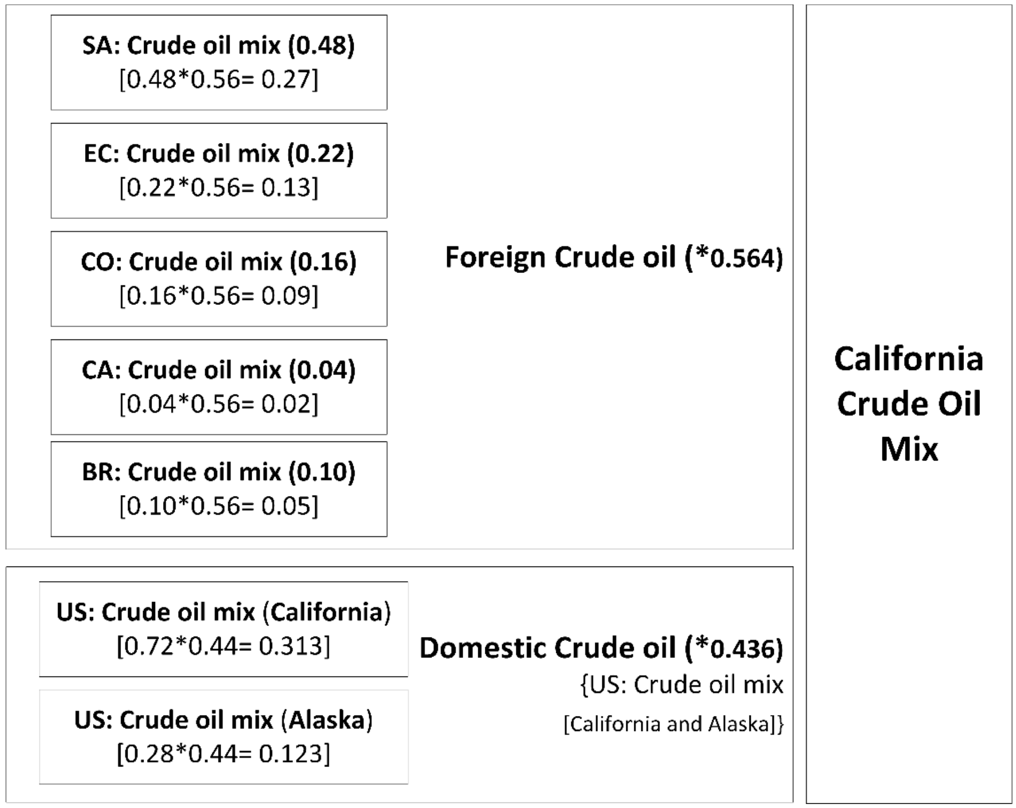
Crude Oil Country of Origin	EIA and CEC Percentage (by mass) (%)	Assumed Percentage (by mass) (%)
Saudi Arabia (SA)	29	48
Ecuador (EC)	20	22
Colombia (CO)	14	16
Canada (CA)	3	4
Iraq (IQ)	8	—
Kuwait (KW)	7	—
Brazil (BR)	4	10
Mexico (MX)	4	—
Other countries	10	—
All foreign countries	100	100

Sources: US Energy Information Administration (2020) *(9)*; California Energy Commission (2020) *(20)*.

Table 2.5: Foreign and Domestic Crude Oil Resources of United States, PADD 5, and California in 2017

Crude Oil Resource	Barrels (1,000)			Percentage by Mass (%)		
	United States	PADD 5	California	United States	PADD 5	California
Domestic	3,413,376	410,191	274,748	54	47	44
Foreign	2,908,670	462,589	355,150	46	53	56

Sources: US Energy Information Administration (2020) *(9)*; California Energy Commission (2020) *(20)*.



Sources: US Energy Information Administration (2020) *(9)*; California Energy Commission (2020) *(20)*.

Figure 2.9: California crude oil slate calculations for 2017.

2.3.1.3 Crude Oil Transportation

Crude oil is transported from the origin ports/wells to the destination ports and refineries by pipeline, rail, ocean freighter, barge, truck, or a combination of these transport modes. Crude oil transport was calculated based on information about the location of the port/well, mode of transport, and distance, summarized in Table 2.6 and Table 2.7. A sea distances online tool was used to calculate distances between origin and destination ports traveled by the ocean freighter (oil tanker) *(34)*. The distances for other modes of transport were calculated based on the US, PADD 5, and California fuel resiliency; West Coast fuels markets; and petroleum and other liquids inventory by the EIA *(35–37)*. The portion of each mode of transportation based on the crude oil origin-destination distances for PADD 5 and California are also shown in Table 2.6 and Table 2.7. The *GaBi* 2019 database sources used for the modeling are shown in Table 2.8 *(12)*.

Table 2.6: Crude Oil Transportation Distances and Quantities for Different Transportion Modes to PADD 5 Locations

Route	Origin Port	Destination Port	PADD5 Import (thousand barrels/day)	Distance (miles)	Mass Times Distance (thousand barrels*miles/day)
Transport Mode: Pipeline					
Canada to PADD 5	Edmonton, CAN	Puget Sound, WA	279	793	221,105
PADD3 to PADD 5	El Paso, TX	Phoenix, AZ	34	402	13,520
PADD4 to PADD 5	Salt Lake City, UT	Spokane, WA	32	721	22,777
PADD4 to PADD 5	Salt Lake City, UT	Las Vegas, NV	8	421	3,325
PADD4 to PADD 5	Billings, MT	Moses Lake, WA	8	645	5,094
PADD 5 to PADD 5	Los Angeles, CA	San Francisco, CA	84	382	32,088
PADD 5 to PADD 5	Bakersfield, CA	Los Angeles, CA	79	113	8,927
PADD 5 to PADD 5	Blaine, WA	Portland, OR	284	285	80,940
Total					**387,775 (4.56 %)**
Transport Mode: Rail					
PADD 2 to PADD 5	Bakken Play	Tacoma, WA	38	1,026	39,034
PADD4 to PADD 5	Salt Lake City, UT	Los Angeles, CA	16	688	10,867
PADD5 to PADD 5	Tacoma, WA	San Francisco, CA	54	777	41,958
PADD5 to PADD 5	SF, CA	Long Beach, CA	57	405	23,085
Total					**114,944 (1.35 %)**
Transport Mode: Tanker					
Saudi Arabia to PADD 5	Ras Tanura, Saudi Arabia	Los Angeles, CA	507	11,370	5,763,986
Ecuador to PADD 5	Balao, Ecuador	Los Angeles, CA	228	3,005	685,519
Colombia to PADD 5	Barranquilla, Colombia	Los Angeles, CA	152	3,289	500,204
Brazil to PADD 5	Belem, Brazil	Los Angeles, CA	89	5,267	467,266
PADD 5 to PADD 5	Valdez, AK	Anacortez, WA	119	202	142,681
PADD 5 to PADD 5	Valdez, AK	San Francisco, CA	98	1715	168,070
PADD 5 to PADD 5	Valdez, AK	Los Angeles, CA	103	2,056	211,768
PADD 5 to PADD 5	San Francisco, CA	Portland, OR	97	645	62,565
Total					**8,002,059 (94.03 %)**
Transport Mode: Barge					
PADD 5 to PADD 5	Valdez, AK	Anacortez, WA	1	1,199	1,199
PADD5 to PADD 5	Valdez, AK	San Francisco, CA	1	1,715	1,715
Total					**2,914 (0.03 %)**
Transport Mode: Truck					
PADD 5 to PADD 5	Assumed Average Intra-PADD Distance		17	150	2,580
Total					**2,580 (0.03 %)**

Source: US Energy Information Administration (2020) *(9)*.

Table 2.7: Crude Oil Transportation Distances and Quantities for Different Transport Modes to California Locations

Route	Origin Port	Destination Port	PADD5 Import (thousand barrels/day)	Distance (miles)	Mass Times Distance (thousand barrels*miles/day)
Transport Mode: Pipeline					
PADD 5 to PADD 5	Los Angeles, CA	San Francisco, CA	84	382	32,088
PADD 5 to PADD 5	Bakersfield, CA	Los Angeles, CA	79	113	8,927
Total					**41,015 (0.56 %)**
Transport Mode: Rail					
PADD4 to PADD 5	Salt Lake City	Los Angeles, CA	16	688	11,008
PADD5 to PADD 5	Tacoma, WA	San Francisco, CA	54	777	41,958
PADD5 to PADD 5	San Francisco, CA	Long Beach, CA	57	405	23,085
Total					**76,051 (1.05 %)**
Transport Mode: Tanker					
Saudi Arabia to PADD 5	Ras Tanura, Saudi Arabia	Los Angeles, CA	453	11,370	5,146,921
Ecuador to PADD 5	Balao, Ecuador	Los Angeles, CA	207	3,005	623,466
Colombia to PADD 5	Barranquilla, Colombia	Los Angeles, CA	151	3,289	496,283
Brazil to PADD 5	Belem, Brazil	Los Angeles, CA	89	5,267	467,266
PADD 5 to PADD 5	Valdez, AK	San Francisco, CA	98	1,715	168,070
PADD 5 to PADD 5	Valdez, AK	Los Angeles, CA	103	2,056	211,768
Total					**7,115,271 (98.31 %)**
Transport Mode: Barge					
PADD 5 to PADD 5	Valdez, AK	Anacortez, WA	1	1,199	1,199
PADD 5 to PADD 5	Valdez, AK	San Francisco, CA	1	1,715	1,715
Total					**2,914 (0.04 %)**
Transport Mode: Truck					
PADD 5 to PADD 5	Assumed Average Intra-PADD Distance		17	150	2,550
Total					**2,550 (0.04 %)**

Source: US Energy Information Administration (2020) *(9)*.

Table 2.8: Transportation and Fuel Datasets from GaBi

Mode	Database	Fuel
Pipeline	GLO: Pipeline average	Electricity power
Ocean Freighter (Oil tanker)	US: Transport, ocean freighter, average fuel mix	Diesel power, residual fuel oil
Barge Transport	US: Transport, barge, average fuel mix	Diesel power, residual fuel oil
Rail	US: Transport, train, diesel-powered	Diesel power
Heavy Truck	US: Heavy heavy-duty diesel truck	Diesel power

Source: Schuller (2020) *(12)*.

An example of crude oil transportation GW emissions calculations is shown in Table 2.9 and Table 2.10.

Table 2.9: Crude Oil Transportation Global Warming Impact by Transport Mode Type to PADD 5

Transportation Mode	Fuel	GW per 1000 kg-km (kg CO_2 eq)	Mass-Distance Allocation (percent of total mass*distance) (%)	Average GW per Mass-Distance Allocation (kg CO_2 eq per 1000 kg-km)
Pipeline	Electricity power	2.87E-03	4.56	1.31E-04
Rail	Diesel power	2.20E-02	1.35	2.97E-04
Oil tanker	Diesel power, residual fuel oil	1.83E-02	94.03	1.72E-02
Barge Transport	Diesel power, residual fuel oil	3.31E-02	0.03	1.13E-05
Heavy Truck	Diesel power	7.80E-02	0.03	2.36E-05
Total GW per 1000 kg-km for all transportation modes				**1.78E-02**

Table 2.10: Crude Oil Transportation Global Warming Impact by Transport Mode Type to California

Transportation Mode	Fuel	GW per 1000 kg-km (kg CO_2 eq)[a]	Mass-Distance Allocation (percent of total mass*distance) (%)	Average GW per Mass-Distance Allocation (kg CO_2 eq per 1000 kg-km)
Pipeline	Electricity power	2.87E-03	0.56	1.62E-05
Rail	Diesel power	2.20E-02	1.05	2.30E-04
Oil tanker	Diesel, residual fuel oil power	1.83E-02	98.31	1.80E-02
Barge Transport	Diesel, residual fuel oil power	3.31E-02	0.04	1.33E-05
Heavy Truck	Diesel power	7.80E-02	0.04	2.74E-05
Total GW per 1000 kg-km per all transportation modes				**1.83E-02**

[a] Source: US Energy Information Administration (2020) *(9)*.

2.3.1.4 Life Cycle Impact Assessment

TRACI 2.1 (Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts) was selected as the impact assessment methodology so that a comparison of results could be made with the AI LCA study *(38)*. TRACI 2.1 includes US average conditions to establish characterization factors.

The life cycle impact assessment (LCIA) environmental impact categories selected for this study include the following:

- Global warming potential (GWP): in kg of CO_2 eq. The evaluation of GWP is based on the characterization factors from the Intergovernmental Panel on Climate Change (IPCC) *Fourth Assessment Report* (*IPCC AR4*) published in 2007, which is the approach used in TRACI 2.1, for a 100-year timeframe (GWP_{100}) *(4)*.
- Ozone depletion potential (ODP): in kg CFC-11 eq. A measure of air emissions that contribute to the depletion of the stratospheric ozone layer resulting in higher levels of ultraviolet B (UVB) rays that reach Earth. *(39)*.
- Photochemical ozone creation potential (POCP): in kg of O3e. A measure of smog formation potential.
- Human health: in kg of PM2.5. A measure of particulate matter smaller than or equal to 2.5 micrometers in diameter.
- Acidification potential: in kg SO2 eq. A measure of emissions leading to acidifying effects to the environment.
- Eutrophication potential: in kg N eq. A measure of the pollution state of aquatic ecosystems *(40)*.
- Water consumption: in kg. A measure of the net intake and release of freshwater.
- Renewable primary energy demand (PED renewable, PED-R): in MJ. A measure of fuel used from renewable resources (net calorific value excluding feedstock energy).
- Nonrenewable primary energy demand (PED nonrenewable, PED-NR): in MJ. A measure of fuel used from nonrenewable resources (net calorific value excluding feedstock energy).
- Feedstock energy: in MJ. A measure of energy that is not used but is stored in the material (nonrenewable resource; also called PED non-fuel).

Renewable and nonrenewable PED and feedstock energy were used to measure energy consumption. According to ISO 14040, feedstock energy is defined as "the heat of combustion of a raw material input that is not used as an energy source to a product system, expressed in terms of higher heating value or lower heating value" *(41)*. Because asphalt (bitumen) is an oil-based product that is used as a material (not as an energy source), it has high feedstock energy content, and the recommendation is to reported it separately in LCA studies *(39,41,42)*. It should be noted that global warming, ozone depletion, and the use of PED-NR are impact categories that have global effects *(43,44)*.

2.3.2 *Results (Life Cycle Inventory and Life Cycle Impact Assessment)*

The asphalt binder LCI covers crude oil slate (material stage) and crude oil transportation (transport from origin well/port to the destination port and refinery, which is collected and calculated in the current study) and refinery processes, transport to the terminal (from the AI LCA study), and terminal storage (from the AI LCA study) *[10]*). Table 2.11 shows the LCI (energy and water consumption) and LCIA results of the material extraction stage of 1 kg of asphalt binder for PADD 5; Table 2.12 shows the LCI and LCIA results from the transport of 1 tonne-km of asphalt binder in 2017 for PADD 5; and Table 2.13 shows the LCI and LCIA for transporting 1 tonne-km with allocation based on the percentages of each mode used for PADD 5. Table 2.14 shows the LCI (energy and water consumption) and LCIA results of the material extraction stage of 1 kg of asphalt binder for California, Table 2.15 shows the LCI and LCIA for transportion of 1 tonne-km of binder (same values as in Table 2.13), and Table 2.16 show the crude oil transport allocation results for California.

Table 2.17 and Table 2.18 show the LCI results for the extraction to terminal supply chain for 1 kg of asphalt binder for PADD 5 and California, respectively. As previously discussed, the LCIAs from the refinery processes and terminal storage are taken from the AI LCA study *(10)*.

Table 2.11: LCI and LCIA Results from the Material Extraction Stage of 1 kg of Asphalt Binder for PADD 5 (2017)

Impact Category and Unit	Asphalt Binder Crude Oil						
	United States[a]	Canada[b]	Saudi Arabia[c]	Colombia[d]	Ecuador[e]	Brazil[f]	Avg. PADD 5
IPCC AR5							
Global warming potential (GWP100) (kg CO2 eq)	3.05E-01	4.22E-01	8.08E-02	1.84E-01	2.60E-01	2.45E-01	2.58E-01
Global warming potential (GWP20) (kg CO2 eq)	4.06E-01	5.08E-01	8.88E-02	3.08E-01	4.52E-01	3.92E-01	3.50E-01
TRACI 2.1 (IPCC AR4)							
Ozone depletion (kg CFC-11 eq)	-8.48E-15	-2.85E-14	-4.46E-16	-3.25E-16	-2.83E-16	-4.39E-16	-7.56E-15
Acidification (kg SO_2 eq)	1.28E-03	1.15E-03	3.00E-04	5.20E-04	9.30E-04	9.03E-04	9.63E-04
Eutrophication (kg N eq)	7.30E-05	6.45E-05	1.36E-05	3.12E-05	2.81E-05	5.05E-05	5.16E-05
Smog formation (kg O_3 eq)	2.50E-02	2.19E-02	4.49E-03	8.59E-03	8.26E-03	1.62E-02	1.73E-02
Human health particulate effects (kg PM2.5 eq)	9.21E-05	7.50E-05	1.80E-05	4.07E-05	6.51E-05	6.57E-05	6.77E-05
Resource Use							
Primary energy (nonenewable) (MJ)	4.66E+01	5.03E+01	4.38E+01	4.40E+01	4.50E+01	4.54E+01	4.61E+01
Primary energy (renewable) (MJ)	1.40 E-01	3.85 E-01	1.7 E-03	8.43 E-02	7.24 E-02	6.98 E-02	1.28 E-01
Water consumption (kg)	1.09 E+00	1.62 E+00	8.35 E-01	1.36 E-01	1.18 E-01	2.32 E-01	9.12 E-01

[a] United States = 47% of asphalt binder extraction for PADD 5.
[b] Canada = 12% of asphalt binder extraction for PADD 5.
[c] Saudi Arabia = 21% of asphalt binder extraction for PADD 5.
[d] Colombia = 6% of asphalt binder extraction for PADD 5.
[d] Ecuador = 10% of asphalt binder extraction for California.
[e] Brazil = 4% of asphalt binder extraction for California.

Table 2.12: LCI and LCIA Results from Transport for 1 tonne-km Functional Unit of Asphalt Binder for PADD 5 (2017)

Impact Category and Unit	Transport LCIA for 1 tonne-km Functional Unit				
	Pipeline	Ocean Freighter (Oil Tanker)	Barge Transport	Rail-Train	Truck
IPCC AR5					
Global warming potential (GWP100) (kg CO2 eq)	2.91E-03	1.84E-02	3.33E-02	2.21E-02	7.88E-02
Global warming potential (GWP20) (kg CO2 eq)	3.36E-03	1.97E-02	3.54E-02	2.36E-02	8.51E-02
TRACI 2.1 (IPCC AR4)					
Ozone depletion (kg CFC-11 eq)	1.63E-13	6.85E-13	1.24E-12	8.35E-13	3.31E-12
Acidification (kg SO_2 eq)	6.48E-06	3.80E-04	3.79E-04	3.93E-04	4.98E-04
Eutrophication (kg N eq)	3.61E-07	2.05E-05	1.83E-05	2.38E-05	2.86E-05
Smog formation (kg O_3 eq)	8.17E-05	1.11E-02	9.58E-03	1.29E-02	9.86E-03
Human health particulate effects (kg PM2.5 eq)	3.52E-07	1.87E-05	1.96E-05	1.88E-05	2.59E-05
Global warming air (kg CO2 eq)	2.87E-03	1.83E-02	3.31E-02	2.20E-02	7.82E-02
Resource Use					
Primary energy (nonrenewable) (MJ)	4.50E-02	2.31E-01	4.17E-01	2.82E-01	1.12E+00
Primary energy (renewable) (MJ)	1.50E-02	0	0	0	0
Water consumption (kg)	6.23E-01	0	0	0	0

Table 2.13: LCI and LCIA Results from Transport of Asphalt Binder for PADD 5 (2017)

Impact Category and Unit	Transport LCIA for Mass-Distances Allocation for Each Transport Mode					
	Pipeline	Ocean Freighter (Oil Tanker)	Barge Transport	Rail-train	Truck	Total Crude Transport
IPCC AR5						
Global warming potential (GWP100) (kg CO2 eq)	1.33E-04	1.73E-02	1.14E-05	2.99E-04	2.36E-05	1.78E-02
Global warming potential (GWP20) (kg CO2 eq)	1.53E-04	1.85E-02	1.21E-05	3.19E-04	2.55E-05	1.90E-02
TRACI 2.1 (IPCC AR4)						
Ozone depletion (kg CFC-11 eq)	7.44E-15	6.45E-13	4.23E-16	1.13E-14	9.92E-16	6.65E-13
Acidification (kg SO_2 eq)	2.95E-07	3.57E-04	1.30E-07	5.31E-06	1.49E-07	3.63E-04
Eutrophication (kg N eq)	1.65E-08	1.93E-05	6.27E-09	3.22E-07	8.57E-09	1.96E-05
Smog formation (kg O_3 eq)	3.72E-06	1.05E-02	3.28E-06	1.74E-04	2.95E-06	1.07E-02
Human health particulate effects (kg PM2.5 eq)	1.60E-08	1.76E-05	6.72E-09	2.54E-07	7.77E-09	1.79E-05
Global warming air (kg CO2 eq)	1.31E-04	1.72E-02	1.13E-05	2.97E-04	2.34E-05	1.77E-02
Resource Use						
Primary energy (nonrenewable) (MJ)	2.05E-03	2.17E-01	1.43E-04	3.81E-03	3.34E-04	2.24E-01
Primary energy (renewable) (MJ)	6.83E-04	0	0	0	0	6.83E-04
Water consumption (kg)	2.84E-02	0	0	0	0	2.84E-02

Table 2.14: LCI and LCIA Results from the Material Extraction Stage of 1 kg of Asphalt Binder for California (2017)

Impact Category and Unit	United States[a]	Canada[b]	Saudi Arabia[c]	Colombia[d]	Ecuador[e]	Brazil[f]	Avg. California
	Asphalt Binder, Crude Oil	Asphalt Binder, Crude Oil	Asphalt Binder, Crude Oil	Asphalt Binder, Crude Oil	Asphalt Binder, Crude Oil	Asphalt Binder, Crude Oil	Asphalt Binder, Crude Oil
IPCC AR5							
Global warming potential (GWP100) (kg CO2 eq)	3.05E-01	4.22E-01	8.08E-02	1.84E-01	2.60E-01	2.45E-01	2.25E-01
Global warming potential (GWP20) (kg CO2 eq)	4.06E-01	5.08E-01	8.88E-02	3.08E-01	4.52E-01	3.92E-01	3.15E-01
TRACI 2.1 (IPCC AR4)							
Ozone depletion (kg CFC-11 eq)	-8.48E-15	-2.85E-14	-4.46E-16	-3.25E-16	-2.83E-16	-4.39E-16	-4.51E-15
Acidification (kg SO2 eq)	1.28E-03	1.15E-03	3.00E-04	5.20E-04	9.30E-04	9.03E-04	9.00E-04
Eutrophication (kg N eq)	7.30E-05	6.45E-05	1.36E-05	3.12E-05	2.81E-05	5.05E-05	0.00E+00
Smog formation (kg O3 eq)	2.50E-02	2.19E-02	4.49E-03	8.59E-03	8.26E-03	1.62E-02	1.53E-02
Human health particulate effects (kg PM2.5 eq)	9.21E-05	7.50E-05	1.80E-05	4.07E-05	6.51E-05	6.57E-05	1.00E-04
Resource Use							
Primary energy (nonrenewable) (MJ)	4.66E+01	5.03E+01	4.38E+01	4.40E+01	4.50E+01	4.54E+01	4.54E+01
Primary energy (renewable) (MJ)	1.40E-01	3.85E-01	1.70E-03	8.43E-02	7.24E-02	6.98E-02	8.98E-02
Water consumption (kg)	1.09E+00	1.62E+00	8.35E-01	1.36E-01	1.18E-01	2.32E-01	7.85E-01

[a] United States = 47% of asphalt binder extraction for California.
[b] Canada = 2% of asphalt binder extraction for California.
[c] Saudi Arabia = 27% of asphalt binder extraction for California.
[e] Colombia = 9% of asphalt binder extraction for California.
[d] Ecuador = 13% of asphalt binder extraction for California
[e] Brazil = 5% of asphalt binder extraction for California.

