Submission for
Verification of Eco-Efficiency Analysis Under
NSF Protocol P352, Part B

Cape Seal Eco-Efficiency Analysis
Final Report – January 2018

Submitted by:

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1. Purpose and Intent of this Guidance Document

1.1. The purpose of this submission is to provide a written report of the methods and findings of BASF Corporation's Cape Seal Eco-Efficiency Analysis, with the intent of having it verified under the requirements of NSF Protocol P352, Part B: Verification of Eco-Efficiency Analysis Studies.

1.2. The Cape Seal Eco-Efficiency Analysis was performed by BASF according to the methodology validated by NSF International under the requirements of Protocol P352. More information on BASF's methodology and the NSF validation can be obtained at http://www.nsf.org/services/by-industry/sustainability-environment/product-transparency-reporting.

2. Content of this Guidance Document

2.1. This submission outlines the methodology, study goals, design criteria, target audience, customer benefits (CB), process alternatives, system boundaries, and scenario analyses for the Cape Seal EEA study, which was conducted in accordance with BASF Corporation's EEA (BASF EEA) methodology. This submission will provide the basis of the eco-analysis preparation and documentation of the study results and conclusions.

2.2. As required under NSF P352 Part B, along with this document, BASF is submitting the final computerized model programmed in Microsoft® Excel. The computerized model, together with this document, will aid in the final review and ensure that the data and critical review findings have been satisfactorily addressed.

3. BASF's EEA Methodology

3.1. Overview:

The process for performing a BASF EEA has been previously published [Saling et al 2002][1] [Shonnard et al 2003][2] and it involves measuring the life cycle environmental impacts and life cycle costs for product alternatives for a defined level of output. In other words, a BASF EEA evaluates both the economic and environmental impacts that products and processes have over the course of their life cycle. The methodology was created by BASF, initially in partnership with an external consultant, and has since been further developed. BASF EEA follows the ISO 14040 [ISO 2006][3] and 14044 [ISO 2006][3] standards for the environmental assessment evaluation and ISO 14045 [ISO 2012][4] for Eco-Efficiency assessment. In addition to these standards, BASF EEA also includes additional enhancements that allow for the expedient review and decision-making at all business levels. The EEA evaluates the life cycle costs associated with the product or process by calculating the total costs related to, at a minimum, materials, labor, manufacturing, waste disposal, and energy. BASF EEA also evaluates the most relevant environmental impact categories and sufficient environmental impact as determined by our "Relevance Check".

3.2. Preconditions:

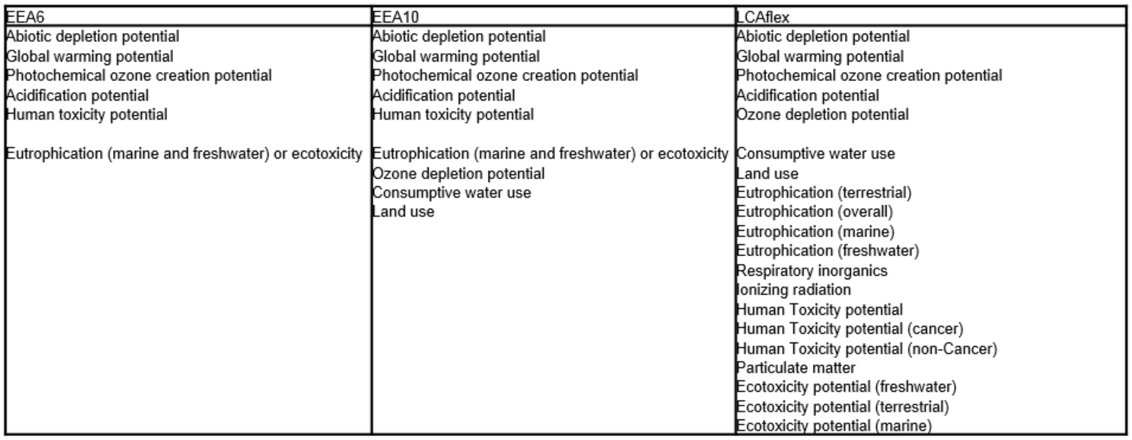
The eco-efficiency methodology utilized in this study has been validated to the requirements of Part A of NSF P352 Validation and Verification of Eco-Efficiency Analyses. In addition, all alternatives that are being evaluated are being compared against a common Functional Unit (FU) or Customer Benefit (CB). This allows for an objective comparison between the various alternatives. The scoping and definition of the customer benefit are aligned with the goals and objectives of the study. Data gathering and constructing the system boundaries are consistent with the CB and consider both the environmental and economic impacts of each alternative over their life cycle or a defined specific time period in order to achieve the specified CB. An overview of the scope of the environmental and economic assessment carried out is defined in this report. Cut off rules applied to data collection and for material and process evaluation were consistent with our approach defined in Section 6.5 (De Minimis Levels) of our Part A Methodology submittal.