Table 2.15: LCI and LCIA Results from the Transport for 1 tonne-km Functional Unit of Asphalt Binder for California (2017)

Impact Category and Unit	Transport LCIA for 1 tonne-km Functional Unit				
	Pipeline	Ocean Freighter (Oil Tanker)	Barge Transport	Rail-Train	Truck
IPCC AR5					
Global warming potential [GWP100] (kg CO2 eq)	2.91E-03	1.84E-02	3.33E-02	2.21E-02	7.88E-02
Global warming potential [GWP20] (kg CO2 eq)	3.36E-03	1.97E-02	3.54E-02	2.36E-02	8.51E-02
TRACI 2.1 (IPCC AR4)					
Ozone depletion (kg CFC-11 eq)	1.63E-13	6.85E-13	1.24E-12	8.35E-13	3.31E-12
Acidification (kg SO2 eq)	6.48E-06	3.80E-04	3.79E-04	3.93E-04	4.98E-04
Eutrophication (kg N eq)	3.61E-07	2.05E-05	1.83E-05	2.38E-05	2.86E-05
Smog formation (kg O3 eq)	8.17E-05	1.11E-02	9.58E-03	1.29E-02	9.86E-03
Human health particulate effects (kg PM2.5 eq)	3.52E-07	1.87E-05	1.96E-05	1.88E-05	2.59E-05
Global warming air (kg CO2 eq)	2.87E-03	1.83E-02	3.31E-02	2.20E-02	7.82E-02
Resource Use					
Primary energy (nonrenewable) (MJ)	4.50E-02	2.31E-01	4.17E-01	2.82E-01	1.12E+00
Primary energy (renewable) (MJ)	1.50E-02	0	0	0	0
Water consumption (kg)	6.23E-01	0	0	0	0

Table 2.16: LCI and LCIA Results from Transportation of Asphalt Binder for California (2017)

Impact Category and Unit	Transport LCIA for Mass-Distances for Each Transport Mode					
	Pipeline	Ocean Freighter (oil tanker)	Barge Transport	Rail-train	Truck	Total Crude Transport
IPCC AR5						
Global warming potential (GWP100) (kg CO2 eq)	1.65E-05	1.81E-02	1.34E-05	2.33E-04	2.78E-05	1.84E-02
Global warming potential (GWP20) (kg CO2 eq)	1.90E-05	1.93E-02	1.43E-05	2.48E-04	3.00E-05	1.97E-02
TRACI 2.1 (IPCC AR4)						
Ozone depletion (kg CFC-11 eq)	9.25E-16	6.74E-13	4.98E-16	8.78E-15	1.17E-15	6.85E-13
Acidification (kg SO2 eq)	3.67E-08	3.73E-04	1.53E-07	4.13E-06	1.75E-07	3.78E-04
Eutrophication (kg N eq)	2.05E-09	2.02E-05	7.37E-09	2.50E-07	1.01E-08	2.04E-05
Smog formation (kg O3 eq)	4.63E-07	1.10E-02	3.86E-06	1.36E-04	3.47E-06	1.11E-02
Human health particulate effects (kg PM2.5 eq)	1.99E-09	1.84E-05	7.90E-09	1.98E-07	9.14E-09	1.86E-05
Global warming air (kg CO2 eq)	1.63E-05	1.80E-02	1.33E-05	2.31E-04	2.76E-05	1.83E-02
Resource Use						
Primary energy (nonrenewable) (MJ)	2.55E-04	2.27E-01	1.68E-04	2.96E-03	3.93E-04	2.31E-01
Primary energy (renewable) (MJ)	8.50E-05	0	0	0	0	8.50E-05
Water consumption (kg)	3.53E-03	0	0	0	0	3.53E-03

Table 2.17: Extraction to Terminal LCIA Results for 1 kg of Asphalt Binder for PADD 5 (2017)

Impact Category and Unit	Crude Oil Extraction - PADD5	Transport from Crude Oil Well/Port to PADD 5 Refinery	Refinery	Transport to Terminal	Terminal	Total PADD 5
IPCC AR5						
Global warming potential (GWP100) (kg CO2 eq)	2.58E-01	1.78E-02	7.69E-02	3.30E-02	1.01E-01	4.87E-01
Global warming potential (GWP20) (kg CO2 eq)	3.50E-01	1.90E-02	8.70E-02	3.51E-02	1.17E-01	6.08E-01
TRACI 2.1 (IPCC AR4)						
Ozone depletion (kg CFC-11 eq)	-7.56E-15	6.65E-13	6.79E-12	4.97E-12	6.41E-12	1.88E-11
Acidification (kg SO2 eq)	9.63E-04	3.63E-04	1.68E-04	2.04E-04	1.36E-04	1.83E-03
Eutrophication (kg N eq)	5.16E-05	1.96E-05	7.30E-05	9.85E-06	1.76E-05	1.72E-04
Smog formation (kg O3 eq)	1.73E-02	1.07E-02	1.76E-03	4.82E-03	3.44E-03	3.80E-02
Human health particulate effects (kg PM2.5 eq)	6.87E-05	1.79E-05	2.21E-05	1.14E-05	1.93E-05	1.39E-04

Table 2.18: Extraction to Terminal LCIA Results for 1 kg of Asphalt Binder for California (2017)

Impact Category and Unit	Crude Oil - California	Transport from Crude Oil Well/Port to California Refinery	Refinery	Transport to Terminal	Terminal	Total California
IPCC AR5						
Global warming potential (GWP100) kg CO2 eq)	2.25E-01	1.84E-02	7.69E-02	3.30E-02	1.01E-01	4.55E-01
Global warming potential (GWP20) (kg CO2 eq)	3.15E-01	1.97E-02	8.70E-02	3.51E-02	1.17E-01	5.74E-01
TRACI 2.1 (IPCC AR4)						
Ozone depletion (kg CFC-11 eq)	-4.51E-15	6.85E-13	6.79E-12	4.97E-12	6.41E-12	1.89E-11
Acidification (kg SO2 eq)	9.00E-04	3.78E-04	1.68E-04	2.04E-04	1.36E-04	1.79E-03
Eutrophication (kg N eq)	0.00E+00	2.04E-05	7.30E-05	9.85E-06	1.76E-05	1.21E-04
Smog formation (kg O3 eq)	1.53E-02	1.11E-02	1.76E-03	4.82E-03	3.44E-03	3.64E-02
Human health particulate effects (kg PM2.5 eq)	1.00E-04	1.86E-05	2.21E-05	1.14E-05	1.93E-05	1.71E-04

2.4 Interpretation

2.4.1 *Results*

Figure 2.10 to Figure 2.13 show the environmental impacts of three steps of asphalt binder production to the gate of the refinery or terminal for PADD 5 and California. The three steps are (1) crude oil extraction and transportation, (2) refinery operations and transportation, and (3) terminal storage and operations. Figure 2.10 and Figure 2.11 further divided the three steps into five steps of the asphalt binder material stage and supply chain, including crude oil extraction and production, transport from the origin port to the destination port and refinery, refinery operations, terminal storage, and transport to the terminal for PADD 5 and California. Figure 2.12 and Figure 2.13 show the overall contribution at each step in the supply chain for all impacts from the material stage of asphalt binder.

Within the cradle-to-gate stages of the life cycle, crude oil extraction and transportation have the greatest environmental impacts and energy consumption in most categories, followed by the terminal storage. The only impact category showing a different behavior is ozone depletion potential (ODP). The terminal storage has the highest ODP, while ODP from the crude oil extraction has the lowest impact for both PADD 5 and California. A high amount of emitted carbon monoxide at terminals is the reason for the higher amount of ODP compared with crude oil extraction and refining. As previously discussed in Section 2.3.1, this study used the refinery and terminal inventories from the AI LCA study. According to that study, all participating companies had terminals that were offsite from the refineries because there were no data available for co-located terminals.

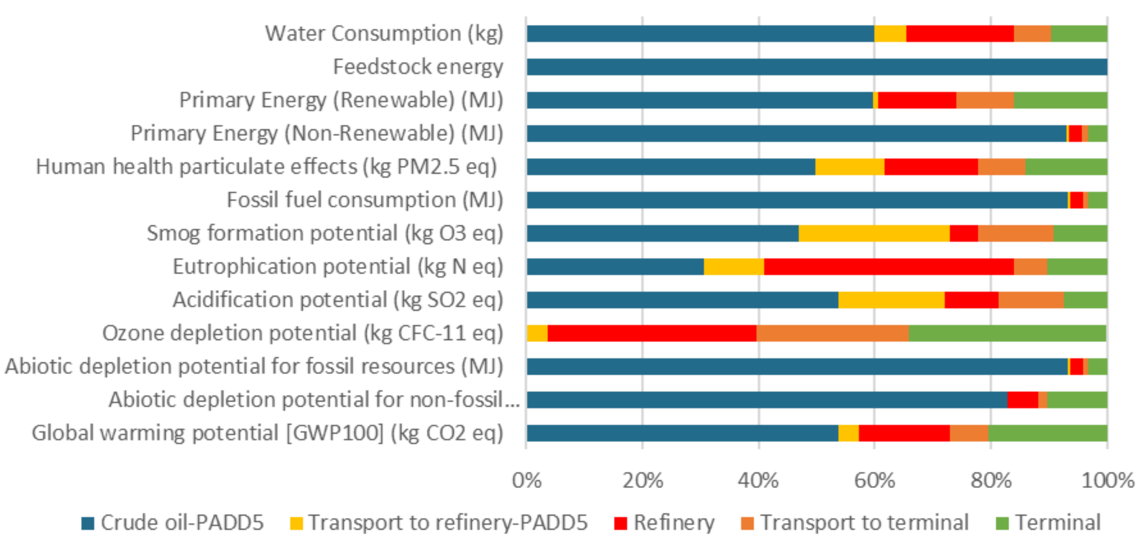


Figure 2.10: Environmental impacts from the asphalt binder material stage considering five sub-stages for PADD 5.

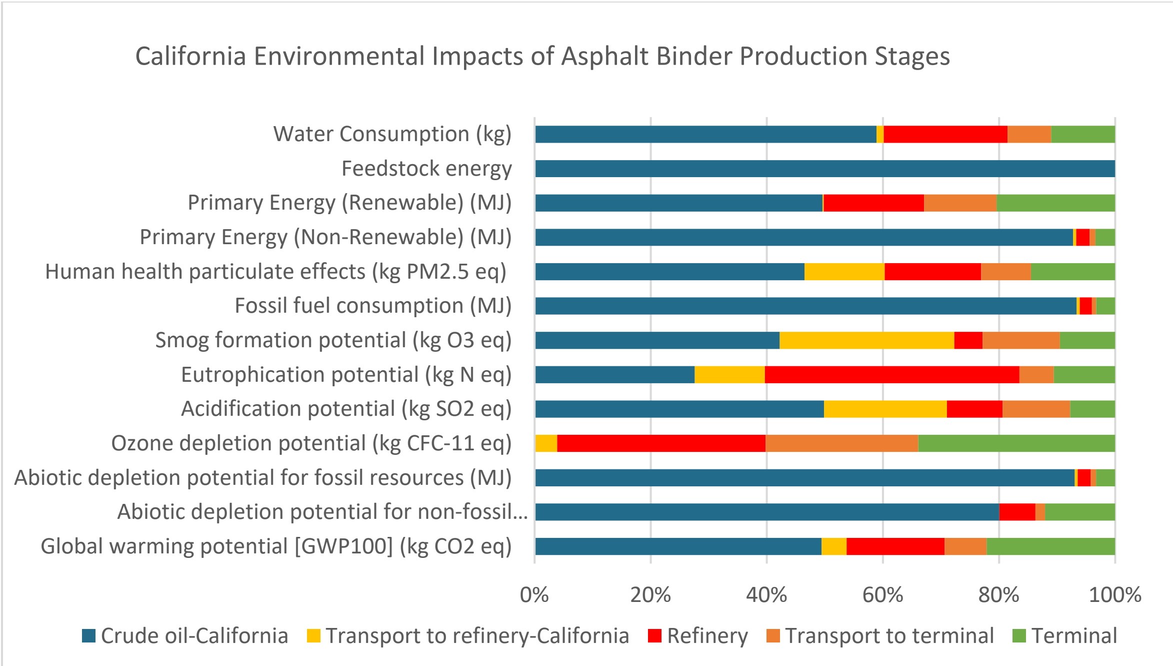


Figure 2.11: Environmental impacts from the asphalt binder material stage considering five sub-stages for California.

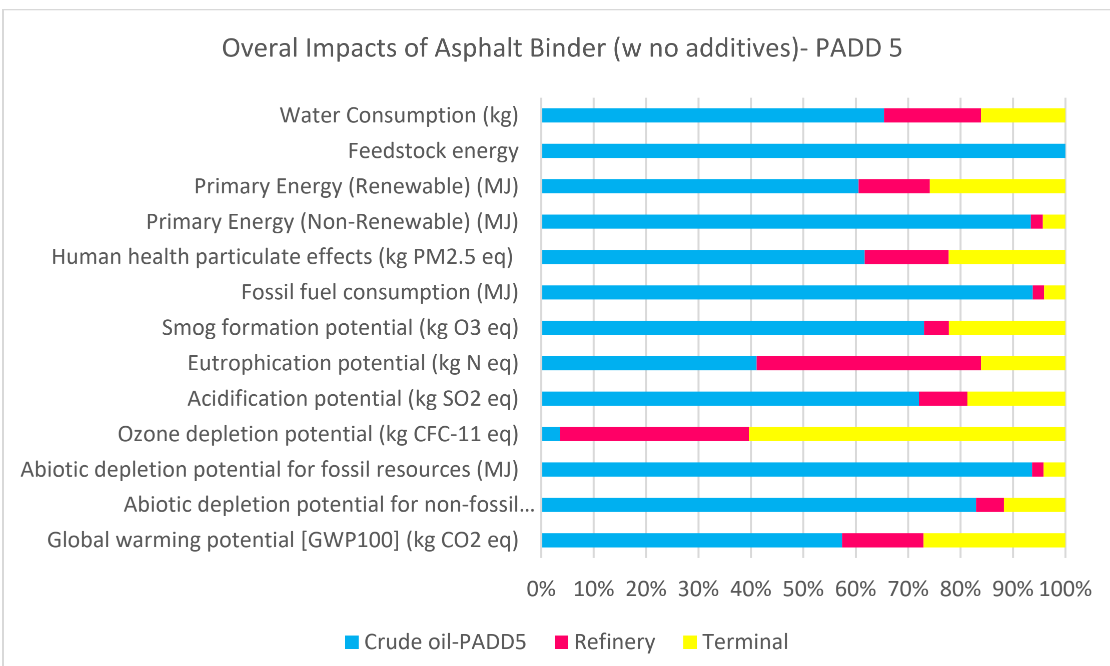


Figure 2.12: Overall environmental impacts of asphalt binder material stage considering three sub-stages for PADD 5.

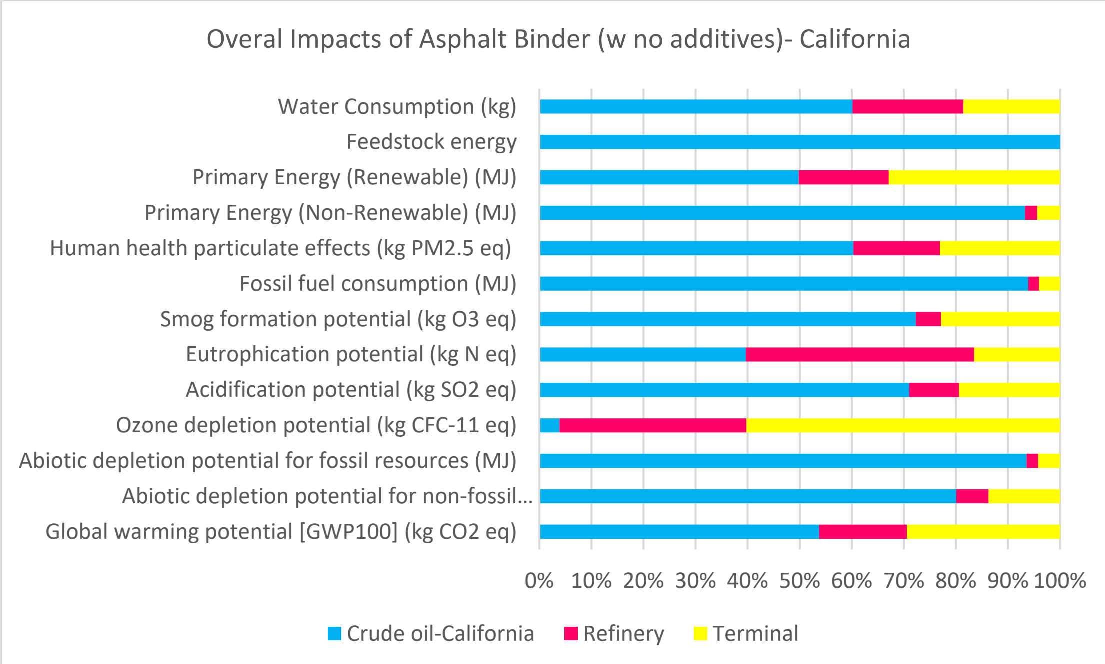


Figure 2.13: Overall impacts of asphalt binder material stage considering three sub-stages for California.

Figure 2.14 shows the comparison of GW, as a global impact category, for 1 kg of asphalt binder across the different steps for PADD 5, California, and the AI LCA study. California had the lowest GW while the AI LCA study had the highest GW results. This difference is due to the percentage of heavy Canadian oil sands in the crude oil slates in the AI LCA study compared to PADD 5 and California. The heavy oil imported from Canada is 53% of crude input in the AI study *(8)*, 18% in PADD 5 (Table 2.2), and 3% in California (Table 2.4). This difference in GW between the AI study, PADD 5 and California caused by the difference in crude sources and transportation to the refinery can also be seen in the differences in atmospheric ozone depletion (ODP), which like GW is a global impact category (Figure 2.15). Similar comparisons for 1 kg of asphalt binder between the AI study, PADD 5 and California can be seen in Figure 2.16 to Figure 2.22 for smog formation, PM2.5, acidification, eutrophication, nonrenewable energy use, renewable energy use, and water consumption.

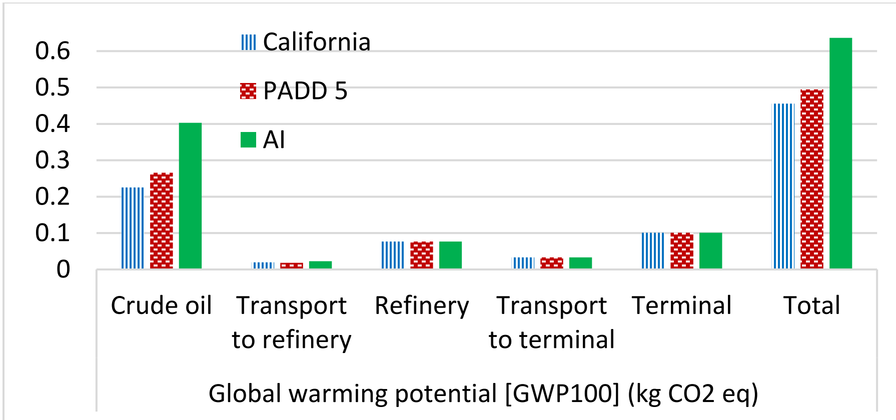


Figure 2.14. GW results for 1 kg of asphalt binder in California, PADD 5, and Asphalt Institute continental average study.

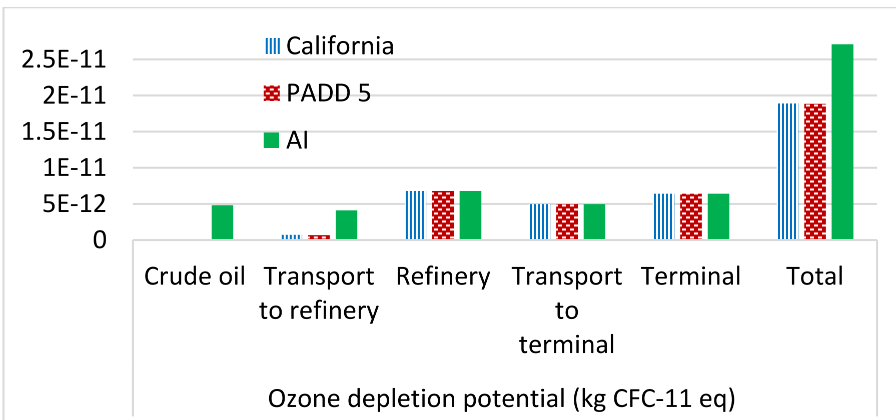


Figure 2.15. Ozone depletion results for 1 kg of asphalt binder in California, PADD 5, and Asphalt Institute continental average study.

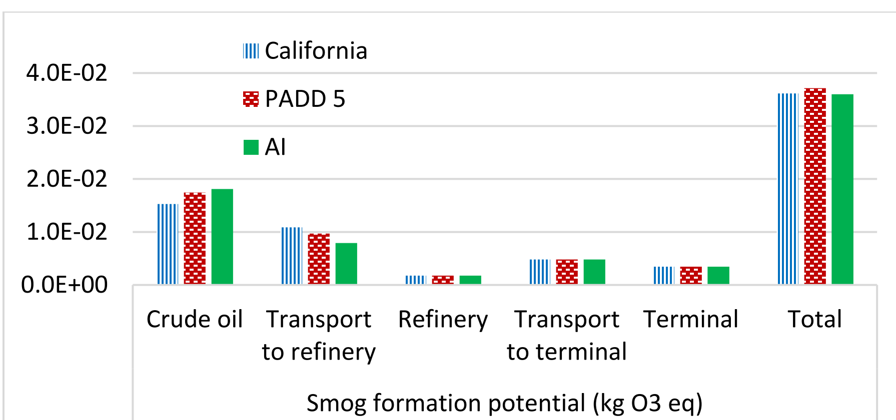


Figure 2.16: Smog formation results for 1 kg of asphalt binder in California, PADD 5, and Asphalt Institute continental average study.

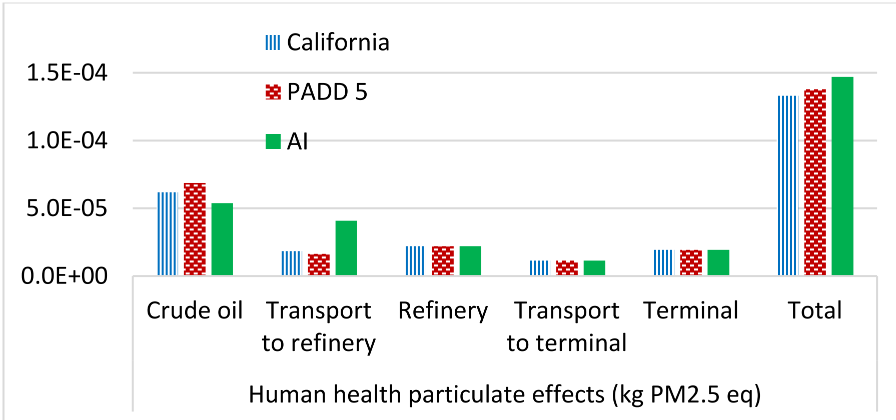


Figure 2.17: Human health particulate effects results for 1 kg of asphalt binder in California, PADD 5, and Asphalt Institute continental average study.

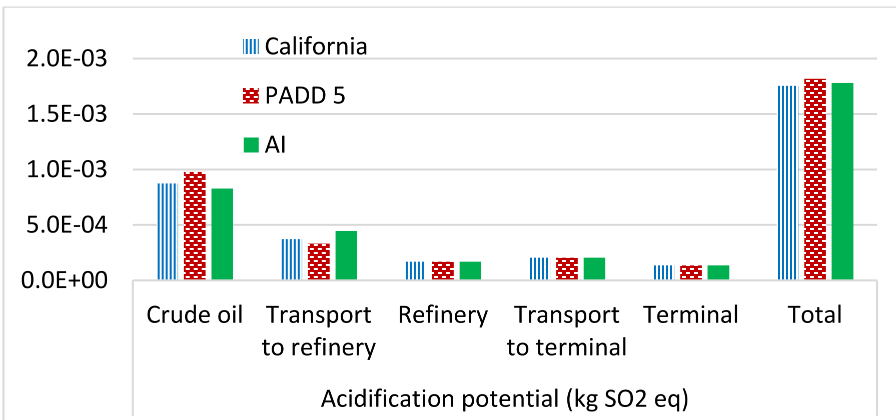


Figure 2.18: Acidification results for 1 kg of asphalt binder in California, PADD 5, and Asphalt Institute continental average study.

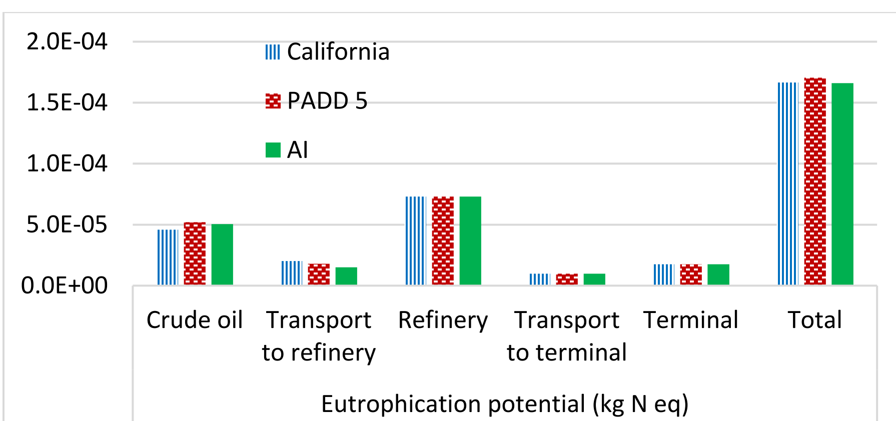


Figure 2.19: Eutrophication results for 1 kg of asphalt binder in California, PADD 5, and Asphalt Institute continental average study.

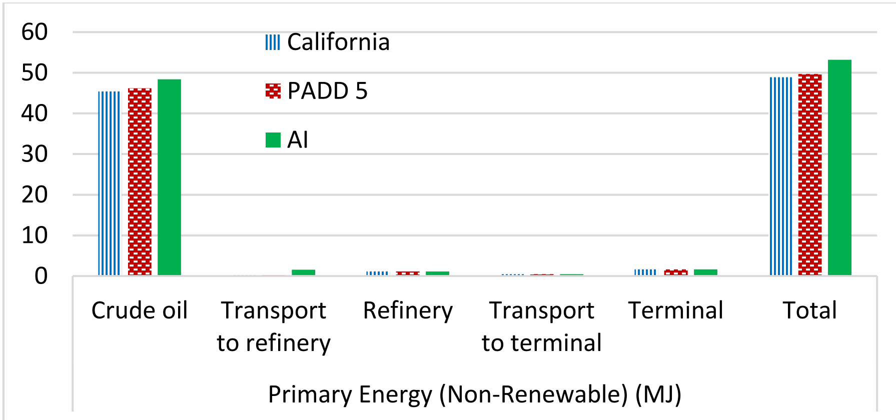


Figure 2.20: Nonrenewable energy results for 1 kg of asphalt binder in California, PADD 5, and Asphalt Institute continental average study.

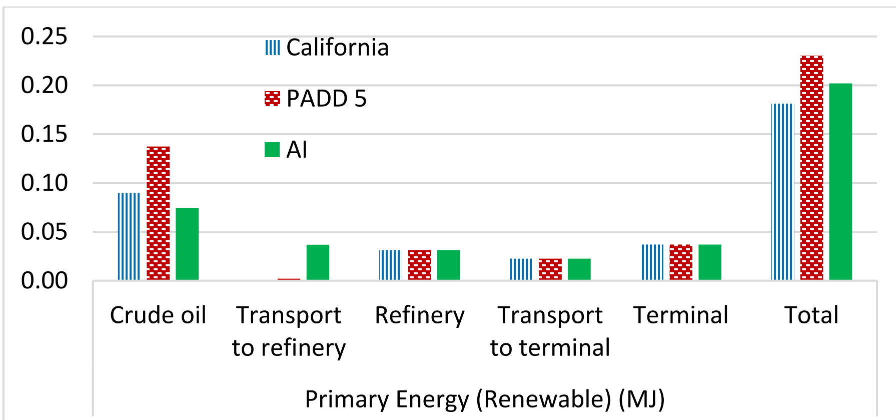


Figure 2.21: Renewable energy results for 1 kg of asphalt binder in California, PADD 5, and Asphalt Institute continental average study.

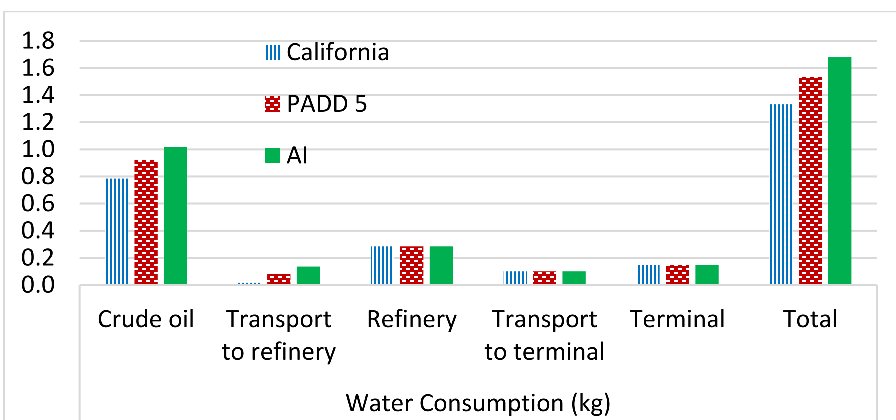


Figure 2.22: Water consumption results for 1 kg of asphalt binder in California, PADD 5, and Asphalt Institute continental average study.

2.4.2 *Sensitivity Analysis Considering Extraction Method*

The sensitivity analysis compared use of the US average crude oil slate and the associated extraction environmental impacts for the domestic crude use by California refineries (presented in previous sections of this chapter) versus a calculation that used the percentage of heavy crude in California and Alaska crude sources and their associated extraction methods, since those crudes are predominant in the domestic oil used in California refineries.

According to the EIA and CEC, 44% of crude oil brought into California belongs to domestic (inside the United States) production, including crude oil production in California and Alaska *(18,23)*. Considered in this sensitivity study is the fact that the percentage of heavy crude oil in California and Alaska crude sources is different from the national average, and the heavy crude is extracted differently than the average US heavy crude oil assumed in the current study's model. The sensitivity analysis only considered the GW value and no other impacts (Figure 2.8).

Most of California's crude oil is heavy, and 91% of this crude oil has an API gravity less than 30 *(9)*. California's heavy crude oil uses energy-intensive extraction techniques to pump oil from the ground *(45)*. Crude oil fields have been in operation for 100 years or more and have become more depleted and waterlogged over time. Therefore, extreme extraction technologies are used to loosen the viscous heavy crude oil and push it toward production wells. Common extraction techniques used in California include cyclic steam injection, steam flooding and waterflooding, and fracking.

In cyclic steam or water injection, steam or water is injected into the oil well repeatedly. This process requires the transport of massive quantities of water and often steam generators (huge boilers burning natural gas or other fossil fuels) to heat the crude within the underground formation and then help it flow up to the well more easily. Hydraulic fracturing or fracking is an oil and gas well development process where large volumes of water, sand, and chemicals are pumped at high pressures into the "tight" rock formation where oil is distributed in very small fissures in the rock, causing it to crack and release oil and gas. In 2016, 3,045 out of 57,000 wells, about 5%, in California used fracking techniques (*9,45–49*).

According to the Center for Biological Diversity (CBD), 75% of California's crude oil production uses these extreme extraction techniques and is considered heavy oil (API≤25) *(45)*. California's crude oil is made up of 16% medium (25<API≤30) and 9% light (API>30) based on the data from 2019. In the average US model, almost half of the crude oil extraction is done through fracking technology, which uses a tertiary method of extraction; the other half is extracted using primary and secondary techniques *(9)*.

Figure 2.23 shows the process diagram for the percentage of heavy crude oil brought into California from foreign countries (Foreign) and brought into California from within the United States (Domestic). The figure shows how domestic crude oil calculated in this senstivity study is different from the domestic crude oil calculated from the 2017 EIA and CEC data sources in the main study *(9,20)*.

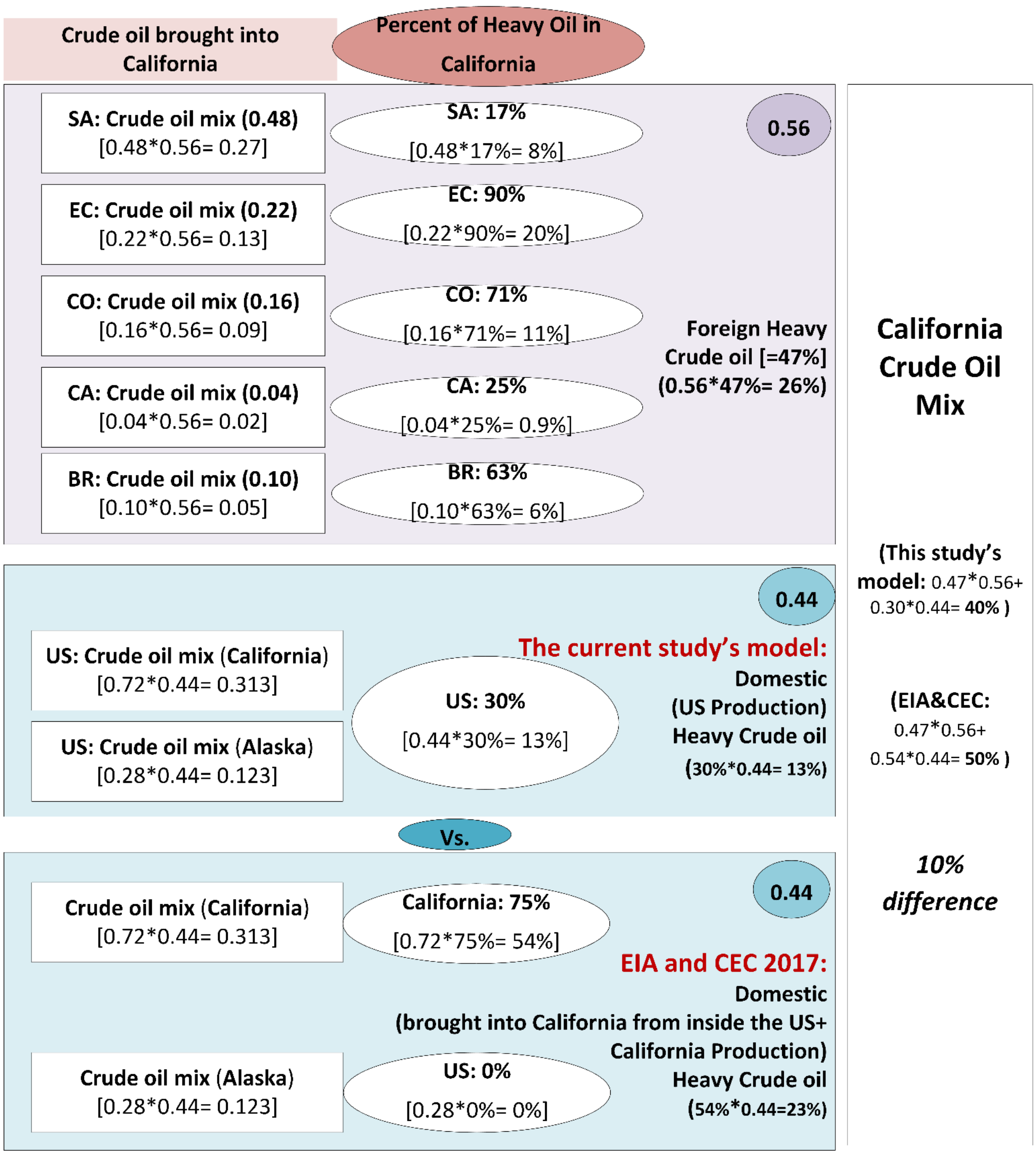


Figure 2.23: California heavy crude oil calculation process diagram.

Figure 2.23 shows that 30% of crude production from the United States used in California (which comes only from Alaska and California) is heavy crude. Using this value and the assumption that the 44% of oil refined in California is domestic and matches the US average percentage of heavy oil results in a calculation of 13% of oil refined is heavy domestic crude (Figure 2.23). When combined with similar calculations for foreign oil refined in California showing 26% is foreign heavy crude, the result (with rounding) is 40% heavy crude refined. For the sensitivity comparison and based on EIA and CEC data and as called out in the CBD report, it can be assumed that California provides 72% of domestic crude refined in the state and Alaska provides 28% and that California crude is 75% heavy while Alaska crude has no heavy oil (it is all medium). As shown in Figure 2.23, this assumption results in 54% of domestic crude used in California refineries being heavy, which when multiplied by 44% of total crude refined coming from California and Alaska results in 23% of total crude being domestic heavy oil. When combined with the 26% of total oil refined being foreign heavy, this results (with rounding) in 50% of all oil refined in California being heavy. Based on the calculations shown in Figure 2.23, the difference between the percentage of heavy crude oil refined in California assuming use of California and Alaska crude sources only versus the percentage of heavy crude oil refined considering the average US crude oil production is calculated to be a 10% (23% – 13%) difference.

Table 2.19 compares the crude oil extraction methods reported in the AI LCA study. Steam injection is used in most of California's extraction (94%), while in the United States half of extraction is done using primary and secondary extraction methodologies and the other half is done using tertiary extraction methodologies *(10)*. Using the extraction impacts shown in Table 2.19 and the assumed percentages of extraction methods used for California and US heavy crudes, the calculations of the GW for the heavy crude for California and the US averages are shown as follow:

<u>California extraction:</u> $\text{fraction}_{\text{steam extraction}} * \text{GW}_{\text{steam extraction}} + \text{fraction}_{\text{avg all tertiary extraction}} * \text{GWavg}_{\text{all tertiary extraction}}$

$= 0.94 * 0.59 + 0.06 * (0.59 + 0.29 + 0.25)/3$

<u>US average extraction:</u> $\text{fraction}_{\text{all tertiary extraction}} * \text{GWavg}_{\text{alltertiary extraction}} + \text{fraction}_{\text{primary and secondary extraction}}$

$* \text{GWavg}_{\text{primary and secondary extraction}} = (0.5 * (0.59 + 0.29 + 0.25)/3) + (0.5 * (0.2 + 0.1)/2)$

<u>California extraction/US extraction:</u> 2.19

Table 2.19: Crude Oil Extraction Method Impacts as Reported (Asphalt Institute Study)

Crude Oil Extraction Method	GW (kgCO2e)/kg
Primary extraction	0.1
Secondary extraction	0.2
Tertiary extraction- natural gas injection	0.25
Tertiary extraction - CO2 injection	0.29
Tertiary extraction - steam injection	0.59

Source: Wildnauer et al. (2019) *(10)*.

Since the California extraction has more than twice the GW for the US average extraction, based on the assumptions of this sensitivity analysis, the final GW for California crude refined assuming that the 44% of total crude refined is from domestic oil and that domestic oil is from California and Alaska, is estimated to be 12% greater than the GW assuming the US average domestic crude GW. This value is calculated as 2.19 California/US average GW for heavy crude extraction times 10% more heavy crude if using only California and Alaska crude for the domestic oil inputs to the refineries times 44% of all crude refined is domestic (2.19*0.10*0.44 = 0.12).

Table 2.20 compares the asphalt binder GW for all crude refined in California, considering the two different assumptions explained in the sensitivity analysis. Assumption 1 assumes the US average crude oil slate for the domestic portion of total crude refined is used and heavy oil in that slate follows assumed national average extraction methods, and Assumption 2 assumes that all domestic crude refined in California comes from California and Alaska crude sources and the assumed extraction methods for the California heavy crude.

Table 2.20: Estimated California Global Warming Impact for Sensitivity Analysis Comparing US Average Domestic Crude Versus California and Alaska Domestic Crude in California Refinery Crude Oil Slates

	Impact Category and Unit	Crude Oil Extraction California	Transport from Crude Oil Well/Port to California Refinery	Refinery	Transport to Terminal	Terminal	Total California
Assumption 1	GW (kg CO2 eq)	0.2254	1.84E-02	0.0769	0.033	0.101	0.456
Assumption 2	GW (kg CO2 eq)	0.2525	1.96E-02	0.0769	0.033	0.101	0.483

The sensitivity analysis presented in this section has discussed the different types of oil and different methods of extraction, focusing on the extraction methods for heavy crude and amount of heavy crude in US average domestic crude oil and the same for California crude. This one change of assumptions resulted in an increase in estimated GW for the crude oil refined in California of 6%. It is known that the crude oil slates used by California refineries vary year to year and within the year based on prices for different crudes and the products that the refineries are producing to maximize profits, within the constraints of the setups of the refineries. The results suggest that asphalt binder GW should be considered to be a distribution of values rather than a single value, or if a single value is used it should be understood that there can be considerable variability around it.

3 WARM MIX ASPHALT ADDITIVES

3.1 Introduction

Warm mix asphalt (WMA) is considered a potential means for reducing energy consumption and emissions during the material and construction stages of asphalt concrete by allowing for lowering mixing temperatures in the asphalt plant *(52,53)*. WMA can also be used with the same mixing temperatures to allow for compaction at lower temperatures at the construction site. This process does not reduce energy and emissions from mixing, but it can result in better compaction and longer pavement life. Lowered mixing temperatures result in less emissions at the construction site as well as the plant, producing better conditions for workers and neighbors. According to previous UCPRC research, the use of warm mix asphalt additives (WMAAs) in asphalt mixes, especially in asphalt rubber projects, should be encouraged *(54,55)*. Studies conducted in European countries and the United States have indicated the possibility of reductions in the asphalt concrete mixing and placement temperatures and of potentially related emissions. *(56-59)*.

For conventional hot mix asphalt (HMA), the asphalt viscosity reduction and aggregate dryness required for thorough coating of aggregates by the asphalt binder during the mixing are gained by using heat. Increasing the heat during the mixing reduces the asphalt viscosity and moisture content of the aggregate (dryness). For WMA, however, water, special organic additives, or chemical additives, or a combination of these, are added to the mixture to reduce the viscosity, resulting in an adequate coating of asphalt binder on the aggregate surfaces. The reduction in mixture viscosity also improves workability and compaction at lower temperatures *(53,59)*.

Several studies have been conducted globally to assess the environmental impacts of WMA. However, many unanswered questions remain pertaining to the environmental benefits of WMA. In this study, the life cycle environmental impacts of different types of WMA containing different WMAAs were evaluated and compared with conventional HMA. No study was found in the literature until June 2021 on the environmental impacts of some WMA technologies used in California. Therefore, the UCPRC took the initiative to develop estimated LCI datasets for different WMAAs. Because there are no definitive ingredient lists and proportions, this study used the best available knowledge and created proxies. There were also no EPDs for WMA until one was produced by Ingevity in December 2021 *(60)*.

3.2 Goal and Scope of Warm Mix Additives LCI Study

This study aims to quantify the potential environmental impacts that occur during the material production stage of WMA. Thus, the scope of the study is from cradle to gate, including the materials extraction, transportation to plants, and all the processes conducted at the plant to prepare the final mix. A comparative attributional LCA approach is adopted where life cycle environmental impacts from the production of WMA using different

WMAAs are compared with the conventional HMA. The asphalt mix designs are mainly reflecting California-specific mix designs. The different WMAAs that have been studied and evaluated for environmental impacts include Evotherm DAT (A1), Cecabase RT, Sasobit, Rediset LQ, Advera, Gencor Ultrafoam GX2, SonneWarmix, and Astec Double Barrel Green. A complete list of WMAAs that Caltrans has authorized for use in WMA in 2020 *(61)* is shown in Figure 3.1 and Section 3.2.1.

Authorized WMAAs (2020)
Additive Technologies
Evotherm DAT (A1)
Evotherm 3G (J1, M1)
Rediset LQ
Advera
Cecabase RT
Sasobit
SonneWarmix
Zycotherm SP
Water Injection Technologies
Astec Double Barrel Green
Gencor Ultrafoam GX2
Maxam AQUABlack

Source: Ingevity (2022) *(60)*.

Figure 3.1: Caltrans-authorized list of WMAAs.

The declared unit for this study is 1 kg of WMA. The transportation stage for WMAAs is considered to be movement of the product from their manufacturing/production plant to the asphalt mix plant where they are added to the asphalt mix. Except for the transportation of WMAAs to the asphalt mix plant, all other material transports are not considered in this study as they are common for both HMA and WMA. In order to determine the quantity of natural gas used and consumed to produce different types of WMAs, a sensitivity analysis was conducted using different data and methods. Figure 3.2 shows the system diagram for calculating WMA impacts.

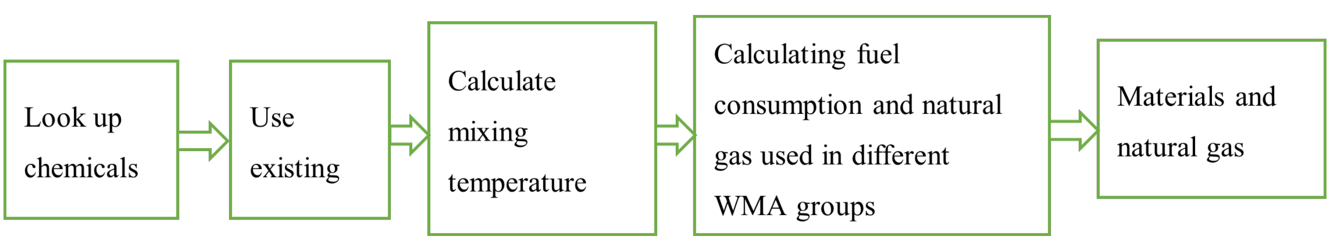


Figure 3.2: System diagram for calculating WMA impacts.

3.2.1 *Product System*

The following life cycle environmental impacts from three different groups of asphalt mixes were compared in this study:

(1) Conventional HMA where no WMAA is used.
(2) WMAAs added to the asphalt mixtures, but the asphalt mixing temperatures remain the same as conventional HMA.
(3) WMAAs added to the asphalt mixtures, and the asphalt mixing temperatures are reduced due to the addition of the additives. The WMAAs are evaluated in terms of their softening points to ensure that the mixing temperature does not go over the softening points. Reducing the heat during the mixing increase the asphalt viscosity and moisture content of the aggregate.

3.2.2 *Warm Mix Asphalt Additives*

Caltrans has approved a number of additives that can be used in the production of WMA. The authorized list includes the additive technologies and water injection technologies shown in Figure 3.1.

3.2.3 *Data Collection, Software, and Database*

The chemical components of the WMAAs were obtained from safety data sheets (SDSs, previously called material safety data sheets) and online published materials. UC Davis researcher Dr. Peter Green, an environmental chemistry expert, was consulted about the additives for which not enough information available online and about the final chemical components . The WMAAs considered in the current study include the following:

- Additive Technologies
  - Evotherm DAT (A1), chemical surfactant technology, referred to as Evotherm in this report
  - Rediset LQ, chemical surfactant technology referred to as Rediset in this report
  - Cecabase RT, chemical surfactant technology, referred to as Cecabase in this report
  - Advera, chemical water foaming technology, referred to as Advera in this report
  - Sasobit, organic wax technology, referred to as Sasobit in this report
  - SonneWarmix, organic wax technology, referred to as SonneWarmix in this report
- Water Injection Technologies
  - Astec Double Barrel Green, water injection technology, referred to as Astec in this report
  - Gencor Ultrafoam GX2, water injection technology, referred to as Gencor in this report

Table 3.1 presents each WMA additive's chemical components, dosage by weight of asphalt binder, and mixing temperature according to the additive's SDS. The second column shows the exact chemical components derived from the SDSs of the additives *(62-68)*. The third column presents the WMAA ingredients found in *GaBi* and reviewed and confirmed by Dr. Peter Green. The *GaBi* model was developed for each WMA technology based on the chemical components as well as the dosage of each component in the additive. This study used the 2017 electricity grid mix for California to calculate the environmental impacts of asphalt concrete mixes. The electricity input to produce 1 kg of WMA was assumed to be 0.00618 MJ.

Table 3.1: Assumed Chemical Components of WMAAs from Safety Data Sheets, Dosage by Weight of Asphalt Binder, and Asphalt Mixing Temperatures

WMAA[a]	WMAA Ingredients Based on SDS[b]	WMAA Ingredients Found in GaBi (2019)	Dosage by Weight of Asphalt Binder (%)	Asphalt Concrete Mixing Temperatures
Additive Technologies				
Advera	Zeolite	Aluminum silicate (Zeolite type A) (80%)	4.5 (Range: 0.2–5)	295ºF (145ºC)
	Water	Water (20%)		
Evotherm	Hydrochloride salt of fatty amine derivatives	Hexamethylenediamine (HMDA) (30%)	0.5 (Range: 0.375–0.5)	248ºF (125ºC) Range: 125 ºC–135ºC
	Water	Water (70%)		
SonneWarmix	Paraffineic hydrocarbons	Wax/paraffins	0.7 (Range: 0.50–1)	295ºF (145ºC) >230ºC
Cecabase	Tetraethylenepentamine	HMDA (96.9%)	0.5 (Range: 0.2–0.5)	295ºF (145ºC)
	Propanol, 1(or 2)-[methyl-2-(methyl-2-propoxyethoxy)ethoxy]	Propylene glycol (3%)		
	Potassium hydroxide	Potassium hydroxide (KOH) (0.1%)		
Sasobit	Wax	Wax/paraffins	1.5 (Range: 1–3)	300ºF (149ºC) < 230ºF/ 446ºC
Rediset	Including amine	HMDA	2 (Range: 0.3–3)	285ºF (140ºC) 20ºC–35ºC lower than HMA
Water Injection Technologies				
Astec	Water	Water	1.5 (Range: 0.0012–1.5)	295ºF (145ºC)
Gencor	Water	Water	1.5 (Range: 0.0012–1.5)	285ºF (140ºC)

[a] WMAA: warm mix asphalt additive.
[b] MSDS: material safety data sheet.
Source: Schuller, Hengstler, and Thellier (2019) *(17)*.

GaBi was also used for modeling the different groups of mix types. Figure 3.3 to Figure 3.10 show the process diagrams used for the modeling.

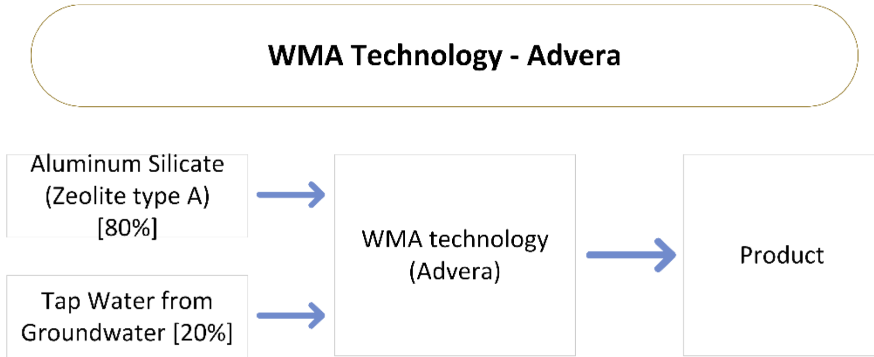


Figure 3.3: Process diagram used for modeling WMA technology—Advera.

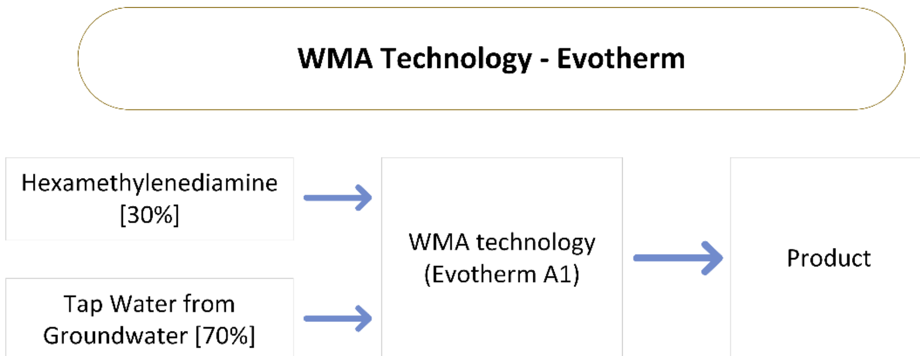


Figure 3.4: Process diagram used for modeling WMA technology—Evotherm.

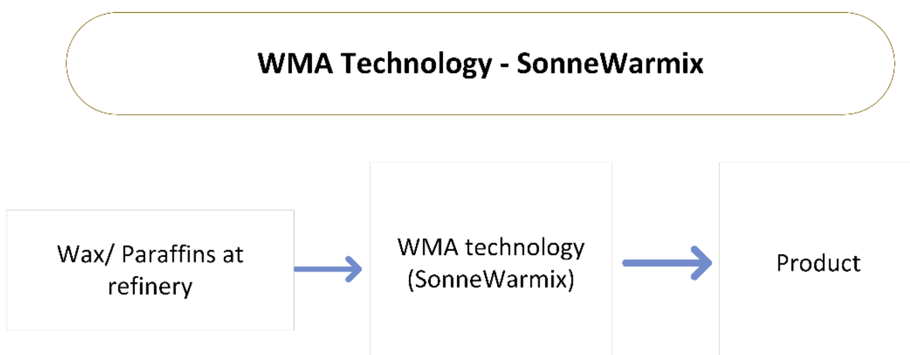


Figure 3.5: Process diagram used for modeling WMA technology—SonneWarmix.

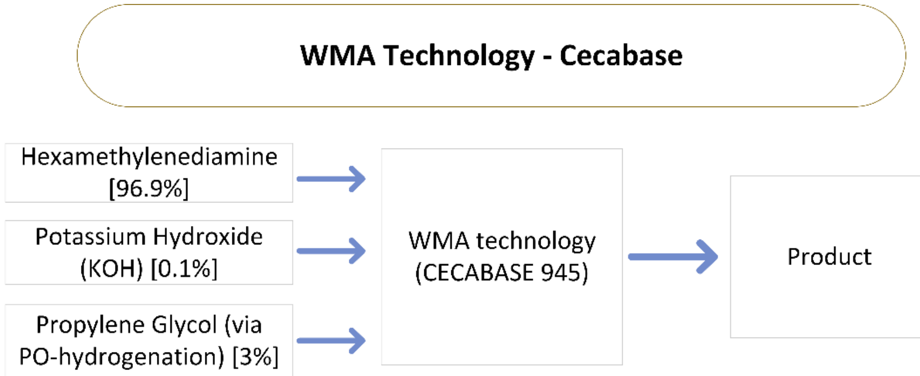


Figure 3.6: Process diagram used for modeling WMA technology—Cecabase.

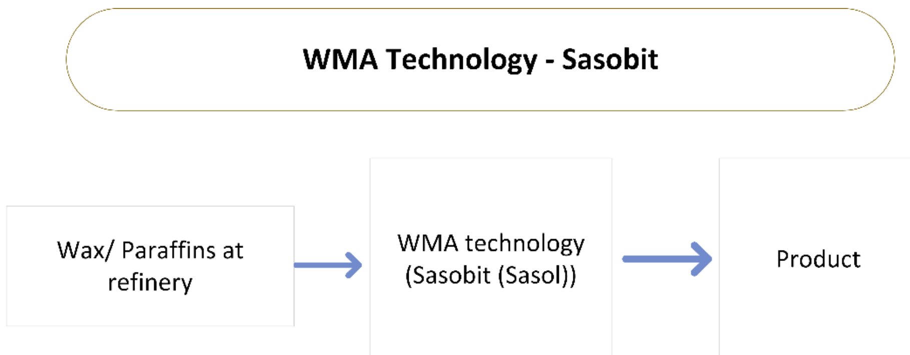


Figure 3.7: Process diagram used for modeling WMA technology—Sasobit.

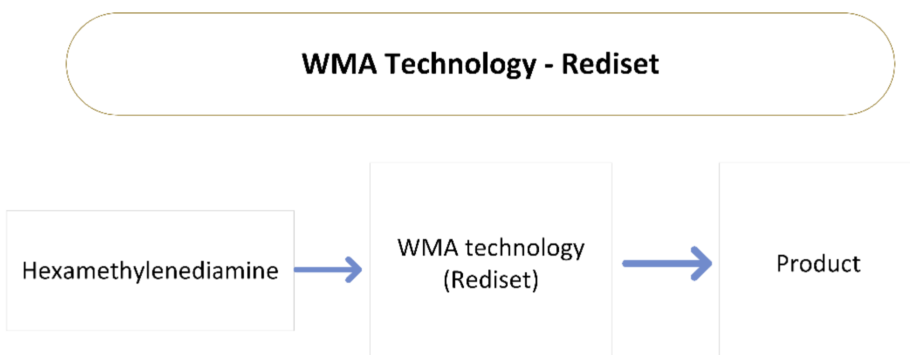


Figure 3.8: Process diagram used for modeling WMA technology—Rediset.

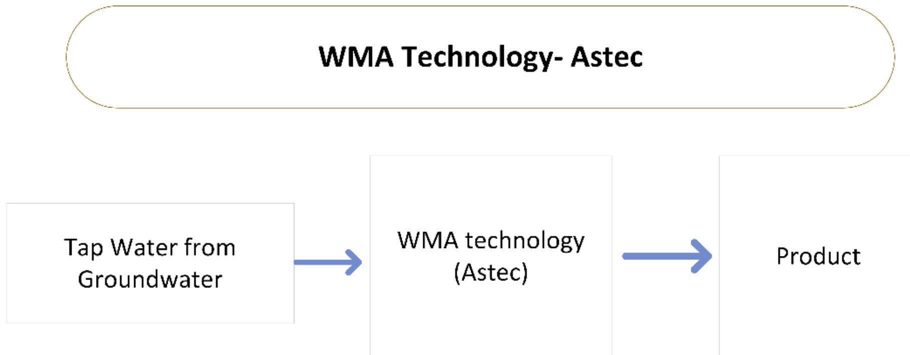


Figure 3.9: Process diagram used for modeling WMA technology—Astec.

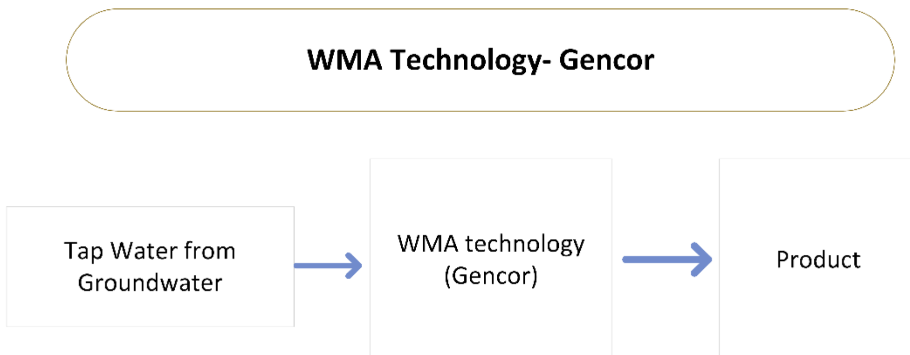


Figure 3.10: Process diagram used for modeling WMA technology—Gencor.

3.3 Life Cycle Inventory and Life Cycle Impact Assessment

3.3.1 *Life Cycle Inventory*

This study used the *GaBi* software to develop models for different asphalt mixes. Different non-rubberized and rubberized asphalt concrete mix designs are presented in Table 3.2 and Table 3.3, respectively, based on a UCPRC research report that evaluated the mix properties and performance under accelerated pavement testing of the WMA technologies shown *(54,55)*. The California asphalt binder analysis from Chapter 2, considering the US average domestic crude in the crude oil slate, was used for the calculations in this chapter.

Table 3.2: Mix Designs for Different Groups of Non-Rubberized Asphalt Concrete Mixes (Dosage in Percentages by Weight of Asphalt Concrete Mix)

Asphalt Concrete Mix Type	Aggregate (%)	Virgin Asphalt Binder (%)	WMAA (%)	Total Asphalt Binder in the Mix (%)
Conventional HMA	93.46	6.54	—	6.54
WMA-Advera	93.18	6.52	0.29	6.82
WMA-Evotherm A1	93.43	6.54	0.033	6.57
WMA-SonneWarmix	93.42	6.54	0.046	6.59
WMA-Cecabase	93.43	6.54	0.0266	6.57
WMA-Sasobit	93.37	6.54	0.0986	6.63
WMA-Rediset	93.34	6.53	0.131	6.66
WMA-Gencor	93.37	6.54	0.098	6.63
WMA-Astec	93.37	6.54	0.098	6.63

Table 3.3: Mix Designs for Different Groups of Rubberized Asphalt Concrete Mixes (Dosage in Percentages by Weight of Asphalt Concrete Mix)

Asphalt Concrete Mix Type	Aggregate (%)	Virgin Asphalt Binder (%)	Crumb Rubber (%)	Extender Oil (%)	WMAA (%)	Total Asphalt Binder in the Mix (%)
Conventional RHMA	92.19	6.453	1.226	0.13	—	7.80
RWMA-Advera	91.92	6.435	1.223	0.13	0.290	8.08
RWMA-Evotherm A1	92.13	6.449	1.225	0.16	0.032	7.87
RWMA-SonneWarmix	92.15	6.451	1.226	0.13	0.045	7.85
RWMA-Cecabase	92.14	6.450	1.225	0.16	0.026	7.86
RWMA-Sasobit	92.10	6.447	1.225	0.13	0.097	7.90
RWMA-Rediset	92.07	6.445	1.225	0.13	0.129	7.93
RWMA-Gencor	92.10	6.447	1.225	0.13	0.097	7.90
RWMA-Astec	92.10	6.447	1.225	0.13	0.097	7.90

Table 3.4 shows the asphalt concrete mixing temperatures that were used to calculate the natural gas consumption, Table 3.5 shows the unit conversions for fuel consumption, Table 3.6 shows the energy content of natural gas and diesel, and Table 3.7 shows the calculation of natural gas for the different WMAs. In Table 3.4 and other tables and figures, three groups of materials are shown:

- Group A is the control HMA mix with no WMAA.
- Group B is the WMA version of the HMA with the WMAA added but mixed at the high end of its mixing temperature range typical of when the WMAA is used to extend mix transport and compaction time but not reduce the mixing temperature.

- Group C is the WMA version of the HMA with the WMAA added and mixed at the low end of its mixing temperature range.

The mixing temperatures shown in Table 3.4 were assumed to be the same for the rubberized mixes (RHMA and RWMA) as well. In reality, the rubberized mix mixing temperatures would likely be uniformly somewhat greater than the non-rubberized mixes. However, that information was not available for this study, and it was assumed that differences in mixing temperature would be similar between the two types of mixes.

Table 3.4: Asphalt Concrete Mix Temperature Used to Calculate Natural Gas Consumption

Group	Asphalt Concrete Mix Types	Aggregate Temperature ºF (ºC)	Binder Temperature ºF (ºC)	Mix Temperature ºF (ºC)
A	HMA	358 (181)	331 (166)	—
B	WMA-Advera	358 (181)	331 (166)	356 (180)
	WMA-Evotherm A1	347 (175)	320 (160)	346 (174)
	WMA-SonneWarmix	358 (181)	331 (166)	356 (180)
	WMA-Cecabase	347 (175)	320 (160)	346 (174)
	WMA-Sasobit	358 (181)	331 (166)	356 (180)
	WMA-Rediset	358 (181)	331 (166)	356 (180)
	WMA-Gencor	358 (181)	331 (166)	356 (180)
	Astec Double Barrel	358 (181)	331 (166)	356 (180)
C	WMA-Advera	320 (160)	293 (145)	318 (159)
	WMA-Evotherm A1	284 (140)	257 (125)	282 (139)
	WMA-SonneWarmix	320 (160)	293 (145)	318 (159)
	WMA-Cecabase	293 (145)	266 (130)	291 (144)
	WMA-Sasobit	327 (164)	300 (149)	325 (163)
	WMA-Rediset	311 (155)	284 (140)	309 (154)
	WMA-Gencor	311 (155)	284 (140)	309 (154)
	Astec Double Barrel	320 (160)	293 (145)	318 (159)

Table 3.5: Unit Conversions for Fuel Consumption

Volume	1 ft^3	0.0283 m^3
Energy	1 BTU	1.0550 kJ

Table 3.6: Energy Content of Natural Gas and Diesel

Natural Gas (NG)	1 ft^3	1037 BTU
Diesel	1 gallon	135 ft^3 of NG
Natural Gas (NG)	1 m^3	38,637.7 kJ
Electricity[a]	1 kg	0.00618 MJ

[a] The electricity input to produce 1 kg of WMA is reported to be 0.00618 MJ.

Table 3.7: Calculation of Natural Gas for the Different Warm Mix Asphalts

Group	Asphalt Concrete Mix Types	HMA/WMA Mix Temperature F° (ºC)	HMA/WMA Fuel (kJ NG/kg)	HMA/WMA NG (m^3)/kg	HMA/WMA NG (ft^3)/lb.
A	HMA	180	162.02	0.00793	0.12704
B	Advera	180	162.02	0.00793	0.12704
	Evotherm	174	156.62	0.00774	0.12405
	SonneWarmix	180	162.02	0.00793	0.12704
	Cecabase	174	156.62	0.00774	0.12405
	Sasobit	180	162.02	0.00793	0.12704
	Rediset	180	162.02	0.00793	0.12704
	Gencor	180	162.02	0.00793	0.12704
	Astec	180	162.02	0.00793	0.12704
C	Advera	159	143.12	0.00728	0.11659
	Evotherm	139	125.12	0.00666	0.10664
	SonneWarmix	159	143.12	0.00728	0.11659
	Cecabase	144	129.62	0.00681	0.10913
	Sasobit	163	146.72	0.00740	0.11858
	Rediset	154	138.62	0.00712	0.11410
	Gencor	154	138.62	0.00712	0.11410
	Astec	159	143.12	0.00728	0.11659

3.3.1.1 Sample Calculation: Warm Mix Asphalt with Advera

The following is an example of the calculation of natural gas consumption for mixing WMA with Advera in Group C. The first step is to calculate the final mixing temperature, including the aggregate temperature and WMA mix temperature, considering the amounts of aggregate and total asphalt binder in the mix. It should be noted that the aggregate and asphalt binder are not heated at the same temprature to minimize the aging of the binder.

Mix Temperature = Aggregate temperature (160ºC) * Aggregate content in the mix (0.9318) + Binder temperature (145ºC) * Total asphalt binder content in the mix (0.0682) = 159ºC

Equation 3.1 is then used to calculate the energy (E) for each type of WMA. Specific heat (c) is the energy needed to raise a unit mass of a substance by one unit of temperature kJ/kg•˚C. The specific heat of asphalt concrete is about 900 J/kg•˚C, or 0.9 kJ/kg•˚C.

$$E = m * c * \Delta\theta \tag{3.1}$$

Where:

m = mass of the material heated up (in kg)

c = specific heat capacity (in kJ/kg•˚C)

$\Delta\theta$ = difference in temperature due to the work done on the substance (in degrees Celsius [˚C])

Another factor to consider in the calculation of the used natural gas is the energy for vaporization of water, which is 2,260 kJ/kg *(69)*. Assuming 3% moisture in the aggregate (i.e., 30 kg water per ton of aggregate), 67.8 KJ/kg, as the energy for vaporization of water, is added to the energy calculated from Equation 3.1. Then a 75% natural gas-fired burner efficiency is assumed to calculate the natural gas for different WMAs *(70)*.

An example of calculating a cubic meter of natural gas used in the production of WMA with Advera is the following:

WMA Energy (cubic meter of natural gas/kg) = ((0.9 kJ/kg•˚C * 180 °C) + 2260 * 0.03)/0.75/38,638 kJ = 0.00793 m^3/kg

3.3.2 *Life Cycle Impact Assessment*

Table 3.8 shows the cradle-to-gate impacts of 1 kg of the WMAAs in addition to their transport to the plant. As previously discussed, no EPDs for WMA existed until June 2021, when one was produced by Ingevity *(60).* The EPD's GW, which shows 5.64 kg CO2e for Evotherm M, is comparable to Evotherm A, shown in Table 3.8.

Table 3.8: Impacts of Material and Transport for Functional Unit (1 kg of Warm Mix Asphalt Additive) During Warm Mix Asphalt Additive Production

Item	Unit	Material Production					Transport to Plant				
		GW (kg CO_2e)	Smog (kg O_3e)	PM 2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	GW (kg CO_2e)	Smog (kg O_3e)	PM 2.5 (kg)	PED-R (MJ)	PED-NR (MJ)
Advera	1 kg	2.83E+00	1.36E-01	7.51E-04	1.18E+00	4.01E+01	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
Evotherm	1 kg	2.16E+00	7.95E-02	1.70E-04	4.01E-01	4.32E+01	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
SonneWarmix	1 kg	1.12E+00	3.93E-02	2.00E-04	4.63E-01	5.47E+01	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
Cecabase	1 kg	7.09E+00	2.63E-01	5.71E-04	1.38E+00	1.42E+02	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
Sasobit	1 kg	1.12E+00	3.93E-02	2.00E-04	4.63E-01	5.47E+01	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
Rediset	1 kg	7.19E+00	2.65E-01	5.68E-04	1.34E+00	1.44E+02	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
Gencor	1 kg	2.26E-04	9.56E-06	4.53E-08	1.30E-04	2.38E-03	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01
Astec	1 kg	2.26E-04	9.56E-06	4.53E-08	1.30E-04	2.38E-03	1.88E-02	3.00E-03	6.01E-06	0.00E+00	2.69E-01

Table 3.9 and Table 3.10 show the life cycle impact results per 1 kg of the non-rubberized and rubberized mix asphalt, respectively, for different groups of asphalt concrete in California.

Table 3.9: Life Cycle Impacts from the Material Stage of 1 kg of Non-Rubberized Asphalt Concrete Mixtures

Group	Asphalt Concrete Mix Types	GW (kg CO_{2e})	POCP (kg O_{3e})	PM2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	PED-FS (MJ)
Group A (No Additives-No Temperature Change)	HMA	5.21E-02	6.26E-03	3.84E-05	8.05E-02	3.57E+00	4.14E+01
Group B (Additives-No Temperature Change)	WMA-Advera	5.21E-02	6.26E-03	3.83E-05	8.03E-02	3.56E+00	4.14E+01
	WMA-Evotherm	5.22E-02	6.27E-03	3.82E-05	8.05E-02	3.57E+00	4.14E+01
	WMA-SonneWarmix	5.26E-02	6.28E-03	3.85E-05	8.07E-02	3.59E+00	4.14E+01
	WMA-Cecabase	5.16E-02	6.25E-03	3.82E-05	8.04E-02	3.56E+00	4.14E+01
	WMA-Sasobit	5.20E-02	6.26E-03	3.84E-05	8.04E-02	3.56E+00	4.14E+01
	WMA-Rediset	6.14E-02	6.61E-03	3.91E-05	8.21E-02	3.75E+00	4.14E+01
	WMA-Astec	5.20E-02	6.26E-03	3.84E-05	8.04E-02	3.56E+00	4.14E+01
	WMA-Gencor	5.20E-02	6.26E-03	3.84E-05	8.04E-02	3.56E+00	4.14E+01
Group C (Additives-Lower Temperature)	WMA-Advera	5.05E-02	6.22E-03	3.75E-05	8.03E-02	3.53E+00	4.14E+01
	WMA-Evotherm	4.96E-02	6.21E-03	3.68E-05	8.05E-02	3.53E+00	4.14E+01
	WMA-SonneWarmix	5.10E-02	6.25E-03	3.76E-05	8.07E-02	3.57E+00	4.14E+01
	WMA-Cecabase	4.94E-02	6.20E-03	3.69E-05	8.04E-02	3.52E+00	4.14E+01
	WMA-Sasobit	5.07E-02	6.23E-03	3.77E-05	8.04E-02	3.54E+00	4.14E+01
	WMA-Rediset	5.94E-02	6.56E-03	3.81E-05	8.21E-02	3.72E+00	4.14E+01
	WMA-Astec	5.05E-02	6.22E-03	3.75E-05	8.04E-02	3.54E+00	4.14E+01
	WMA-Gencor	5.01E-02	6.22E-03	3.73E-05	8.04E-02	3.53E+00	4.14E+01

Table 3.10: Life Cycle Impacts from the Material Stage of 1 kg of Rubberized Asphalt Concrete Mixtures

Group	Asphalt Concrete Mix Types	GW (kg CO_{2e})	POCP (kg O_{3e})	PM2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	PED-FS (MJ)
Group A (No Additives- No Temperature Change)	RHMA	5.25E-02	6.21E-03	3.90E-05	9.52E-02	3.56E+00	4.14E+01
Group B (Additives- No Temperature Change)	RWMA-Advera	5.25E-02	6.20E-03	3.89E-05	9.50E-02	3.53E+00	4.14E+01
	RWMA-Evotherm	5.27E-02	6.22E-03	3.88E-05	9.53E-02	3.54E+00	4.14E+01
	RWMA-SonneWarmix	5.30E-02	6.23E-03	3.91E-05	9.54E-02	3.56E+00	4.14E+01
	RWMA-Cecabase	5.20E-02	6.20E-03	3.87E-05	9.52E-02	3.53E+00	4.14E+01
	RWMA-Sasobit	5.25E-02	6.21E-03	3.89E-05	9.51E-02	3.54E+00	4.14E+01
	RWMA-Rediset	6.17E-02	6.55E-03	3.97E-05	9.68E-02	3.72E+00	4.14E+01
	RWMA-Astec	5.25E-02	6.21E-03	3.89E-05	9.51E-02	3.54E+00	4.14E+01
	RWMA-Gencor	5.25E-02	6.21E-03	3.89E-05	9.51E-02	3.54E+00	4.14E+01
Group C (Additives- Lower Temperature)	RWMA-Advera	5.09E-02	6.17E-03	3.80E-05	9.50E-02	3.50E+00	4.14E+01
	RWMA-Evotherm	5.01E-02	6.17E-03	3.73E-05	9.53E-02	3.50E+00	4.14E+01
	RWMA-SonneWarmix	5.14E-02	6.19E-03	3.82E-05	9.54E-02	3.54E+00	4.14E+01
	RWMA-Cecabase	4.98E-02	6.15E-03	3.75E-05	9.52E-02	3.49E+00	4.14E+01
	RWMA-Sasobit	5.12E-02	6.18E-03	3.83E-05	9.51E-02	3.51E+00	4.14E+01
	RWMA-Rediset	5.98E-02	6.50E-03	3.86E-05	9.68E-02	3.69E+00	4.14E+01
	RWMA-Astec	5.09E-02	6.17E-03	3.81E-05	9.51E-02	3.51E+00	4.14E+01
	RWMA-Gencor	5.05E-02	6.16E-03	3.79E-05	9.51E-02	3.50E+00	4.14E+01

3.4 Interpretation

3.4.1 *Results*

3.4.1.1 Non-Rubberized Mixes

The LCIA results reveal that the combination of WMA mixing temperature, the chemical components of the WMA technologies, and the dosage of additives in the mix are the three main factors influencing the final environmental emissions. Figure 3.11 shows the comparison of GW, as a global impact category, for 1 kg of the non-rubberized asphalt concrete mix types considered in this study. As expected, use of the WMA technology as a means to reduce mixing temperature (Group C in tables in Chapter 3) can reduce GW due to the reduced natural gas consumption during production of the WMA at a reduced temperature. Whether or not there is a reduction and the size of the reduction depend on the relative effects of the three factors listed previously: temperature reduction, WMAA chemistry and production, and WMAA dosage. When the WMAA is used as a compaction and transportation aid without reducing the mixing temperature (Group B in tables in Chapter 3), there is not reduction in GW from mix production and construction, though there may be a life cycle GW reduction if better compaction and sufficiently longer life are achieved from the WMAA to compensate for its use.

Figure 3.11 also shows that WMA-Rediset has the highest GW, while WMA-Cecabase has the lowest GW compared to the other additives, based on the assumptions used in this study regarding the chemistry and production of those WMAA. The temperature used in the mixture of WMA-Rediset is not the highest temperature used among the WMA technologies. Therefore, the chemical components used in Rediset, including hexamethylenediamine (HMDA) as well as the dosage of Rediset in the mix (0.13%), are the reasons for this high amount of GW. HMDA is a colorless, low-melting solid with an important industrial use that produces toxic oxides of nitrogen during combustion. It is the starting material for manufacturing nylon 6-6, which is a polyamide used widely in textiles and plastics. HMDA is also used in the production of polymers *(71)*.

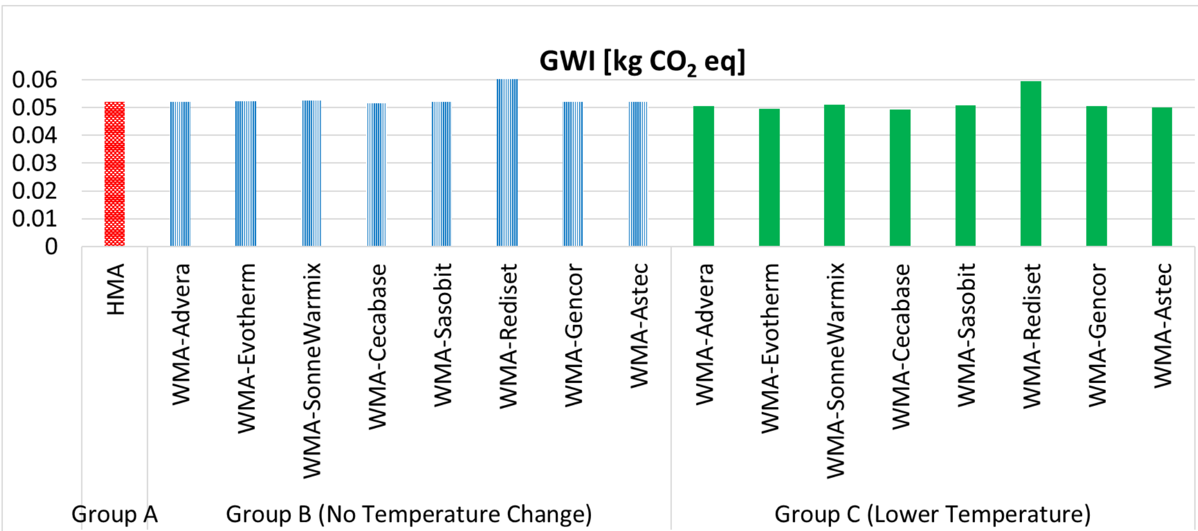


Figure 3.11: Global warming results for 1 kg of non-rubberized warm mix asphalt.

Figure 3.12 to Figure 3.15 show the regional environmental impacts and energy consumption for 1 kg of non-rubberized WMA in California. These figures show that WMA-Rediset has the highest smog formation potential, human health particulate effects, and renewable energy and nonrenewable energy consumption. WMA-Cecabase has the lowest impacts in human health particulate effects and nonrenewable energy consumption, and WMA-Advera has the lowest impacts in smog formation potential and renewable energy consumption.

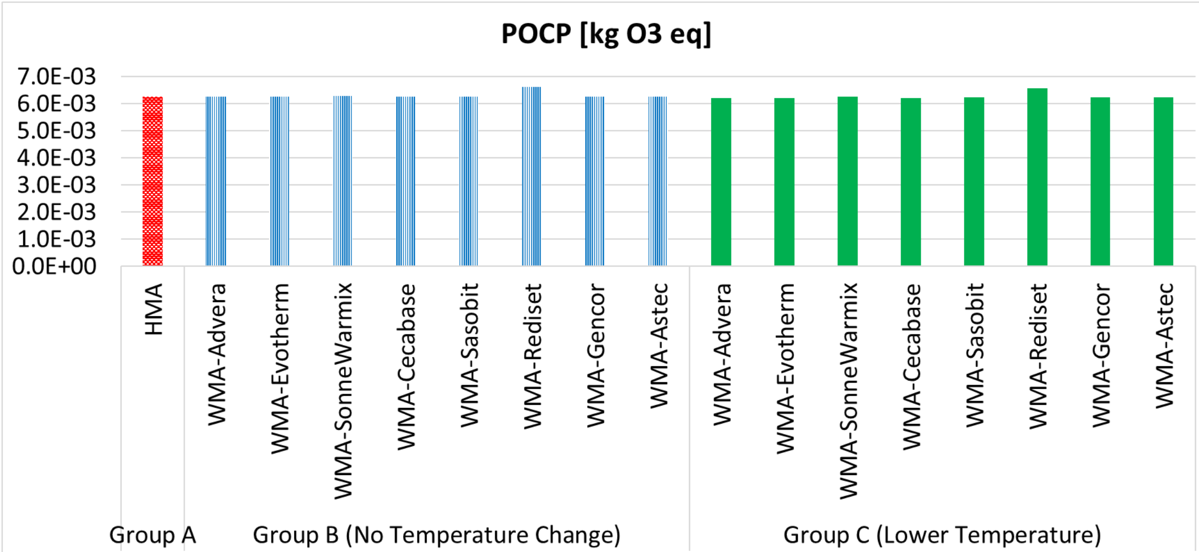


Figure 3.12: Smog formation potential for 1 kg of non-rubberized warm mix asphalt.

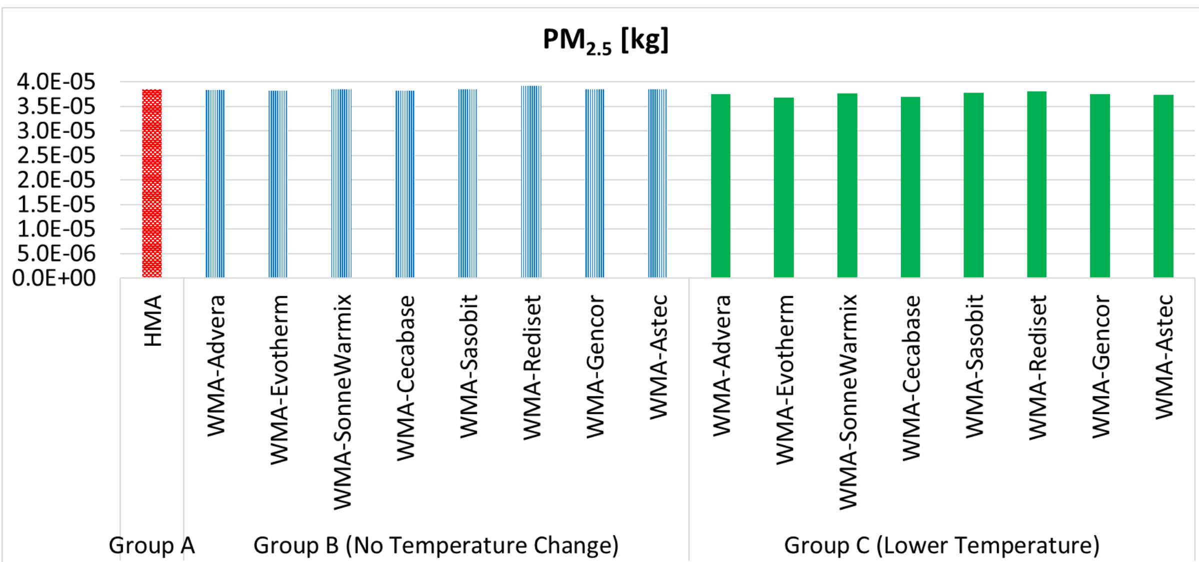


Figure 3.13: Human health particulate effects for 1 kg of non-rubberized warm mix asphalt.

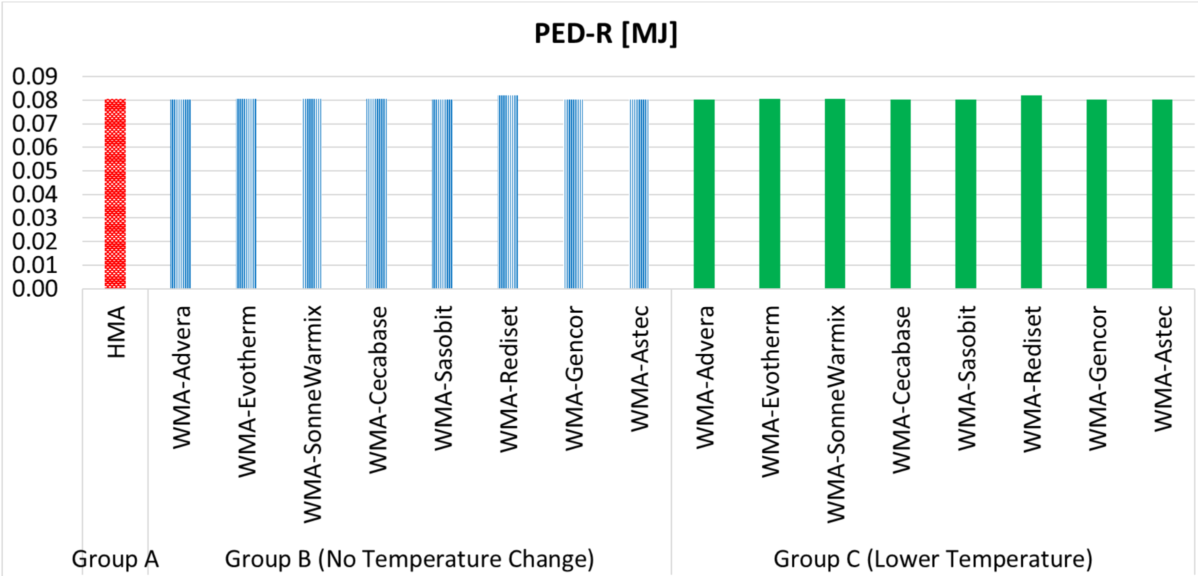


Figure 3.14: Renewable energy for 1 kg of non-rubberized warm mix asphalt.

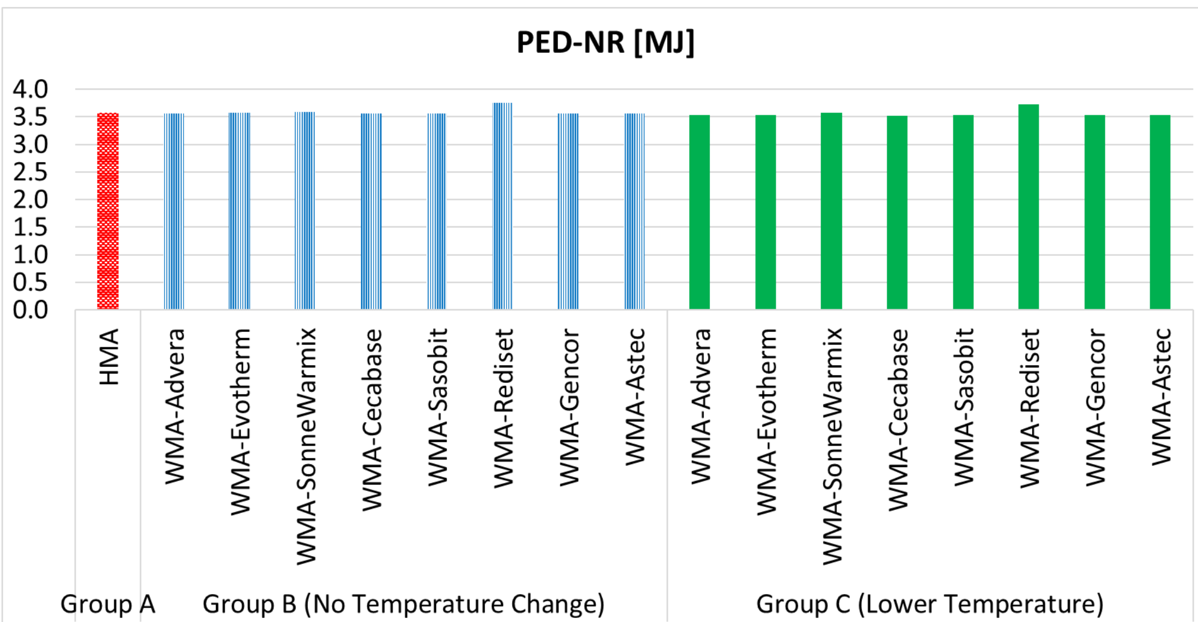


Figure 3.15: Nonrenewable energy for 1 kg of non-rubberized warm mix asphalt.

WMA-Cecabase's mixing temperature, when used to lower mixing temperature, is lower than most of the other WMAs, which indicates the importance of mixing temperature in WMA-Cecabase's low environmental impacts. The lower dosage of WMA-Cecabase in the mix, compared with other additives, is another important factor that results in WMA-Cecabase's low environmental impacts. WMA-Advera's mixing temperature (295ºF) is higher than WMA-Rediset's mixing temperature (285ºF). However, WMA-Rediset has the highest environmental impacts. This indicates that the role of chemical components and the dosage of additives used in these WMA technologies are more significant than mixing temperature in influencing environmental impacts, at least for the mixes evaluated in this study.

Figure 3.16 to Figure 3.20 compare the environmental impacts for each WMA mix at the normal mixing temperature (Group B) and at the lowest mixing temperature (Group C) compared with HMA at its normal mixing temperature (Group A) side by side. As expected, Group C has a lower GW compared to Group B due to the reduced temperatures and natural gas consumption during the production of the WMA.

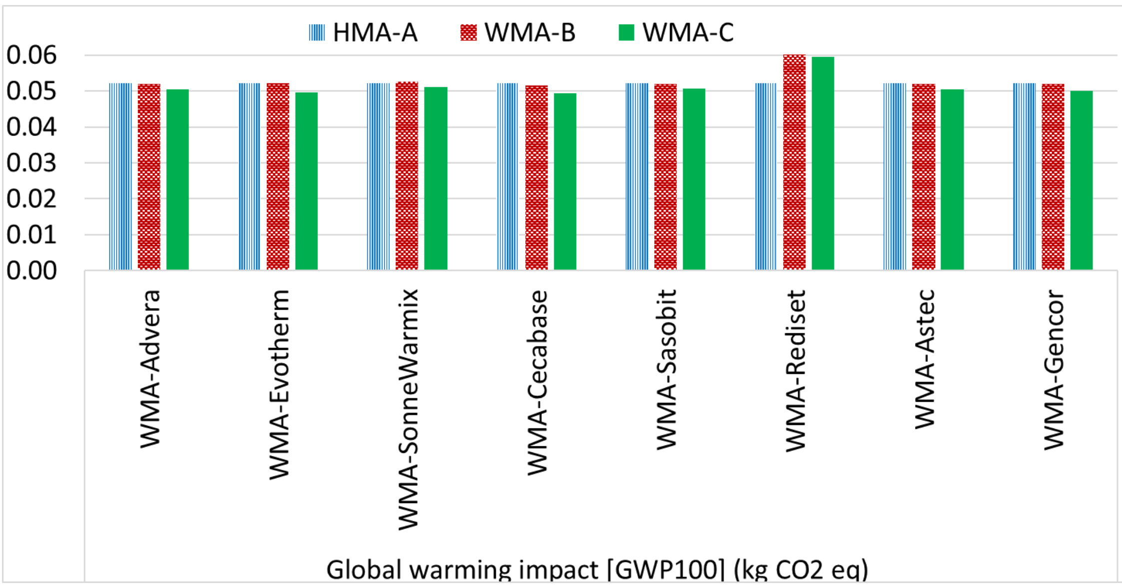


Figure 3.16: Global warming results for 1 kg of non-rubberized warm mix asphalt for different WMA groups.

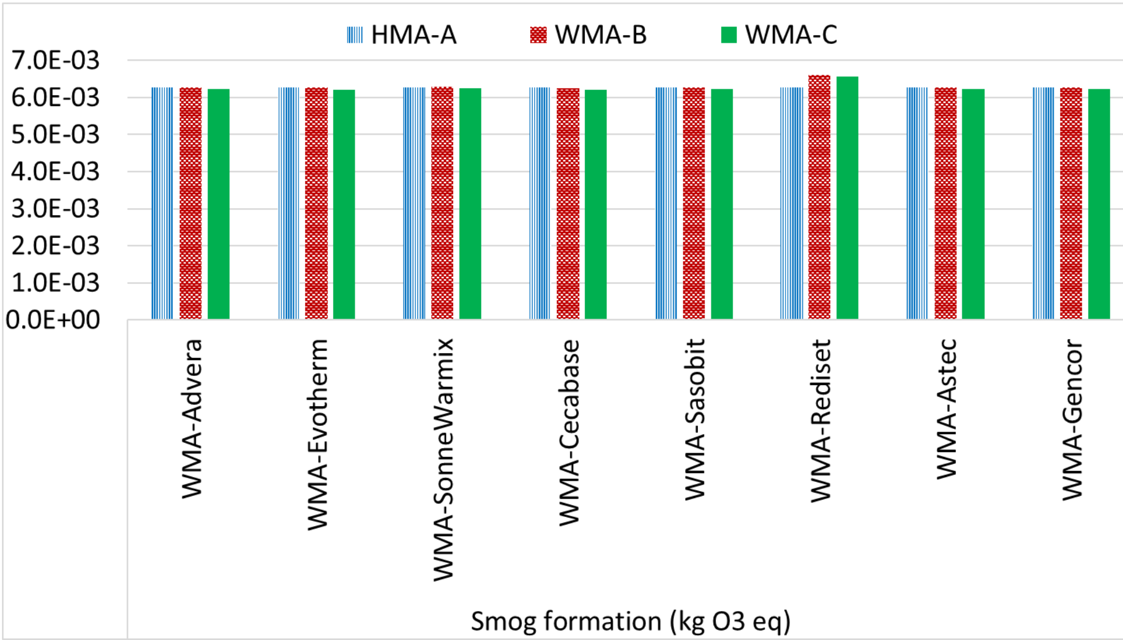


Figure 3.17: Smog formation results for 1 kg of non-rubberized warm mix asphalt for different WMA groups.

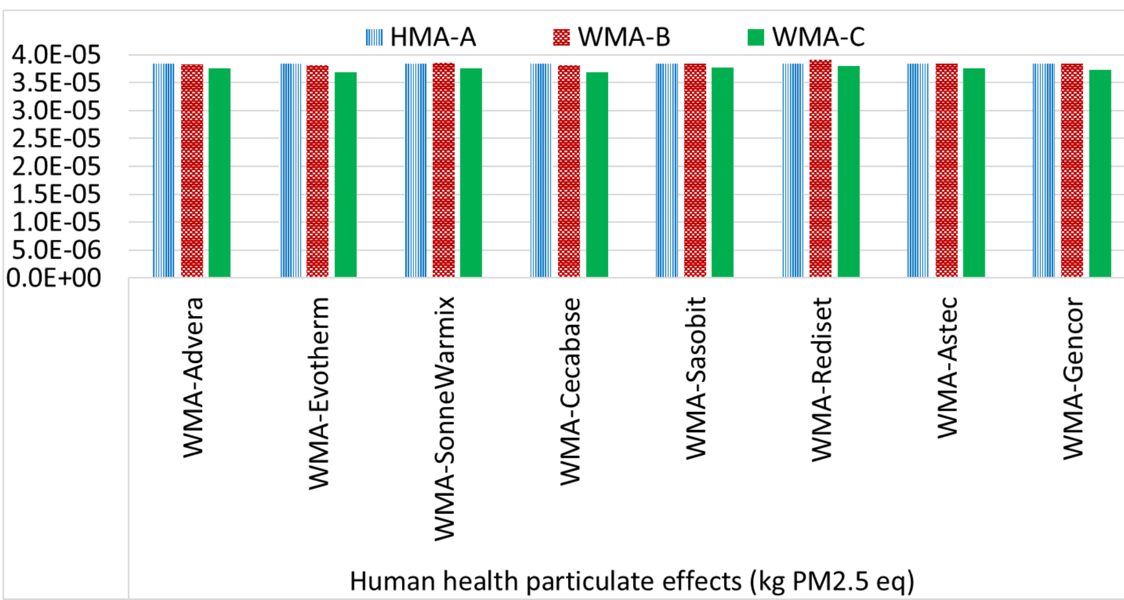


Figure 3.18: Human health particulate effect for 1 kg of non-rubberized warm mix asphalt for different WMA groups.

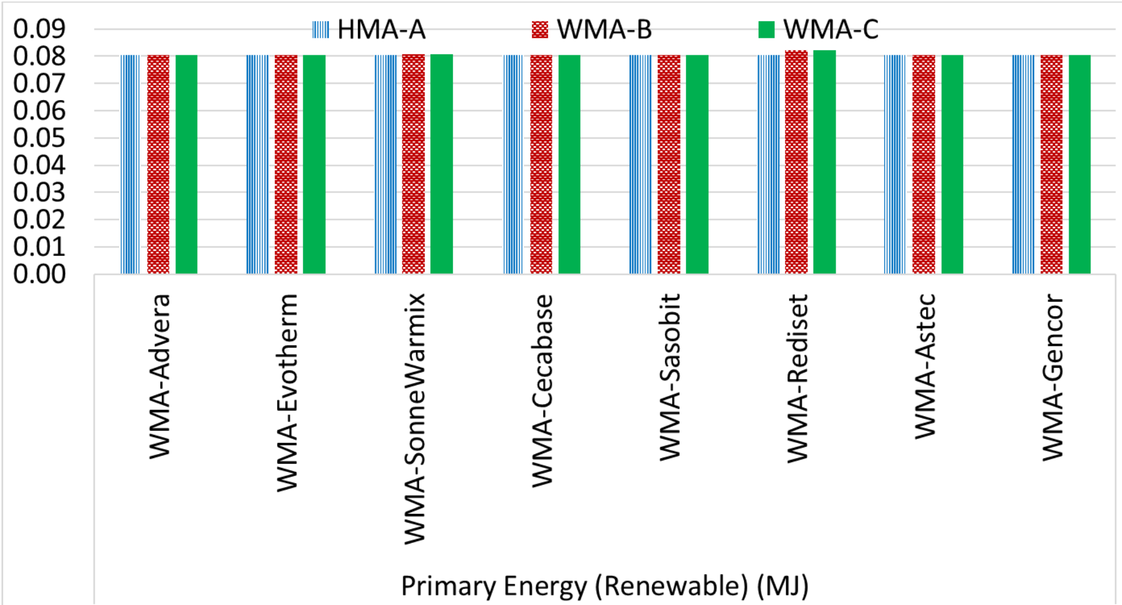


Figure 3.19: Renewable energy results for 1 kg of non-rubberized warm mix asphalt for different WMA groups.

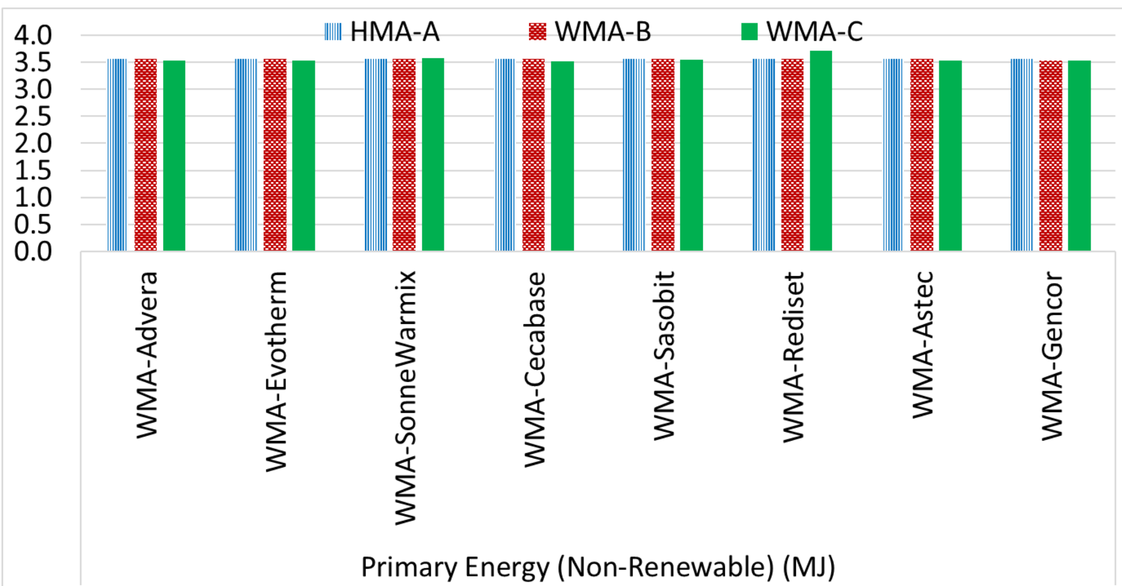


Figure 3.20: Nonrenewable energy results for 1 kg of non-rubberized warm mix asphalt for different WMA groups.

3.4.1.2 Rubberized Mixes

Figure 3.21 to Figure 3.25 show the environmental impacts and energy consumption for 1 kg of rubberized WMA. The LCIA results reveal that the combination of WMA mixing temperature, chemical components of the WMA technologies, and dosage of additives in the mix are the three main factors influencing the final environmental emissions. These figures show that RWMA-Rediset (shown as WMA-Rediset) has the highest environmental impacts and energy consumption in all impact categories. Similar to the results of the non-rubberized WMA, the temperature used in the mixture of WMA-Rediset is not the highest temperature among the WMA technologies. Therefore, the chemical components used in Rediset, including HMDA, and the dosage of Rediset in the mix (0.13%) are the reasons for these high impacts.

WMA-Cecabase has the lowest impacts in most categories, in both Group B and Group C. WMA-Cecabase's mixing temperature is lower than most of the WMAs, which indicates the important role of mixing temperature in WMA-Cecabase's environmental impacts. The lower dosage of WMA-Cecabase in the mix, compared with the other additives, is another important factor that results in WMA-Cecabase's low environmental impacts.

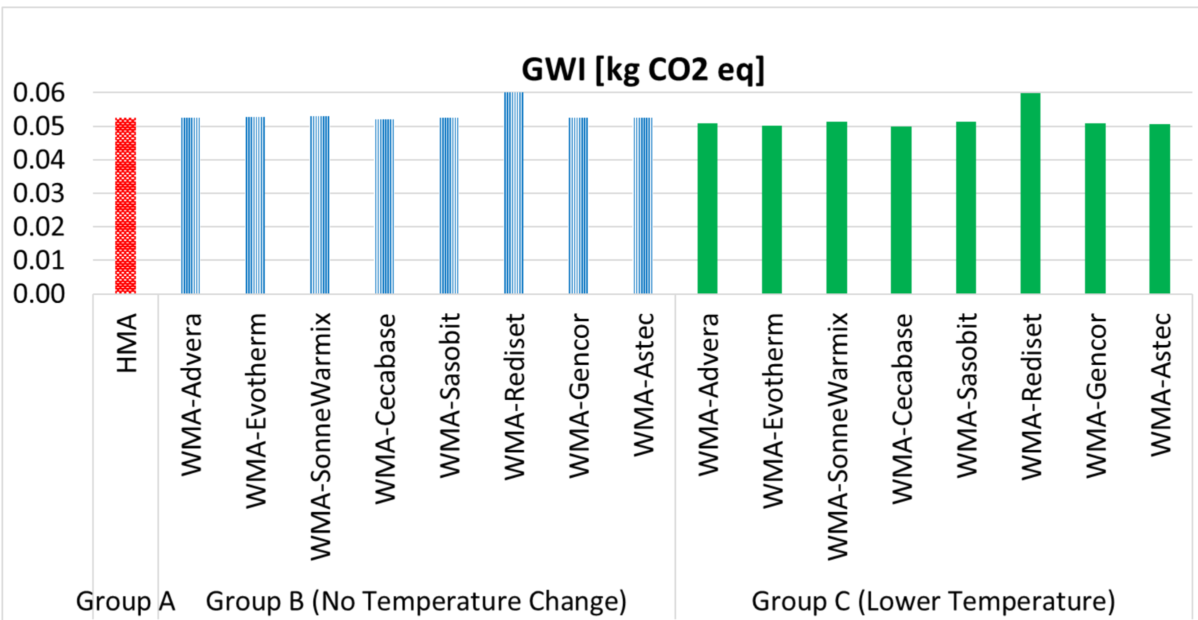


Figure 3.21: Global warming results for 1 kg of rubberized warm mix asphalt.

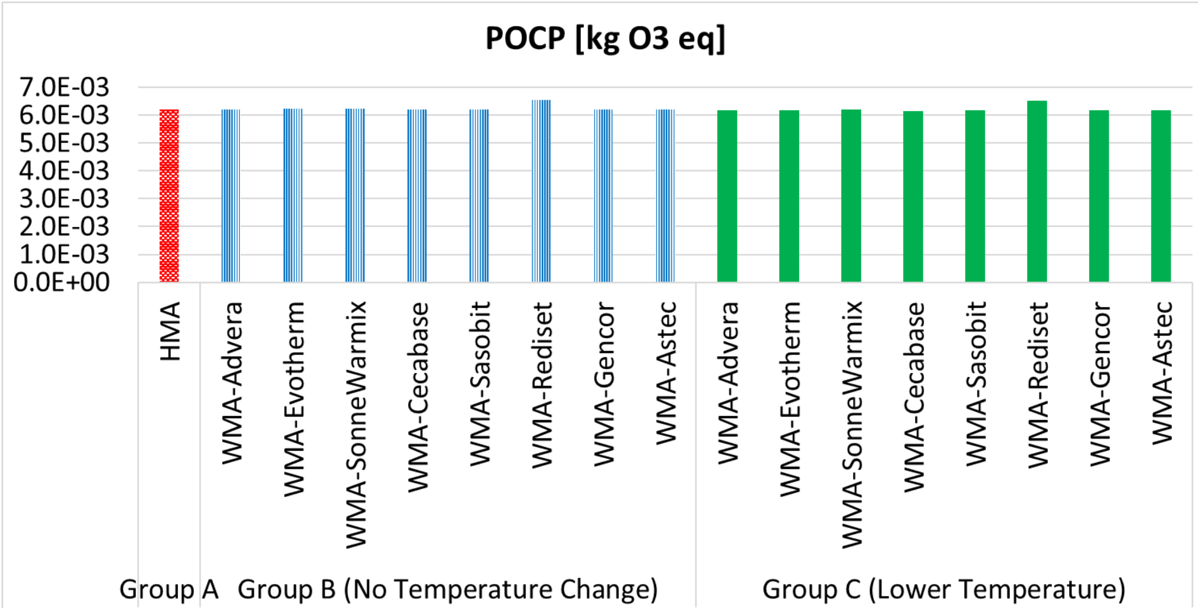


Figure 3.22: Smog formation potential results for 1 kg of rubberized warm mix asphalt.

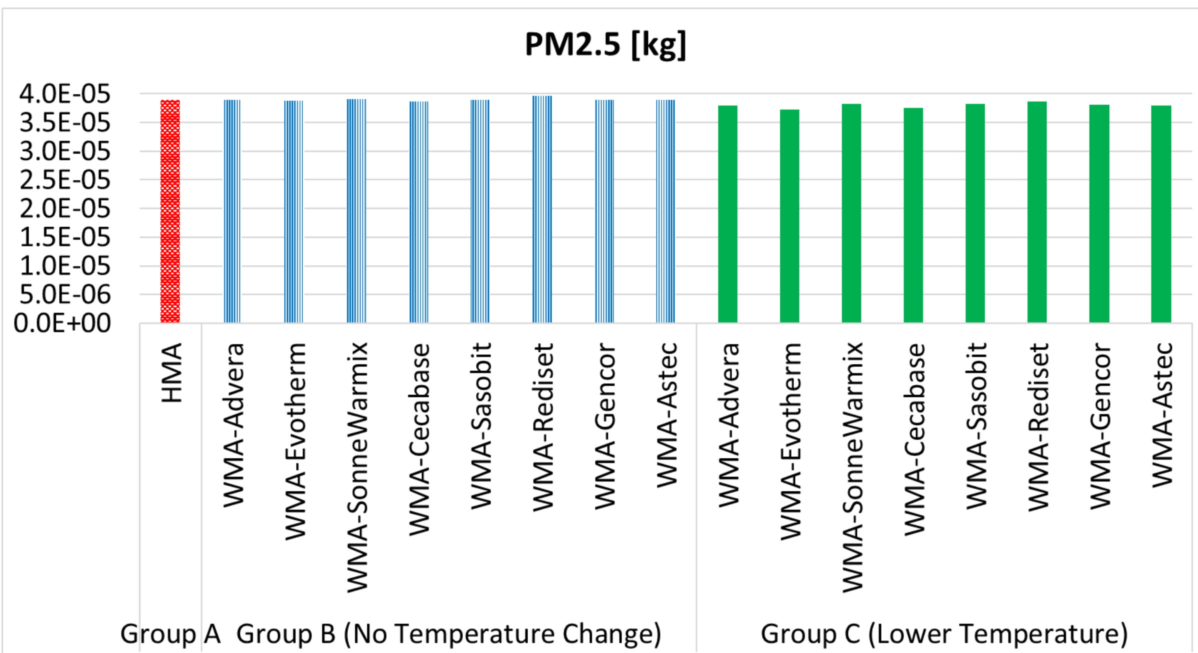


Figure 3.23: Human health particulate effects results for 1 kg of rubberized warm mix asphalt.

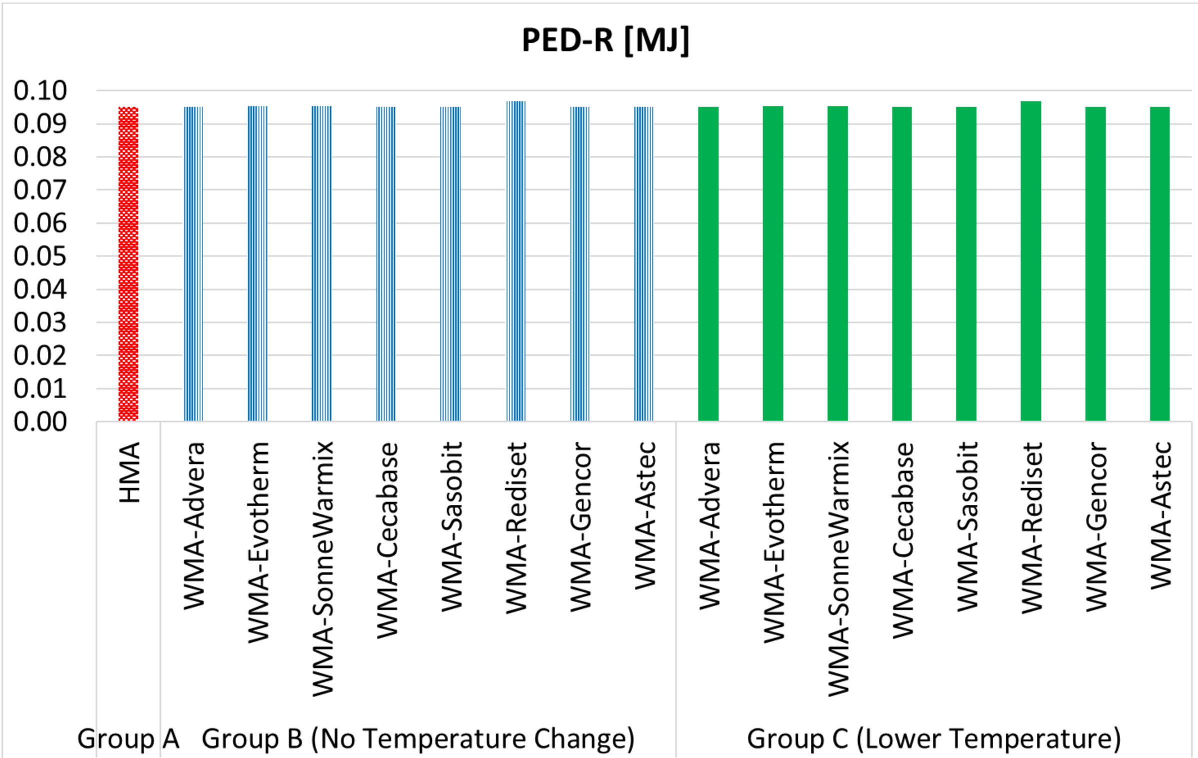


Figure 3.24: Renewable energy results for 1 kg of rubberized warm mix asphalt.

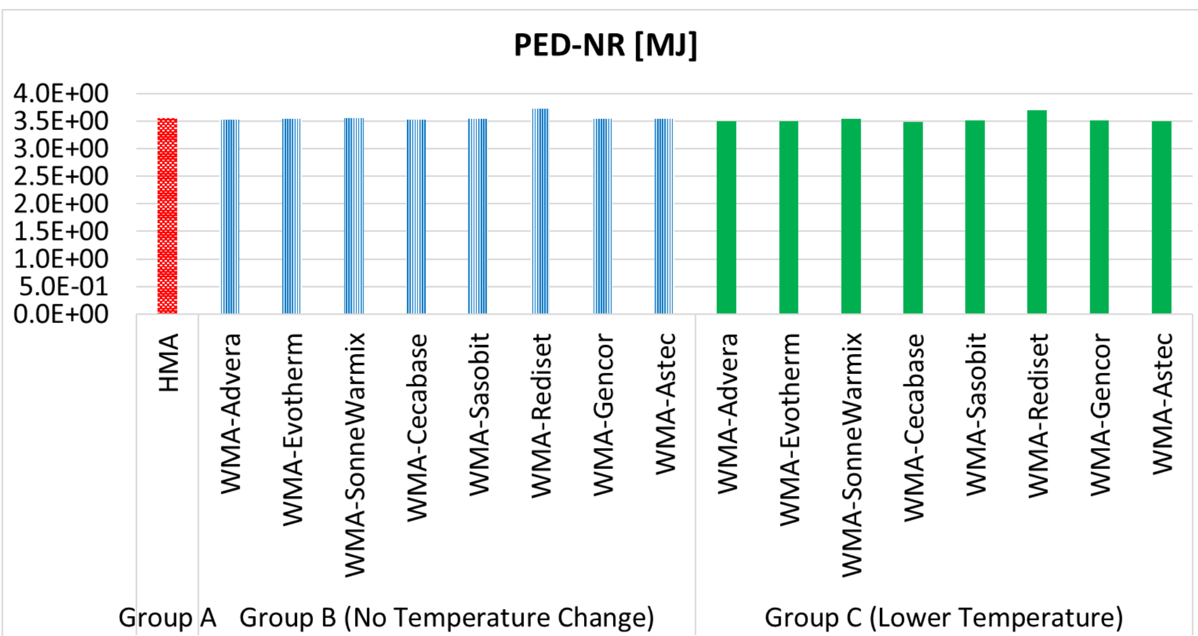


Figure 3.25: Nonrenewable energy results for 1 kg of rubberized warm mix asphalt.

Figure 3.26 to Figure 3.30 compare the environmental impacts for each rubberized WMA mix at the normal mixing temperature (Group B) and at the lowest mixing temperature (Group C) compared with RHMA at its normal mixing temperature (Group A) side by side. As expected, Group C has a lower GW compared with Group B, due to the reduced temperatures and natural gas consumption during the production of the WMA.

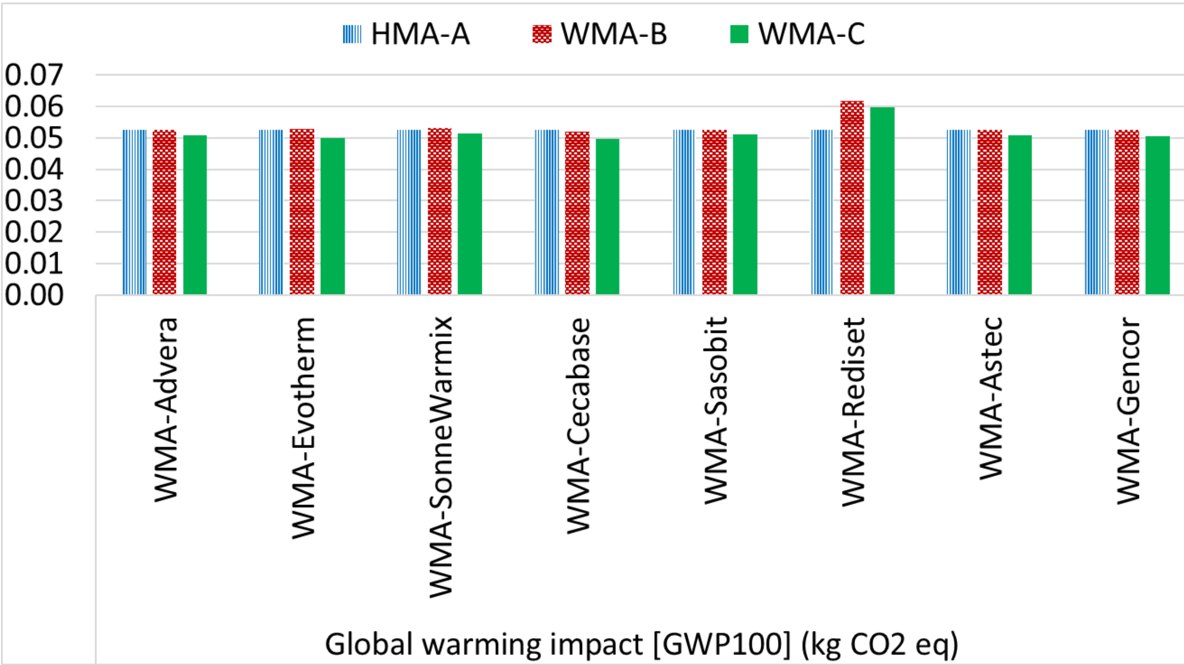


Figure 3.26: Global warming impact results for 1 kg of rubberized warm mix asphalt for different WMA groups (Groups A, B, and C).

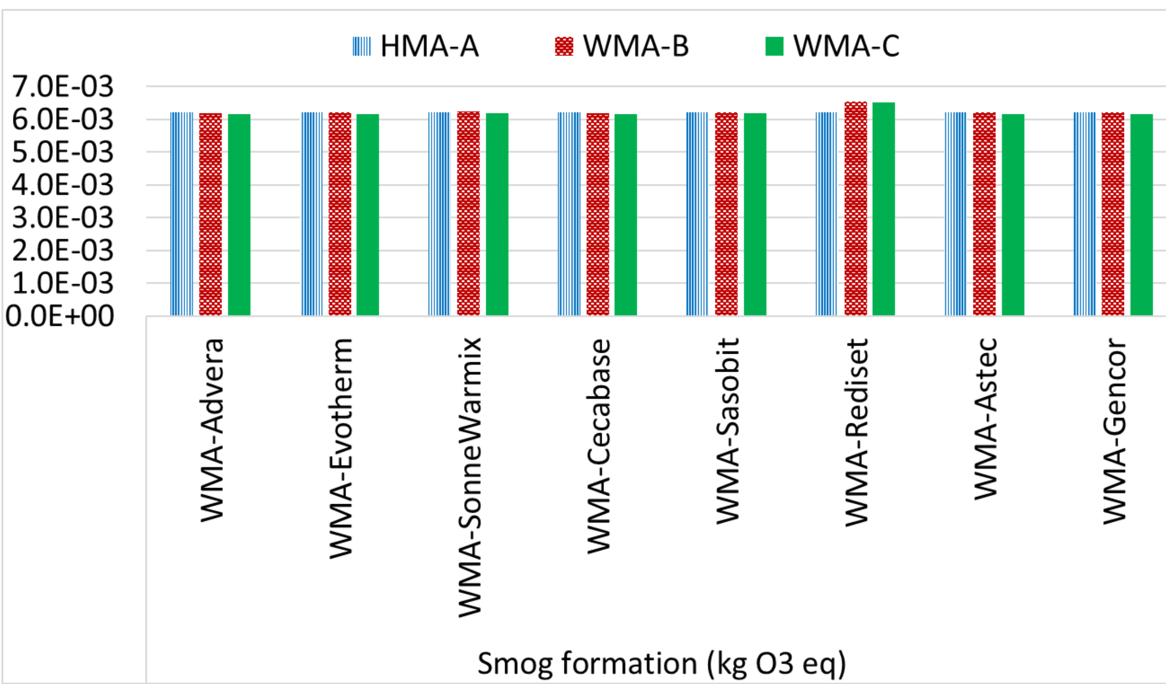


Figure 3.27: Smog formation results for 1 kg of rubberized warm mix asphalt for different WMA groups (Groups A, B, and C).

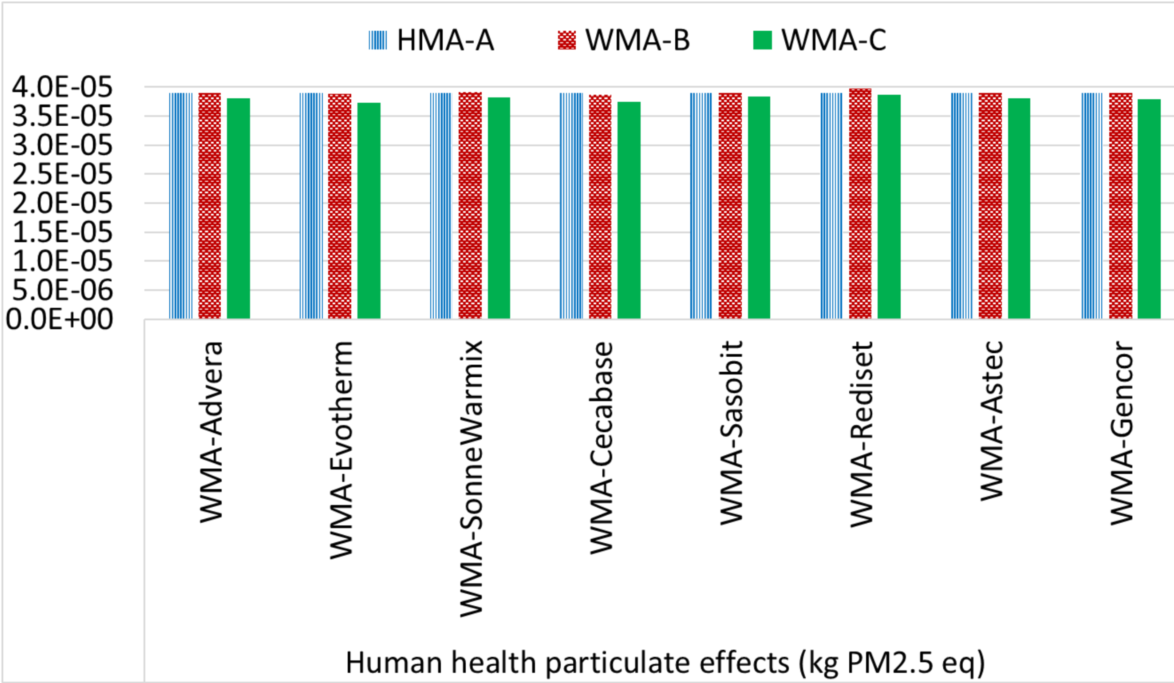


Figure 3.28: Human health particulate effect results for 1 kg of rubberized warm mix asphalt for different WMA groups (Groups A, B, and C).

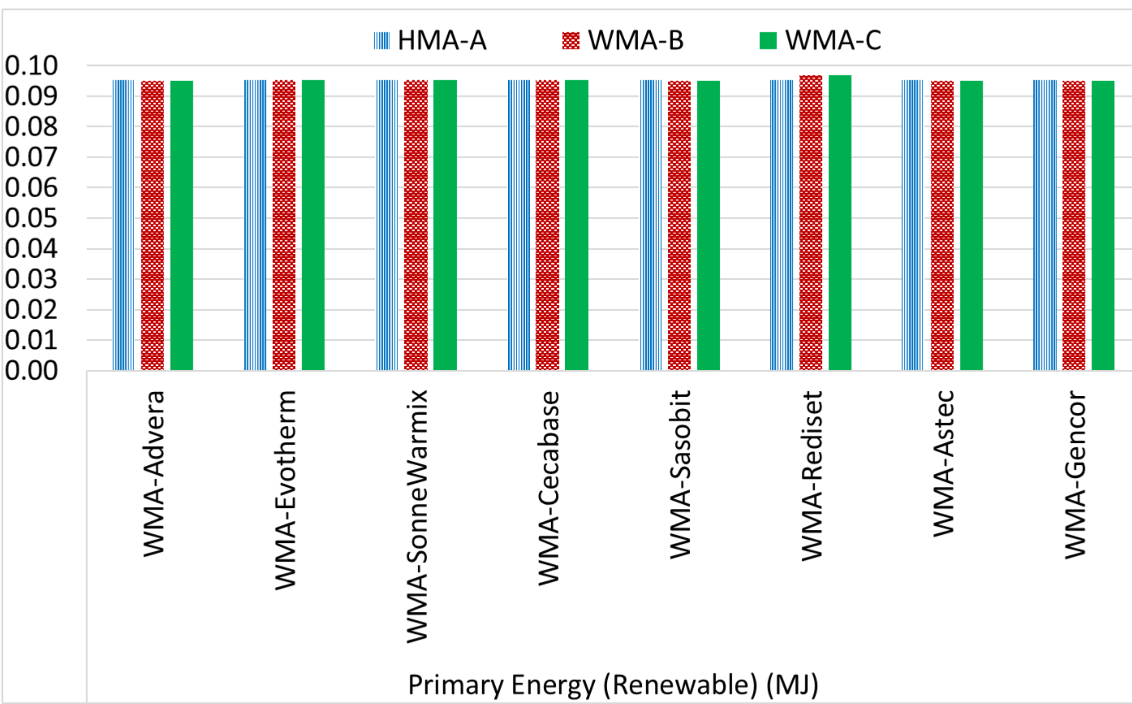


Figure 3.29: Renewable energy results for 1 kg of rubberized warm mix asphalt for different WMA groups (Groups A, B, and C).

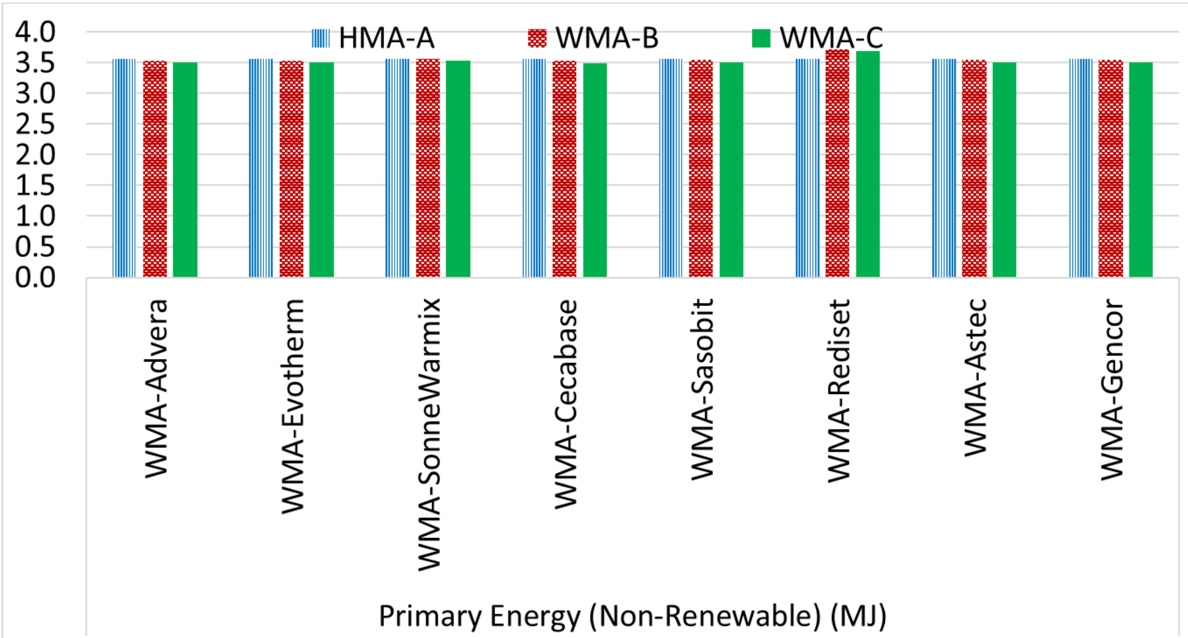


Figure 3.30: Nonrenewable results for 1 kg of rubberized warm mix asphalt for different WMA groups (Groups A, B, and C).

The percent changes in each impact category in the WMA group compared with conventional HMA are shown in Table 3.11 and compared with conventional RHMA in Table 3.12. It can be seen that compared with HMA, use of WMA at the same mixing temperature as a compaction and transportation aid results in changes in GW of less than 1%, except for Rediset, which increases the GW by more than 17%. When the WMA is used to reduce the mixing temperature to the lowest recommended temperature, the net reductions in GW range between approximately 2% and 5% except for Rediset where the reduction in mixing temperature results in a net increase of GW of 14%.

Table 3.11: Changes in Each Impact Category in Non-Rubberized Warm Mix Asphalt Group Compared to Conventional Hot Mix Asphalt

Group	WMA Groups	GW (kg CO2 eq) (%)	POCP (kg O3 eq) (%)	PM2.5 (kg) (%)	PED-R (MJ) (%)	PED-NR (MJ) (%)	PED-FS (MJ) (%)
Group A	HMA	0.0	0.0	0.0	0.0	0.0	0.0
Group B (No Temperature Change)	WMA-Advera	-0.1	-0.1	-0.2	-0.3	-0.3	0.0
	WMA-Evotherm	0.2	0.1	-0.5	0.0	0.0	0.0
	WMA-SonneWarmix	1.0	0.3	0.3	0.3	0.6	0.0
	WMA-Cecabase	-1.0	-0.2	-0.5	-0.1	-0.3	0.0
	WMA-Sasobit	-0.2	0.0	0.0	-0.1	-0.3	0.0
	WMA-Rediset	17.9	5.5	1.9	2.0	5.0	0.0
	WMA-Astec	-0.2	0.0	0.0	-0.1	-0.3	0.0
	WMA-Gencor	-0.2	0.0	0.0	-0.1	-0.3	0.0
Group C (Lower Temperature)	WMA-Advera	-3.2	-0.7	-2.3	-0.3	-1.1	0.0
	WMA-Evotherm	-4.8	-0.9	-4.2	0.0	-1.1	0.0
	WMA-SonneWarmix	-2.1	-0.2	-2.1	0.3	0.0	0.0
	WMA-Cecabase	-5.2	-1.0	-3.9	-0.1	-1.4	0.0
	WMA-Sasobit	-2.7	-0.5	-1.8	-0.1	-0.8	0.0
	WMA-Rediset	14.1	4.8	-0.9	2.0	4.2	0.0
	WMA-Astec	-3.0	-0.7	-2.3	-0.1	-0.9	0.0
	WMA-Gencor	-3.8	-0.7	-2.9	-0.1	-1.1	0.0

Table 3.12: Changes in Each Impact Category in the Rubberized Warm Mix Asphalt Group Compared to Conventional Rubberized Hot Mix Asphalt

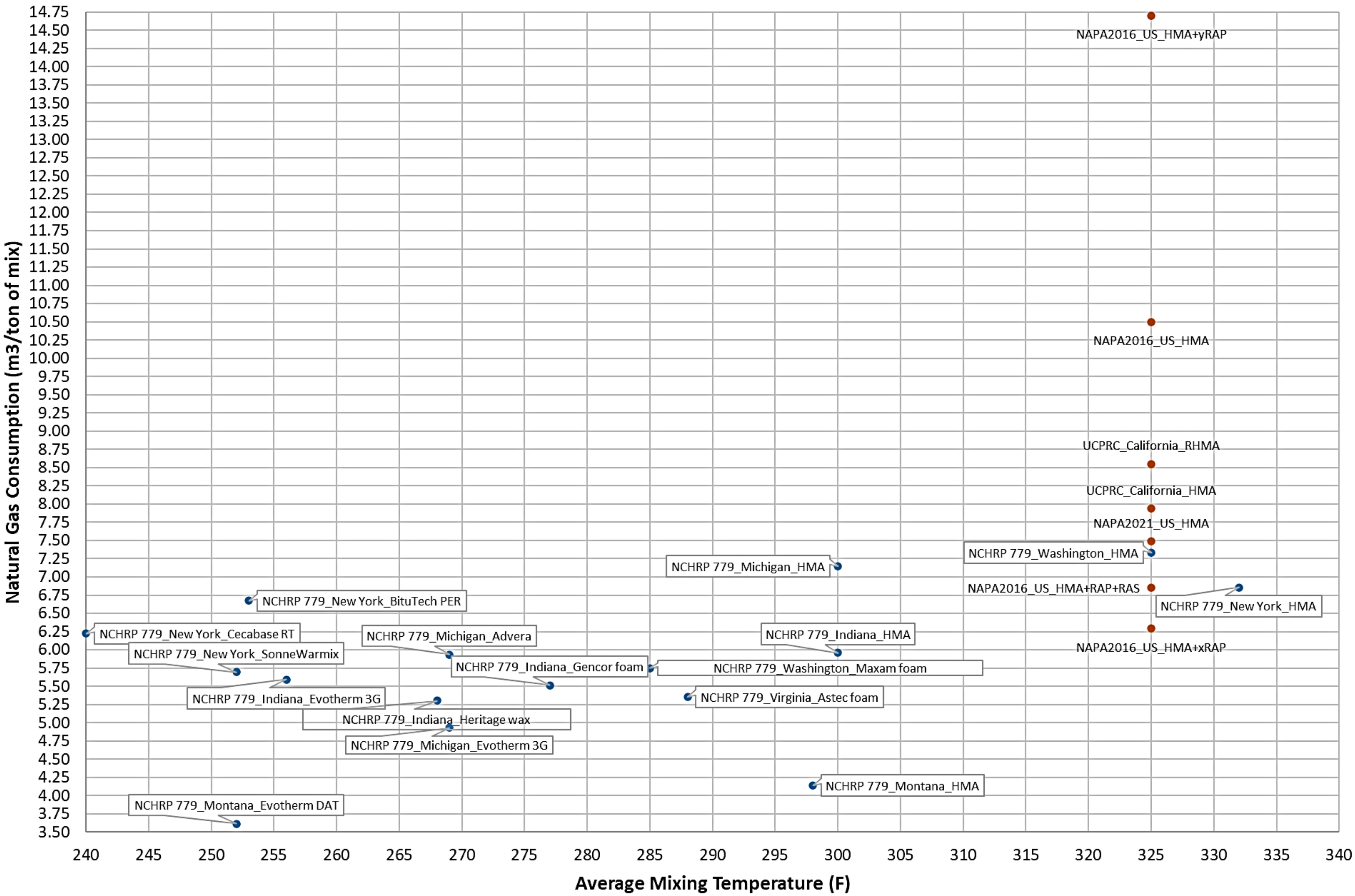
Group	WMA Groups	GW (kg CO2 eq) (%)	POCP (kg O3 eq) (%)	PM2.5 (kg) (%)	PED-R (MJ) (%)	PED-NR (MJ) (%)	PED-FS (MJ) (%)
Group A	RHMA	0.0	0.0	0.0	0.0	0.0	0.0
Group B (No Temperature Change)	RWMA-Advera	-0.1	-0.2	-0.2	-0.2	-0.8	0.0
	RWMA-Evotherm	0.4	0.2	-0.5	0.1	-0.6	0.0
	RWMA-SonneWarmix	1.0	0.3	0.3	0.2	0.0	0.0
	RWMA-Cecabase	-0.9	-0.2	-0.7	0.0	-0.8	0.0
	RWMA-Sasobit	0.1	0.0	-0.2	-0.1	-0.6	0.0
	RWMA-Rediset	17.6	5.5	1.9	1.7	4.5	0.0
	RWMA-Astec	0.1	0.0	-0.2	-0.1	-0.6	0.0
	RWMA-Gencor	0.1	0.0	-0.2	-0.1	-0.6	0.0
Group C (Lower Temperature)	RWMA-Advera	-3.1	-0.7	-2.5	-0.2	-1.7	0.0
	RWMA-Evotherm	-4.5	-0.6	-4.3	0.1	-1.7	0.0
	RWMA-SonneWarmix	-2.1	-0.3	-2.0	0.2	-0.6	0.0
	RWMA-Cecabase	-5.1	-1.0	-3.8	0.0	-2.0	0.0
	RWMA-Sasobit	-2.4	-0.5	-1.7	-0.1	-1.4	0.0
	RWMA-Rediset	14.0	4.7	-1.0	1.7	3.7	0.0
	RWMA-Astec	-3.0	-0.6	-2.2	-0.1	-1.4	0.0
	RWMA-Gencor	-3.7	-0.8	-2.8	-0.1	-1.7	0.0

3.4.2 *Sensitivity Analysis Comparing Natural Gas from Different Sources*

Mixing temperatures for HMA and WMA versus natural gas consumption to produce 1 ton of asphalt mixture were plotted using data from three sources: NCHRP 779 *(72)*, Mukherjee *(73,74)*, and Saboori et al. *(2)*, shown in Figure 3.31. Some asphalt plants used more than one type of fuel for heating and mixing, as reported in NCHRP 779. However, the percentages were not documented. Therefore, it was assumed that the heating energy is obtained from the combustion of natural gas at the plants. The energy density for natural gas was assumed to be 40 MJ/m^3.

Mukherjee collected asphalt production temperature and energy intensity data from 45 plants for 125 mixes, and the study findings did not establish any relationship between the two variables *(74)*. Figure 3.31 also show a wide range and spread of natural gas fuel use (per ton of mix) and asphalt mixing temperatures at an assumed mixing temperature of 325°F, typical of HMA from across the United States. The variability seen in the values may be due to differences in air temperatures in different climate regions; differences in moisture content in the aggregate stockpiles, which would be a function of climate region; aggregate mining and storage practices affecting moisture content; the heat capacity of the aggregate; and the efficiency of the heating units at the asphalt plant. The figure also shows data from the NCHRP 779 study for WMA mixes at plants across the country using different WMAAs. These results also show a wide range of natural gas consumption for a given mixing temperature, which would also be a function of the same variables as HMA.

Additionally, natural gas consumption to produce HMA from studies—including the Athena Institute *(75)*, D'Angelo et. al *(76)*, and Mukherjee *(73,74)*—were compared with the results of the current study. As explained in Section 3.3.1.1, this study used the specific heat (c) of asphalt mixtures and the mixing temperature of each WMA technology for calculating the natural gas used in WMA production. The Athena Institute study collected energy consumption data to produce 1 tonne of HMA from seven asphalt plants and calculated the average natural gas consumption of 4.66 m^3 (177 MJ) *(75)*. In 2016, the Mukherjee study considered four different mixes and the natural gas consumption to produce these mixes, shown in Table 3.13 (also shown in Figure 3.31) *(73)*. The mixes containing recycled asphalt pavement (RAP) and/or reclaimed asphalt shingles (RAS) would be expected to generally have higher consumption because of the stiffer binders in them, assuming that they did not have a rejuvenating agent added. However, this trend is not seen consistently in the table data. The reasons stated earlier (aggregate source and condition) likely contribute to this large variability.



Notes: Values plotted in blue are at different temperatures; values plotted in red are calculated at 325°F from the sources shown.

Sources: National Cooperative Highway Research Program (2014) *(72)*; Mukherjee (2106) *(73)*; Mukherjee (2021) *(74)* (referred to as NAPA2016 and NAPA2021); Saboori et al. (2022) *(2)* (referred to as UCPRC).

Figure 3.31: Asphalt mixtures mixing temperatures versus natural gas consumption for heating purposes.

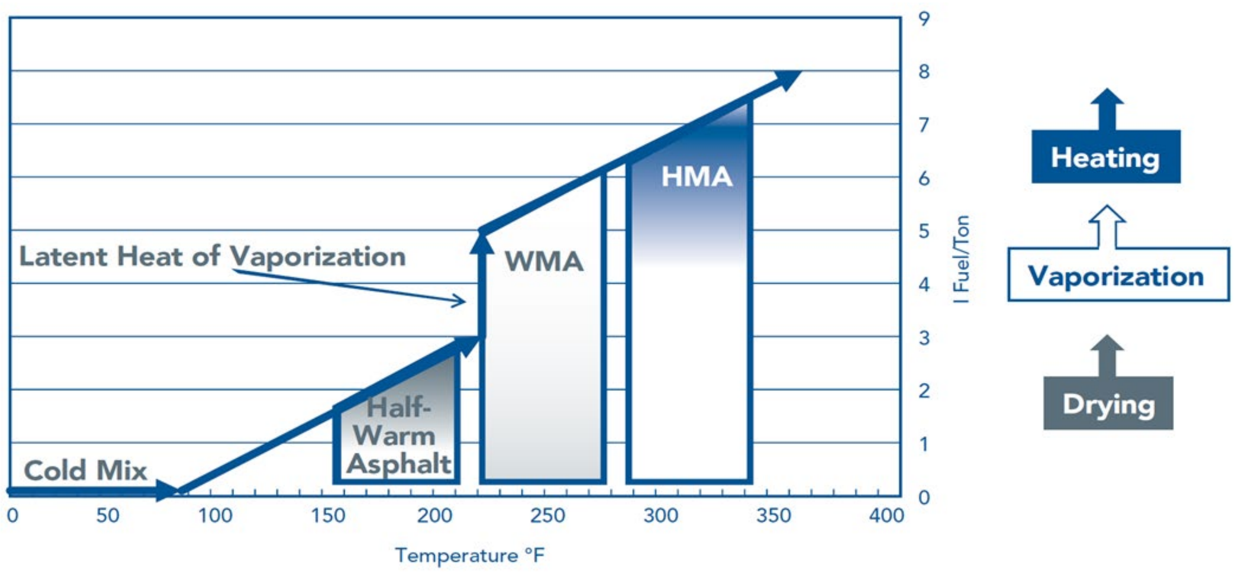
Table 3.13: Natural Gas for Mixing 1 kg of Asphalt Mix

Mixes[a]	Mix 1 HMA	Mix 2 HMA+RAP+RAS	Mix 3 HMA+xRAP	Mix 4 HMA+yRAP
Natural gas consumption (m^3 per kg of asphalt mix)	0.0116	0.0076	0.0069	0.0162

[a] HMA mixes with different RAP and or RAS contents.

Source: Mukherjee (2016) *(73)*.

D'Angelo et al.'s study considered eight European WMAAs, including four wax additives and four foaming technologies *(76)*. These additives are different than the ones evaluated and documented in this study. Figure 3.32 from the D'Angelo et al. study shows the fuel consumption (liters/tonne) of cold to HMA at different production temperatures. This figure was used to estimate the natural gas consumption using linear interpolation, shown in Table 3.14**.**



Source: D'Angelo et al. (2008) *(76)*.

Figure 3.32: Classification of various application temperatures and diesel fuel use for different mix types.

Table 3.14 shows the comparison of natural gas consumption calculated or estimated from all the studies previously cited. The table shows a wide range of natural gas consumption for each study and the ranges from different studies. These results and the discussion of variables likely influencing the large variability indicate that more data need to be collected and considered to facilitate better calculation of the benefits of reduced mixing temperatures when using WMA technologies. Better calculations will likely also indicate that better control of the influencing variables is warranted to reduce the environmental impacts of producing asphalt mixes, which, if they significantly reduce energy use, may also produce operating cost savings.

Table 3.14: Comparison of Study Results to Calculate Natural Gas for Mixing per 1 kg of Asphalt Mix

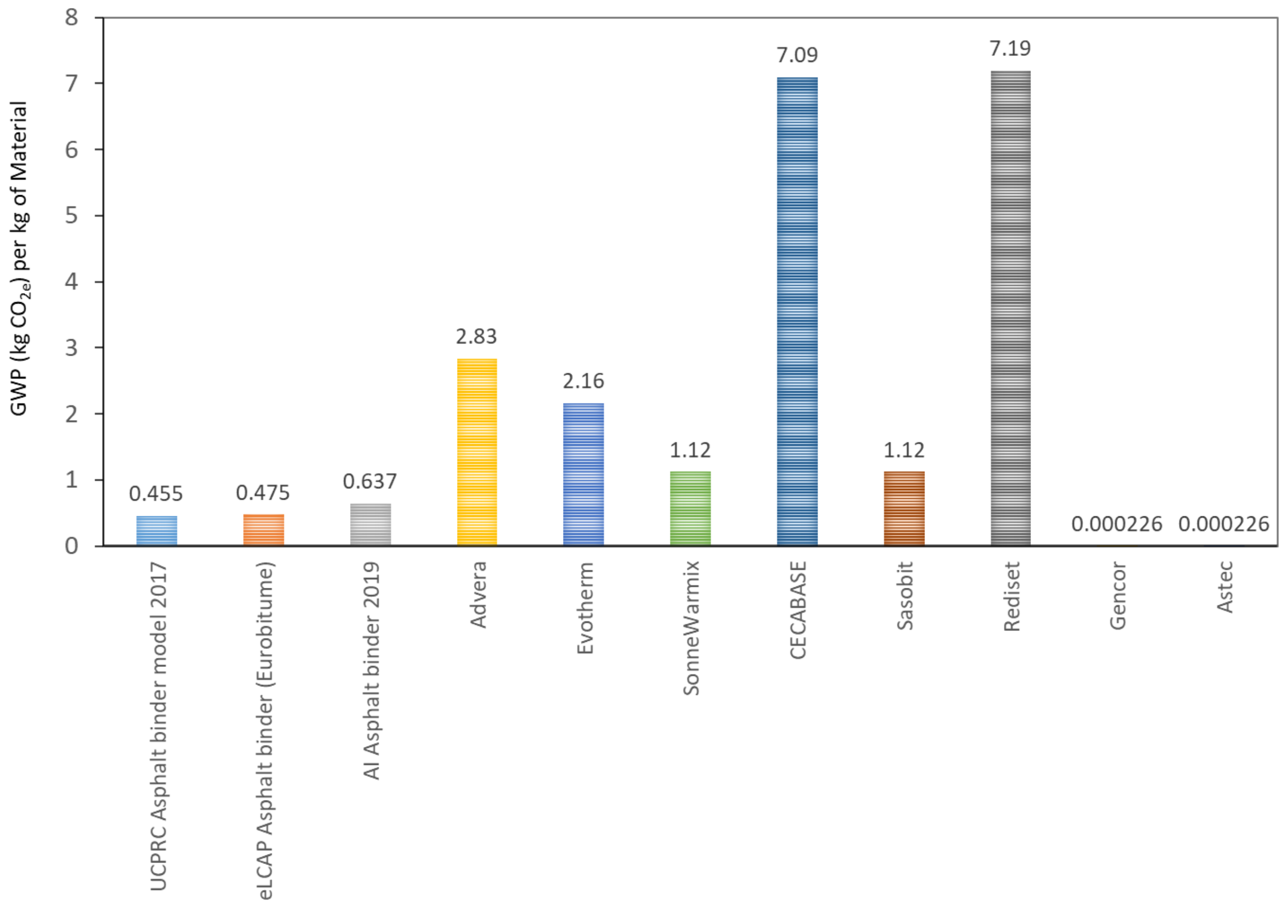
	NCHRP 779 (HMA) *(72)*	NCHRP 779 (WMA) *(72)*	D'Angelo *(76)*[a]	Athena Institute *(75)*	Mukherjee (2016) *(73)*	Mukherjee (2021) *(74)*	Section 3.3.1 Calculations
Temperature range (ºF)	298–332	240–288	210–335	300	—	—	282–356
Natural gas consumption to produce asphalt mix range (m^3/kg)	0.0046–0.0081	0.0040–0.0074	0.0065–0.0073	0.0047	0.0069–0.0162	0.0083	0.0067–0.0079

[a] Natural gas is calculated based on the interpolation using Figure 3.32.

3.4.3 *Global Warming Impact Comparison of Warm Mix Asphalt Additives and Asphalt Binder*

The purpose of this sensitivity analysis is not to compare WMAAs, their performance in HMA, or additive types. Rather, the sentivity analysis is to evaluate and determine how the cradle-to-gate impacts of asphalt binder compare across the different additives. It is important to consider and include material production (cradle-to-gate) impacts of any additives, admixtures, or rejuvenating agents that are used in concrete or asphalt mixtures. Figure 3.33 shows the estimated GW of additives that were considered in this study with SDSs available in 2018. As previously mentioned, the impacts were estimated from the materials and their percentages in the SDSs using proxy data for the listed ingredients.

The figure shows that an additive may have cradle-to-gate impacts that are much higher than those of virgin asphalt binder. Because the impacts of WMAAs are large relative to those of virgin asphalt binder, the change in impact from reduced fuel consumption due to reduced mix temperature at an asphalt plant when using a WMAA must be compared with the impacts from the WMAA itself. It is also important to note that the net sum of the benefits or disbenefits of using a WMAA, or any other additive, should be evaluated based on the pavement's life cycle over a longer analysis period by including mix/pavement performance (durability). At the cradle-to-gate stage, a material that has a better longer life from inclusion of an additive should not be compared with a materIal that is not expected to have the same performance.



Notes: UCPRC asphalt binder model (2017), *eLCAP* asphalt binder, AI asphalt binder (2019) in kg CO2e per kg of material produced estimated from materials data sheets and proxy data.

Sources: Lea et al. (2022) *(3)*; Saboori et al. (2022) *(2)*; Wildnauer, Mulholland, and Liddie (2019) *(10)*.

Figure 3.33: Global warming of WMAA and asphalt binders from different sources.

4 BONDED CONCRETE OVERLAY OF ASPHALT

4.1 Introduction

Bonded concrete overlay on asphalt (BCOA) is a rehabilitation alternative that consists of placing a hydraulic cement concrete overlay on existing asphalt pavement *(73)*. It should be noted that more recent terminology in California is concrete overlay on asphalt (COA). This study is mainly focused on thin BCOA, where the overlay is 100 to 175 mm (4 to 7 in.) thick. BCOA with an overlay thickness of 50 to 100 mm (2 to 4 in), typically referred to as ultrathin, is primarily used in urban areas with light traffic. While the technology for thin BCOA has been used on highways and conventional roads in several US states as well as in other countries for at least 20 years, the use of thin BCOA has been very limited in California. BCOA has been evaluated under accelerated trafficking conducted with the Heavy Vehicle Simulator (HVS) by the UCPRC for Caltrans with positive results *(77)*. Caltrans decided to move forward and built a pilot thin BCOA project on State Route 113 (SR 113) in Woodland in District 3 *(78)* and another on State Route 247 (SR 247) in San Bernardino County in District 8. The experimental data presented in this study come from the Woodland thin BCOA construction project.

BCOA construction typically includes milling the existing asphalt layer to remove surface distresses and/or because of geometry constraints (e.g., to maintain road surface elevation or to change the cross-slope). Asphalt surface pre-overlay repairs such as localized patching and crack sealing may be included as well. Sweeping multiple times, air blasting the asphalt surface to remove dust and debris, and wetting the surface are the other pre-paving activities of BCOA construction.

BCOA construction includes placing the concrete overlay and sawing joints to form 6 x 6 ft. or 6 x 8 ft slabs, with the 6 x 8 ft. used in the outside lane to provide a 2 ft. shoulder to help keep traffic off the edge of the slab and help prevent an edge drop off for safety. In the areas where the asphalt surface reflects excess deterioration, as an alternative, a thin gap-graded rubberized hot mix asphalt (RHMA-G) overlay is placed before the placement of the concrete overlay. This approach has shown good bonding between the concrete overlay and the underlying layers during the HVS testing but has not been validated elsewhere. Thin BCOA joints are not always sealed because of the high cost *(77)*. All these activities were considered in modeling the construction stage, except for sawing.

A UCPRC study on thin BCOA for Caltrans recently concluded that a well-designed, well-built 6 x 6 ft. thin bonded concrete overlay placed on top of an asphalt base that is in fair to good condition could potentially provide 20 years of good serviceability on most of California's non-interstate roadways *(77)*. LCCA and LCA studies are required for such rehabilitation alternatives to understand the economic and environmental benefits and disbenefits. This study is expected to help bridge this gap by presenting a methodology that can be applied to conduct the LCA of thin BCOA construction.

This study presents the development of the LCIs and some initial impact analysis of the BCOA technology as it has been piloted in California. As a sensitivity analysis, this study compares several alternative BCOA cross sections with the pilot project BCOA design and compares the concrete mix used in the pilot project with alternative mixes for faster and slower strength gain. The study does not include comparisons with other technologies because any comparison will be highly context-driven and cannot be comprehensively evaluated yet. Instead, the intent is to place these new inventories in the environmental LCA of pavements software program, *eLCAP*, which will allow users to evaluate their own scenarios *(42)*.

4.2 Goal and Scope of Bonded Concrete Overlay of Asphalt LCI Study

The goal of this study is to quantify the potential environmental impacts due to the material and construction stages of thin BCOA. The scope of the study is from cradle-to-laid, which includes the material and construction stages along with the transportation of the materials. The use and end-of-life stages were not included in the study's scope. The functional unit defined for this study is the construction of 1 lane-km of the pavement surface. A standalone LCA approach has been adopted in this study which focuses on a thin BCOA pilot project built in Woodland in 2018-2019. The two BCOA layers considered include a 0.5 ft. (150 mm) thick portland cement concrete (PCC) overlay on top of a new rubberized hot mix asphalt (RHMA) pavement and a 0.5 ft. (150 mm) thick PCC overlay on top of a milled old asphalt, configurations referred to as 2B and 2A, respectively, in Table 4.1. Figure 4.1 shows the cross section of the pavement designed and laid in the Woodland pilot project.

Table 4.1: Different BCOA Alternative Structures and Materials Considered in This Study

Case	Material	Concrete Thickness in mm (in.)	RHMA Thickness in mm (in.)
1-A	HVS PCC Type III (4-hr OT) + Tie Bar	150 (6)	30 (1.18)
1-B	HVS PCC Type III (4-hr OT) + Tie Bar + RHMA	150 (6)	30 (1.18)
2-A	Woodland PCC Type II (24-hr OT) + Tie Bar	150 (6)	30 (1.18)
2-B	Woodland PCC Type II (24-hr OT) + Tie Bar + RHMA	150 (6)	30 (1.18)
3-A	Caltrans Normal Strength PCC Type II (10-d OT) + Tie Bar	150 (6)	30 (1.18)
3-B	Caltrans Normal Strength PCC Type II (10-d OT) + Tie Bar + RHMA	150 (6)	30 (1.18)
4-A	HVS PCC Type III (4-hr OT) + Tie Bar	125 (5)	30 (1.18)
4-B	HVS PCC Type III (4-hr OT) + Tie Bar + RHMA	125 (5)	30 (1.18)
5-A	Woodland PCC Type II (24-hr OT) + Tie Bar	125 (5)	30 (1.18)
5-B	Woodland PCC Type II (24-hr OT) + Tie Bar + RHMA	125 (5)	30 (1.18)
6-A	Caltrans Normal Strength PCC Type II (10-d OT) + Tie Bar	125 (5)	30 (1.18)
6-B	Caltrans Normal Strength PCC Type II (10-d OT) + Tie Bar + RHMA	125 (5)	30 (1.18)

Note: OT = opening time to traffic for the concrete.

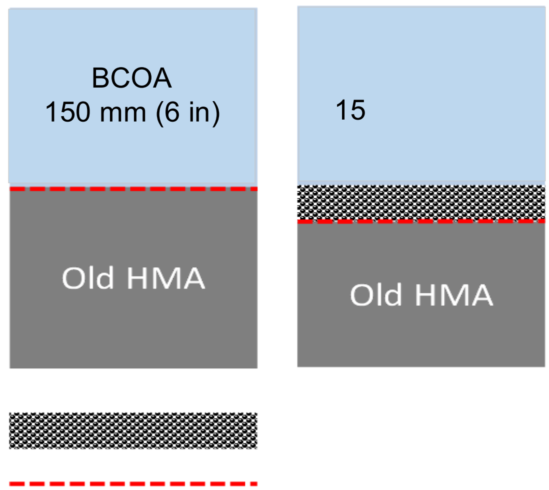


Figure 4.1: Thin BCOA pavement cross section of the Woodland pilot project.

The material stage includes the extraction of raw materials from the ground, transportation to the processing plants, and plant operations. Transportation of the materials from the plant to the site was also included. Additionally, a sensitivity analysis was performed to evaluate several other BCOA design alternatives. This analysis was scoped at cradle-to-gate and performed by comparing 10 different BCOA design alternatives in addition to the two Woodland pilot project alternatives described previously (2A and 2B). Table 4.1 shows the 12 different BCOA design alternatives that were compared in the sensitivity analysis. Each design alternative consists of a PCC overlay on top of either a new RHMA overlay or the milled asphalt pavement. Three concrete mix designs that are used in the BCOA alternatives include the following: (1) a rapid strength concrete, 4-hour opening time to traffic (OT), made with PC Type III (1A and 1B in Table 4.1), (2) PCC Type II/V designed to be open to traffic in 24 hours constructed in Woodland (2A and 2B in Table 4.1), and (3) a normal strength concrete, 10-day design OT, made with PC Type II/V (3A and 3B in Table 4.1). The first mix was used to build one of the sections that were tested with the HVS for a former research project on thin BCOA *(77)*. The third mix presents the typical concrete mix used in Caltrans standard jointed plain concrete pavements. For each of the three BCOA design alternatives, an additional three designs with a thickness of 0.4 ft. (125mm) were also considered in the sensitivity analysis (4A to 6B in Table 4.1).

4.3 Life Cycle Inventory and Life Cycle Impact Assessment

The UCPRC has developed LCA models for different life cycle stages of a pavement using California-specific data and produced an LCI database for Caltrans *(2)*, which is being used in the *eLCAP* software *(3)*. This database is mainly used to develop LCIs and LCIAs of BCOA pavements. All the PCC mix designs, including PCC Type III used for the HVS test sections with 4 hours OT, PCC Type II/V used for the Woodland project with 24 hours OT, and the normal strength PCC Type II/V used by Caltrans with the 10 days OT as well as RHMA mix design used in the pavement layers of the project, are shown in Table 4.2.

The PCCs with 4 hours and 24 hours OT were designed to provide 450 psi (3 MPa) flexural strength (the Caltrans requirement for opening the lane to traffic) after 24 hours, while the PCC with 10 days OT was designed to provide 650 psi (4.5 MPa) flexural strength at 10 days. The 2017 electricity grid mix for California that was used to calculate the impacts of materials and construction for this case study is shown in Table 4.3.

Table 4.2: Portland Cement Concrete and Rubberized Hot Mix Asphalt Mix Designs and Number of Tie Bars in Bonded Concrete Overlay of Asphalt Layers

HVS PCC Mix Design Type III (4-hour opening time [OT][a])			Woodland PCC Type II/V Mix Design (24-hour OT)			Normal Strength PCC Type II/V Mix design (10-day OT)			RHMA Mix Design	
Material	**Mass per Volume (lb./yd^3)**	**% by mass**	**Material**	**Mass per Volume (lb./yd^3)**	**% by mass**	**Material**	**Mass per Volume (lb./yd^3)**	**% by mass**	**Material**	**% by mass**
Accelerator	37. 436	0.89	Accelerator	0.00	0.00	Accelerator	76	1.62	Crushed	92.50
Flyash	0.00	0.00	Flyash	101	2.55	Flyash	704.153	15.00	Natural	0
Crushed Aggregate	1787	31.86	Crushed Aggregate	1200	30.34	Crushed Aggregate	1350	28.76	Bitumen	6.00
Natural Aggregate	1348	42.23	Natural Aggregate	1787	45.18	Natural Aggregate	1875	39.94	Extender oil	0.15
Type III Portland Cement	799	18.88	Type II/V Portland Cement	574	14.51	Type II/V Portland Cement	429	9.14	Crumb Rubber Modifier (CRM)	1.35
Retarder	4	0.095	Retarder	0.897	0.023	Retarder	0.2	0.004	Polymer	0
Water Reducing Admixture	6.25	0.15	Water Reducing Admixture	1.614	0.041	Water Reducing Admixture	2	0.040	RAP	0
Water	250	5.91	Water	291	7.36	Water	258	5.50	—	—

[a] OT = opening time to traffic for the concrete.

Notes: Number of tie bars per slab (slabs are 6 ft. long): 2; number of tie bars per 1 km: 1,094.

Table 4.3: Energy Input for 1 kg of Portland Cement Concrete and Rubberized Hot Mix Asphalt

Energy	PCC	RHMA
Electricity	0.00618 MJ	0.0076319 MJ
Natural Gas	0.000122 m^3	0.0103261 m^3
Diesel	2.54E-007 m^3	—

Source: Lea et al. (2022) *(3)*; Saboori et al. (2022) *(2)*.

For the material production stage, the PCC and RHMA mix designs and the number of tie bars in BCOA layers are shown in Table 4.4 and the environmental impacts of BCOA during the material stage are shown in Table 4.5. For the transportation and construction stages, Table 4.6 shows the transportation impacts for a functional unit of 1,000 kg-km of materials being transported. Table 4.7 and Table 4.8 present the transportation information and the impacts from the transportation of materials, respectively, for PCC Type II/V with 24 hours OT used in the Woodland project.

Table 4.4: Material Stage Impacts for the Functional Unit of 1 kg of Materials

Material	Unit	GW (kg CO2e)	POCP (kg O_3e)	PM2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	PED-FS (MJ)
HVS PCC Type III (4-hr OT)	1kg	1.78E-01	1.50E-02	9.72E-05	2.08E-01	1.08E+00	0.000E+00
Woodland PCC Type II/V (24-hr OT)	1kg	1.296E-01	1.120E-02	8.502E-05	1.418E-01	8.652E-01	0.000E+00
Caltrans Normal Strength PCC Type II/V (10-d OT)	1kg	1.169E-01	8.228E-03	1.183E-04	1.076E-01	8.150E-01	0.000E+00
RHMA	1kg	5.628E-02	5.977E-03	4.036E-05	9.329E-02	3.408E+00	6.487E+00
Tie Bar	Each	3.343E+00	1.667E-01	1.616E-03	1.443E+00	4.147E+01	0.000E+00

Note: OT = opening time to traffic for the concrete.

Table 4.5: Material Stage Impacts for Different Bonded Concrete Overlay of Asphalt Alternatives for 1 ln-km

Case	Material	Concrete Thickness mm (in.)	RHMA Thickness mm (in.)	GW (kg CO_2e)	POCP (kg O_3e)	PM2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	PED-FS (MJ)
1-A	HVS PCC Type III (4-hr OT) + Tie Bar	150 (6)	30 (1.18)	2.41E+05	2.02E+04	1.31E+02	2.79E+05	1.48E+06	0.00E+00
1-B	HVS PCC Type III (4-hr OT) + Tie Bar + RHMA	150 (6)	30 (1.18)	2.56E+05	2.18E+04	1.42E+02	3.03E+05	2.39E+06	1.73E+06
2-A	Woodland PCC Type II (24-hr OT) + Tie Bar	150 (6)	30 (1.18)	1.763E+05	1.510E+04	1.150E+02	1.904E+05	1.198E+06	0.00E+00
2-B	Woodland PCC Type II (24-hr OT) + Tie Bar + RHMA	150 (6)	30 (1.18)	1.913E+05	1.669E+04	1.258E+02	2.153E+05	2.106E+06	1.73E+06
3-A	Caltrans Normal Strength PCC Type II (10-d OT) + Tie Bar	150 (6)	30 (1.18)	1.594E+05	1.114E+04	1.593E+02	1.449E+05	1.131E+06	0.00E+00
3-B	Caltrans Normal Strength PCC Type II (10-d OT) + Tie Bar + RHMA	150 (6)	30 (1.18)	1.744E+05	1.273E+04	1.701E+02	1.697E+05	2.039E+06	1.73E+06
4-A	HVS PCC Type III (4-hr OT) + Tie Bar	125 (5)	30 (1.18)	2.01E+05	1.68E+04	1.10E+02	2.32E+05	1.24E+06	0.00E+00
4-B	HVS PCC Type III (4-hr OT) + Tie Bar + RHMA	125 (5)	30 (1.18)	2.16E+05	1.84E+04	1.20E+02	2.57E+05	2.15E+06	1.73E+06
5-A	Woodland PCC Type II (24-hr OT) + Tie Bar	125 (5)	30 (1.18)	1.475E+05	1.261E+04	9.614E+01	1.590E+05	1.006E+06	0.00E+00
5-B	Woodland PCC Type II (24-hr OT) + Tie Bar + RHMA	125 (5)	30 (1.18)	1.625E+05	1.420E+04	1.069E+02	1.838E+05	1.914E+06	1.73E+06
6-A	Caltrans Normal Strength PCC Type II (10-d OT) + Tie Bar	125 (5)	30 (1.18)	1.334E+05	9.316E+03	1.331E+02	1.210E+05	9.500E+05	0.00E+00
6-B	Caltrans Normal Strength PCC Type II (10-d OT) + Tie Bar + RHMA	125 (5)	30 (1.18)	1.484E+05	1.091E+04	1.438E+02	1.458E+05	1.858E+06	1.73E+06

Note: OT = opening time to traffic for the concrete.

Table 4.6: Truck Transportation Impacts for a Functional Unit of 1,000 kg-km[a]

Transport Type	Functional Unit	GW (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED-NR (MJ)
Heavy Truck	1000 kg-km	7.798E-02	1.243E-02	2.492E-05	1.116E+00

[a] Assumed to be a heavy truck.

Table 4.7: Transportation Information Assumptions

Material	Transportation	Material in 1 lane-km (kg)	Number of Trips	1000 kg-km (1 lane-km)
PCC Type II	1-way 40 km (25 mi.) from plan to the construction field	1,332,000	56	53,280
Cement	1-way 692km (430 mi.) from cement plant to the mixing plant	193,292	9	133,78
RHMA	1-way 56km (35 mi.) from plan to the construction field	266,400	12	14,918
Bitumen	1-way 435km (270 mi.) from refinery to the plant	15,974	1	6,949
Crushed Agg.	1-way 40 km (25 mi.) from quarry to the plant	246,420	11	9,857

Table 4.8: Transport Impact

Material	GW (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED-NR (MJ)
Woodland PCC Type II	4.354E+04	6.941E+03	1.391E+01	6.231E+05
RHMA	7.385E+03	1.177E+03	2.360E+00	1.057E+05
Total Transport Impact	5.092E+04	8.119E+03	1.627E+01	7.288E+05

Table 4.9 shows the fuel LCIAs and PEDs that were used to prepare impact assessments for the material and construction stages. The impact of construction activities for each pavement layer is calculated by estimating total fuel consumption for 1 ln-km of the road considering the equipment used, engine horsepower and fuel efficiency, and number of passes needed. The construction information is shown in Table 4.10. Table 4.11 shows the impact results due to the construction stage for PCC Type II/V with 24 hours OT used in the Woodland project.

Table 4.9: Impacts of Non-Electricity Energy Source

Diesel Burned (1 gallon)	GW (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED-NR (MJ)
	1.194E+01	5.273E+00	9.369E-03	1.645E+02

Table 4.10: Construction Information

Layer	Equipment/ Activity	Engine Power in kW (hp)	Hourly Fuel Use in m^3/hr (gal./hr)	Speed in km/h (ft./min)	Time for 1 Pass Over 1 lane-km (hr)	No. of Passes	Fuel Used in m^3 (gal.)	Total Fuel Used for 1 lane-km in m^3 (gal.)
Woodland PCC Type II	Milling for 25 mm (1 in)	522 (700)	0.076 (20)	0.183 (10)	5.47	1	0.41 (109.36)	0.49 (129.05)
	Sweeping (multiple times)	59.66 (80)	0.008 (2)	1.83 (100)	0.55	2	0.01 (2.19)	
	Wetting	59.66 (80)	0.008 (2)	1.83 (100)	0.55	1	0.004 (1.09)	
	Concrete Placement	67.11 (90)	0.011 (3)	0.183 (10)	5.47	1	0.06 (16.40)	
RHMA	Prime coat application	260.1 (350)	0.027 (7.2)	0.457 (25)	2.19	1	0.06 (16.40)	0.54 (143.15)
	RHMA placement	186.43 (250)	0.040 (10.6)	0.274 (15)	3.65	1	0.15 (39.62)	
	Rolling (vibratory)	111.86 (150)	0.031 (8.1)	0.457 (25)	2.19	2	0.13 (34.34)	
	Rolling (static)	111.86 (150)	0.031 (8.1)	0.457 (25)	2.19	3	0.2 (52.83)	

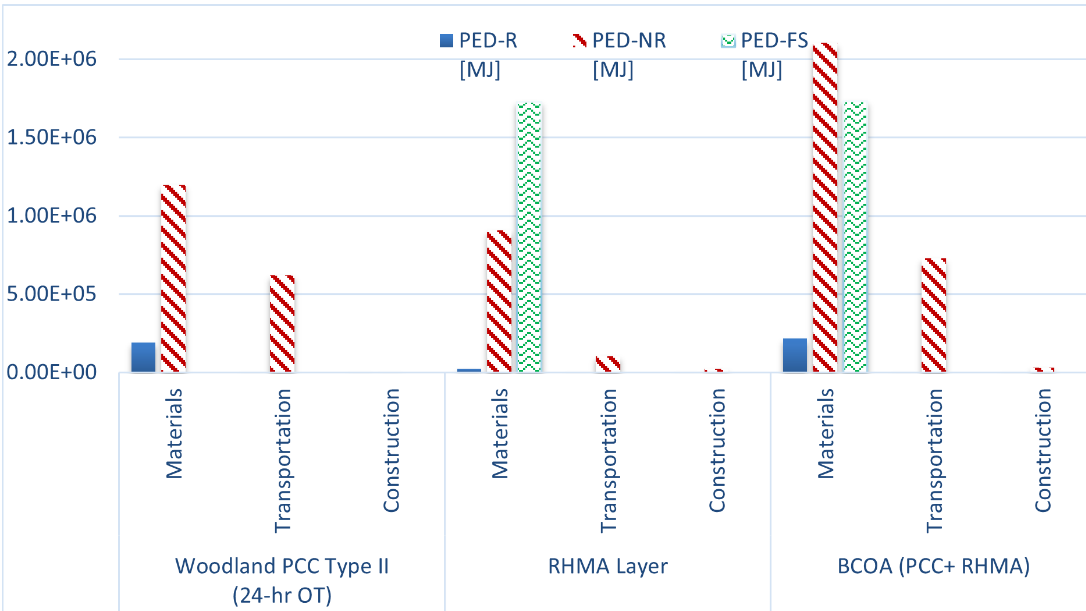
Table 4.11: Construction Impacts

Material	Activity	GW (kg CO2e)	POCP (kg O3e)	PM2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	PED-FS (MJ)
Woodland PCC Type II	Milling for 25mm (1 in.)	1.306E+03	8.304E+01	1.475E-01	0.000E+00	2.591E+03	0.000E+00
	Sweeping (multiple times)	2.612E+01	1.153E+01	2.049E-02	0.000E+00	3.599E+02	0.000E+00
	Wetting	1.306E+01	5.767E+00	1.025E-02	0.000E+00	1.799E+02	0.000E+00
	Concrete placement	1.959E+02	8.650E+01	1.537E-01	0.000E+00	2.699E+03	0.000E+00
	Total	1.541E+03	1.868E+02	3.320E-01	0.000E+00	5.830E+03	0.000E+00
RHMA	Prime coat application	1.883E+02	8.315E+01	1.477E-01	0.000E+00	2.594E+03	0.000E+00
	RHMA placement	4.620E+02	2.040E+02	3.625E-01	0.000E+00	6.366E+03	0.000E+00
	Rolling (vibratory)	4.236E+02	1.871E+02	3.324E-01	0.000E+00	5.838E+03	0.000E+00
	Rolling (static)	6.355E+02	2.806E+02	4.986E-01	0.000E+00	8.756E+03	0.000E+00
	Total	1.709E+03	7.549E+02	1.341E+00	0.000E+00	2.355E+04	0.000E+00
Total Construction Impact		3.250E+03	9.417E+02	1.673E+00	0.000E+00	2.938E+04	0.000E+00

4.4 Interpretation

Figure 4.2 to Figure 4.5 depict the impacts of the different stages of the life cycle for the Woodland PCC Type II/V with 0.5 ft. (150 mm) thickness and 24 hours OT, RHMA layer, and the whole BCOA. The material stage can be considered the hot spot due to high environmental impacts and high energy consumption compared with the transportation and construction stages (Table 4.12). Improvement of the material impacts while maintaining at least the same functionality (time to traffic opening, material properties related to durability) will likely result in the most significant improvement in environmental impacts and energy use.

The transportation stage is of secondary importance to the materials, meaning that methods of shortening the haul distance for aggregate or reusing aggregate sources would be an approach to reduce the transportation impacts. The assumed distances between the stone quarries to the asphalt and concrete plants and other hauling distances are included in the analysis, with longer distances leading to higher environmental impacts.



Notes: PED = primary energy demand, R = renewable, NR = nonrenewable, FS = feedstock.

Figure 4.2: Consumed energy per life cycle stage per pavement layer (Woodland case study).

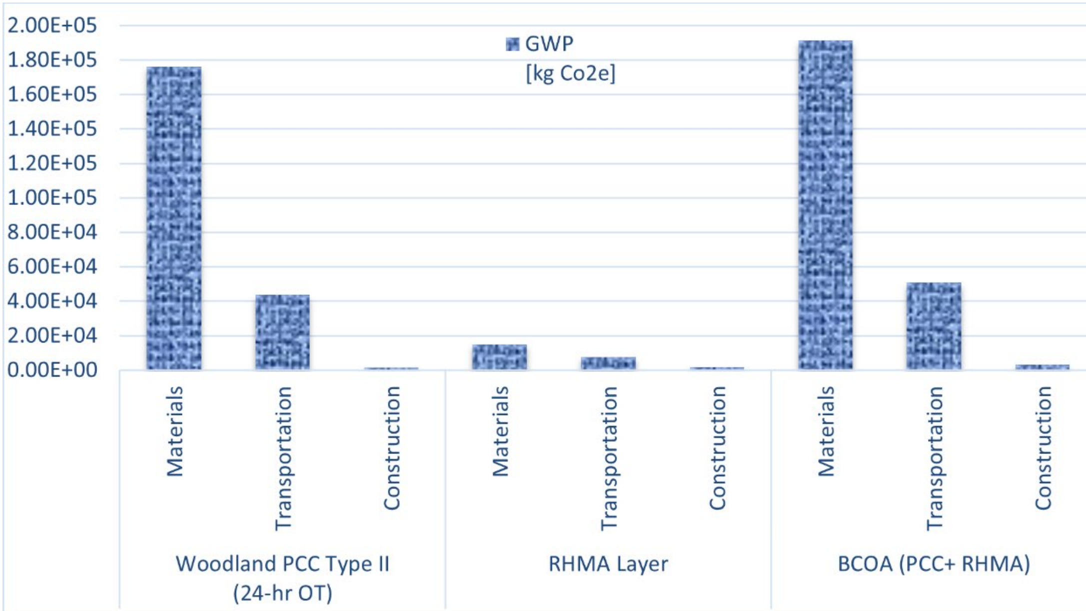


Figure 4.3: Global warming impact results per life cycle stage per pavement layer (Woodland case study).

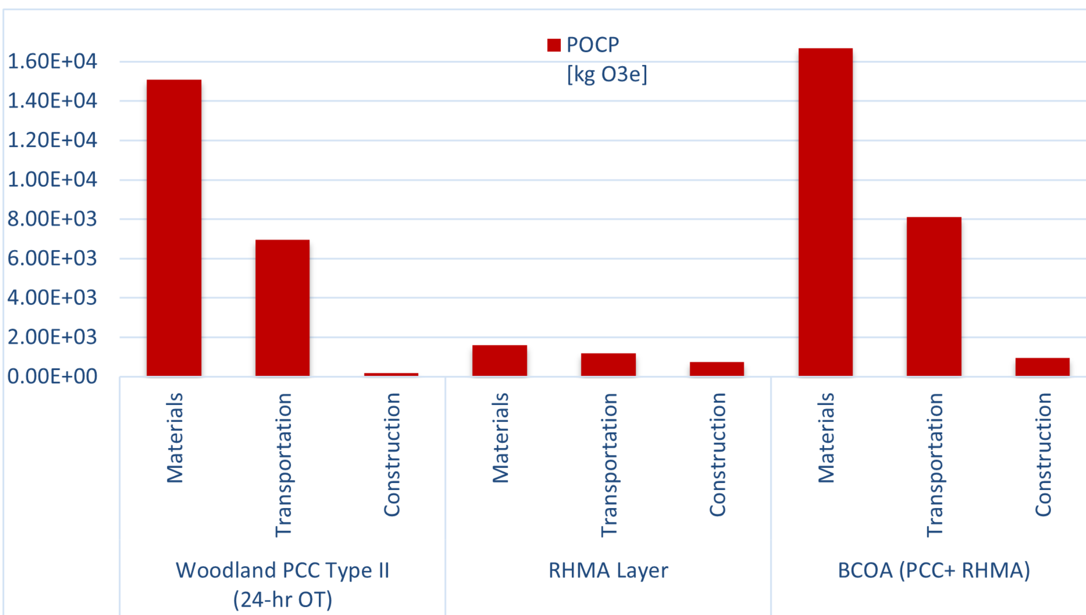


Figure 4.4: Smog formation results per life cycle stage per pavement layer (Woodland case study).

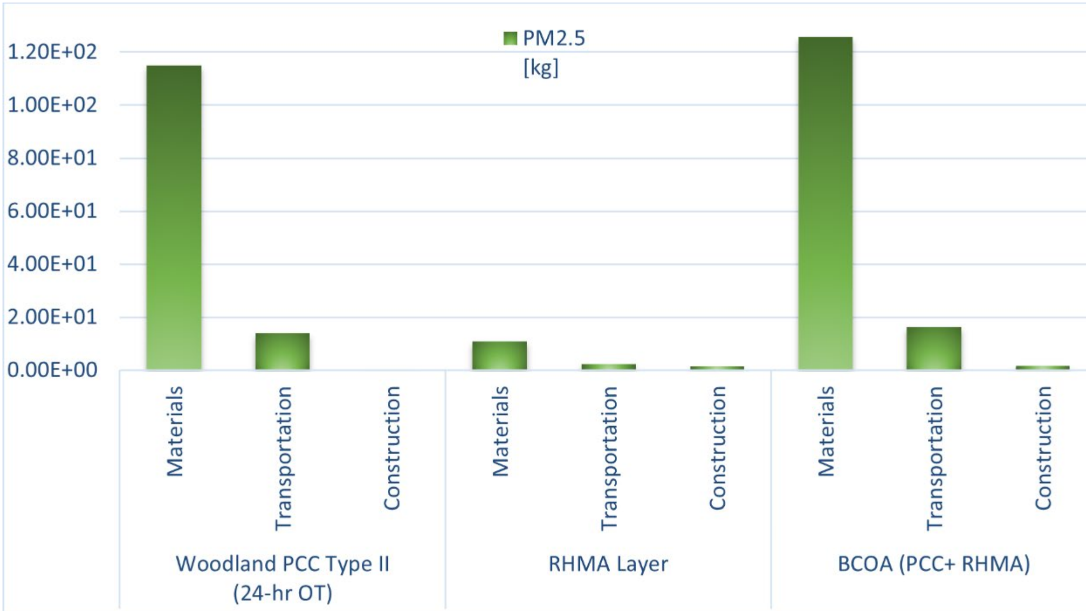


Figure 4.5: Human health particulate effect results per life cycle stage per pavement layer (Woodland case study).

Table 4.12: Final Impacts of Bonded Concrete Overlay of Asphalt in Different Stages (Woodland Case Study)

Layer	Life Cycle Stage	Percent of Total					
		GW (kg CO_2e)	POCP (kg O_3e)	PM2.5 (kg)	PED-R (MJ)	PED-NR (MJ)	PED-FS (MJ)
Total for the Functional Unit[a]		2.45E+05	2.58E+04	1.44E+02	2.15E+05	2.86E+06	1.73E+06
Percent of Total		**(%)**	**(%)**	**(%)**	**(%)**	**(%)**	**(%)**
Woodland PCC Type II (24-hr OT)	Materials	71.8	58.6	80.0	88.5	41.8	0.0
	Transportation	17.7	27.0	9.7	0.0	21.8	0.0
	Construction	0.6	0.7	0.2	0.0	0.2	0.0
	Total	**90.2**	**86.3**	**89.9**	**88.5**	**63.8**	**0.0**
RHMA	Materials	6.1	6.2	7.5	11.6	31.7	100.0
	Transportation	3.0	4.6	1.6	0.0	3.7	0.0
	Construction	0.7	2.9	0.9	0.0	0.8	0.0
	Total	**9.8**	**13.7**	**10.1**	**11.6**	**36.2**	**100.0**
BCOA (PCC+ RHMA)	Materials	77.9	64.8	87.5	100.0	73.5	100.0
	Transportation	20.7	31.5	11.3	0.0	25.5	0.0
	Construction	1.3	3.7	1.2	0.0	1.0	0.0
	Total	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

[a] BCOA = PCC + RHMA.

Notes: PED-R = primary energy demand, R = renewable, NR = nonrenewable, FS = feedstock.

4.4.1 *Sensitivity Analysis*

Figure 4.6 to Figure 4.9 show that the thickness of the surface layer is an important factor affecting environmental impacts and energy consumption in the material stage. The second influential criterion is the additional RHMA layer under the surface rigid layer, resulting in significant increases in the environmental impacts and primary energy demand. The results show an increase of 8% to 13% in GW, POCP, PM2.5, and PED-R. The sharp rise in PED-NR (75%) can also be seen in Figure 4.9 because of the feedstock energy in the asphalt mix.

The difference in the concrete mix designs is another notable factor that causes emissions and energy consumption changes. HVS PCC Type III mix with 4 hours OT has the highest environmental impacts and energy consumption, followed by PCC Type II/V mix designs. It should be noted that the higher amount of cement compared to PC Type II/V lead to higher environmental impacts and to a much lesser extent the finer grinding of PC Type III.

Caltrans normal strength PCC Type II/V with 10-day OT has a higher percentage of cement compared to Woodland PCC Type II/V with 24 hours OT (14% versus 9%, respectively). Based on Figure 4.6 to Figure 4.9, Caltrans normal strength mix has a slightly lower impact in terms of GW, POCP, and energy consumption compared to the Woodland mix. This study demonstrates the use of LCA to quantify and evaluate the environmental impacts of alternative materials, construction, and designs for a pavement structure. This analysis should consider the relative performance of the different designs if it is expected to be different, which was not the assumed expectation of this study.

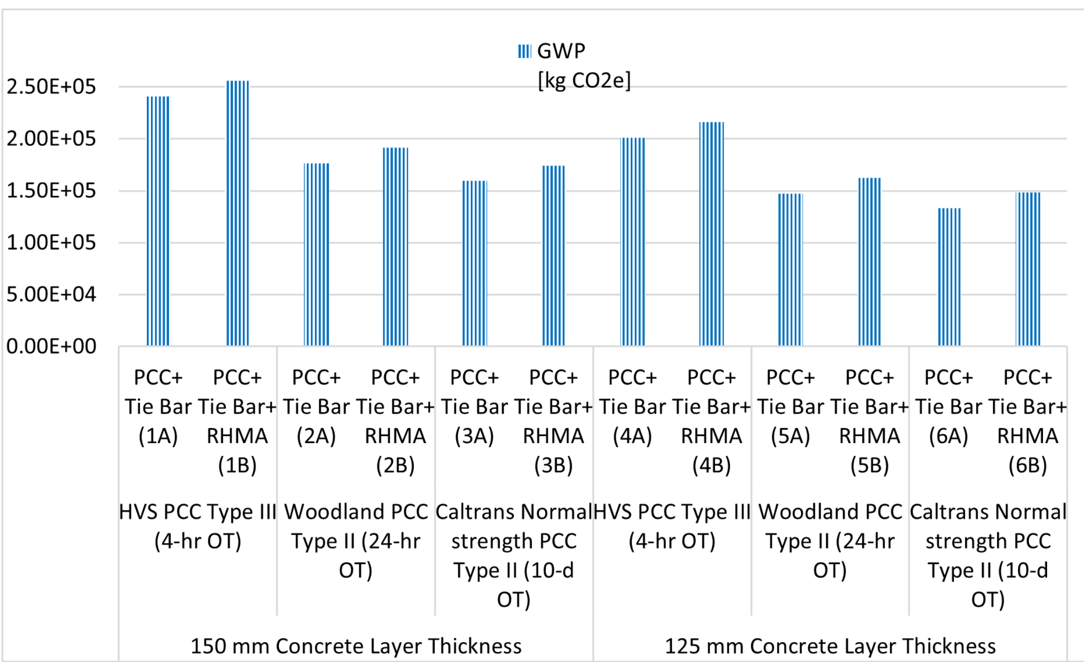


Figure 4.6: Global warming impact results in material stage for different alternatives.

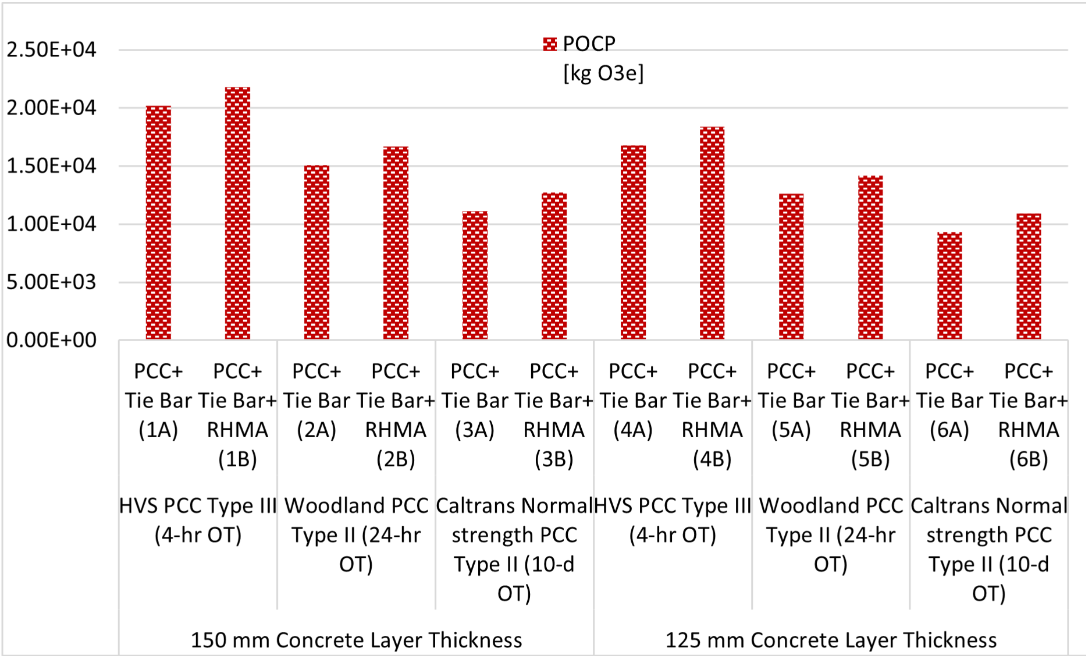


Figure 4.7: Smog formation impact results in material stage for different alternatives.

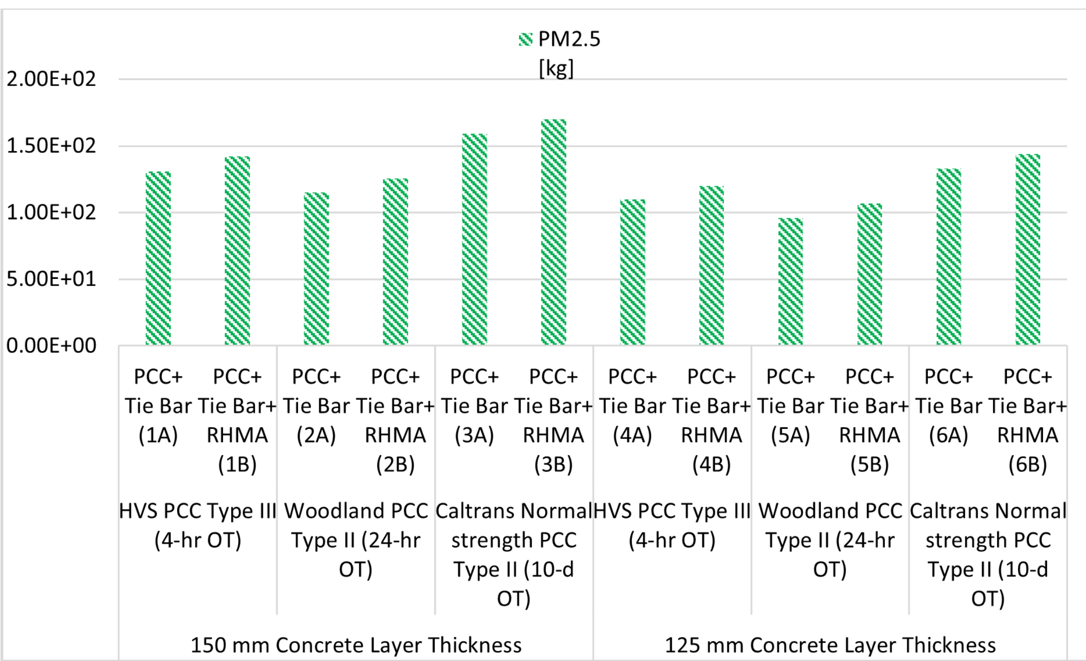
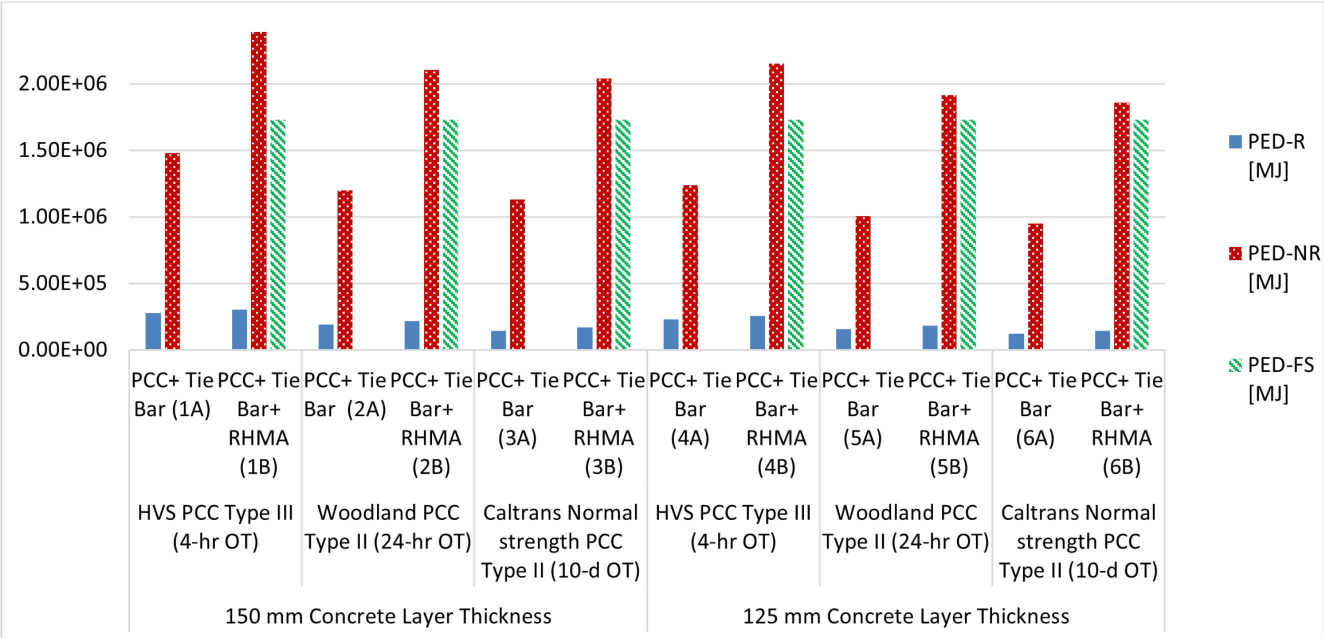


Figure 4.8: Human health particulate effect results in material stage for different alternatives.



Notes: PED = primary energy demand, R = renewable, NR = nonrenewable, FS = feedstock.

Figure 4.9: Energy consumptions result in the material stage for different alternatives.

5 SUMMARY AND RECOMMENDATIONS FOR IMPLEMENTATION AND FUTURE WORK

5.1 Summary of Research Findings

Environmental LCA quantifies the energy, resource use, and emissions to air, water, and land for a product or a system. A reliable LCI database to quantify the environmental consequences of decisions in transportation infrastructure is always a gap and always needs to be updated. The main goal of the three studies presented in this report was to contribute to an up-to-date and regionally representative LCI database for transportation infrastructure. Literature reviews, surveying of local contractors and their practices, review of Caltrans data and interviews, and calculations using databases such as *GaBi* and *EcoInvent* were used to collect the data. The existing UCPRC LCI, which is a comprehensive pavement dataset developed and calibrated for California, was also used and included a comprehensive list of materials, sources of energy, transport modes, and pavement surface treatments. The three developed LCIs and the three case studies that are covered in this report are the following:

(1) Asphalt binder, regionalized to California using the AI 2019 North American (USA and Canada) LCI and information regarding crude oil sources refined in California
(2) Warm mix asphalt (WMA) technologies, estimated using proxy data for the chemical components and their quantities taken from SDSs, because of the lack of other information such as EPDs regarding WMAAs
(3) Bonded concrete overlay of asphalt (BCOA) (now called concrete overlays of asphalt [COA]), a new type of pavement for California

In each of these cases the best available information at the time of development of this report (2019 to 2022) were used. Sensitivity analyses for important variables were performed identifying how changes in those variables affect the environmental and resource use impact indicators.

The primary finding from the asphalt binder study is that asphalt binder produced using typical crude oil slates used in California refineries result in a significantly lower GW and other impacts than the crude oil slate used for the 2019 AI continental average LCA. This regionalized asphalt binder LCI can be used in California pavement LCAs while remaining cognizant of the assumptions and limitations of this study. The primary finding from the warm mix asphalt study is that the different WMAAs can have important differences in the impacts they cause in the asphalt mix impact indicators and that those impacts are driven by the combination of the chemistry of the WMAA and the range of mixing temperatures that can be used when the WMAA is added. The range of temperatures includes no reduction in temperature when the WMAA is used as a compaction aid to extend the time available for compaction and transport, with the maximum reduction possible with the WMAA resulting in less natural gas use and the same compaction time and transport distance that occurs for HMA. The primary finding from the BCOA sensitivity analysis is that the concrete mix designs developed for different time to opening of the concrete to traffic have a significant effect on environmental impact indicators, particularly GW, as does the design choice of including an RHMA base or only milling the existing asphalt surface.

5.2 Recommendations for Future Work

The LCI database and models developed in these studies need to be reviewed and updated peroidically due to the continuous improvements in material production technologies, construction practices, and energy sources used for electricity generation, running plants, and data collection improvement, and new materials and elements for which data inventories do not yet exist in California such as roads, bridges, rails, and culverts. An important improvement to help improve the quality of the data is to collect more primary data (directly measured) instead of secondary data (collected from other sources, estimated or assumed) from local material production plants and contractors. These studies were completed between 2019 and 2022, and while the results fill gaps in information that still exist, some of this work is already in need of updating.

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