3.2.1. Environmental Burden Metrics:

In order to address varying needs according to industry and geographic region three separate but similar Eco-Efficiency Assessment tools have been developed. The EEA6 and EEA10 have defined environmental impact categories as well as set impact assessment methods. The EEA6 includes six environmental impact categories expected to adequately cover environmental impact for most chemical products and processes. The EEA10 includes additional environmental aspects that become significant in, for example, assessments including bio based materials or agricultural products. The LCAflex is, in principle, completely flexible both in terms of environmental impact categories as well as impact assessment methods (see Table 1).

The BASF Relevance Check ensures that each Eco-Efficiency Assessment (a) covers sufficient environmental impact and (b) includes the relevant environmental impact categories. For the Relevance Check the environmental impact of the EEA10 is defined as 100%. The total environmental impact was chosen to be based on the EEA10 impact categories because these categories form the common basis of the widely-used impact assessment models such as CML, TRACI and ReCiPe. In the first step, the impact categories of an EEA10 are normalized with European annual statistics from the EU PEF methodology (Benini 2014) and from Pfister 2009 for water assessment. For BASF's method for assessing human toxicity a normalization value was derived. The normalized results for the 10 impact categories are subsequently summed up to give the total unweighted environmental impact. In the next step the normalized dimensionless values are expressed as a percentage of the total unweighted environmental impact. The impact categories with the largest contributions for each alternative are then included in the analysis; there is no minimum number of impact categories that should be included but at least 80% of the total impact of each alternative needs be covered. Finally, an impact category is included in the environmental assessment if it is relevant for at least one alternative.

The Relevance Check ensures that for each EEA6 and LCAflex sufficient environmental impact is covered and the most relevant impact categories are included. If this is not the case, then an EEA10 assessment is required.



EEA6	EEA10	LCAflex
Abiotic depletion potential	Abiotic depletion potential	Abiotic depletion potential
Global warming potential	Global warming potential	Global warming potential
Photochemical ozone creation potential	Photochemical ozone creation potential	Photochemical ozone creation potential
Acidification potential	Acidification potential	Acidification potential
Human toxicity potential	Human toxicity potential	Ozone depletion potential
Eutrophication (marine and freshwater) or ecotoxicity	Eutrophication (marine and freshwater) or ecotoxicity	Consumptive water use
	Ozone depletion potential	Land use
	Consumptive water use	Eutrophication (terrestrial)
	Land use	Eutrophication (overall)
		Eutrophication (marine)
		Eutrophication (freshwater)
		Respiratory inorganics
		Ionizing radiation
		Human Toxicity potential
		Human Toxicity potential (cancer)
		Human Toxicity potential (non-Cancer)
		Particulate matter
		Ecotoxicity potential (freshwater)
		Ecotoxicity potential (terrestrial)
		Ecotoxicity potential (marine)

Table 1. Environmental impact categories EEA6 and EEA10 (required) and LCAflex (optional)

3.2.2. Economic Metrics:

It is the intent of the BASF EEA methodology to assess the economics of products or processes over their life cycle and to determine an overall total cost of ownership for the defined customer benefit ($/CB). The approaches for calculating costs vary from study to study. When chemical products of manufacturing are being compared, the sale price paid by the customer is predominately used followed by any subsequent costs incurred by the product's use and disposal. When different production methods are compared, the relevant costs include the purchase and installation of capital equipment, depreciation, and operating costs are analyzed. The costs incurred are summed and combined in appropriate units (e.g. U.S. dollar or euro) without additional weighting of individual financial amounts. The BASF EEA methodology will incorporate:

- the real costs that occur in the process of creating and delivering the product to the consumer;
- the subsequent costs which may occur in the future (due to tax policy changes, for example) with appropriate consideration for the time value of money; and
- costs having ecological aspect, such as the costs involved to treat wastewater generated during the manufacturing process.

3.2.3. Work Flow:

Figure 1 presents a flow diagram for the preparation of a BASF EEA study. A BASF EEA study is worked out by following specific and defined ways of calculations: 1) after detailed discussions with the sponsors of the study, the functional unit, the alternatives to be evaluated and the system boundaries are discussed and agreed upon, 2) calculation of total cost from the customer/end-user viewpoint, 3) preparation of a specific life cycle analysis for all investigated products or processes according to the rules of ISO standards 14040 and 14044. For BASF the GaBi software with GaBi and BASF LCI inventories or other related data sources are used as a basis, in order to determine impacts on various environmental categories (see Table 1) over the whole life cycle 4) normalization of single results, 5) weighting of normalized life cycle analysis results with societal factors, 6) determination of overall environmental impact expressed in person time (hours, days, weeks etc.) based on environmental impact of a region, 7) determination of overall costs expressed in person time (hours, days, weeks etc.) based on the GDP of a region 8) creation of an eco-efficiency portfolio following the requirements of ISO 14045, 9) analyses of appropriateness, data quality, uncertainties, completeness and sensitivities 10) Interpretation of results, reporting.

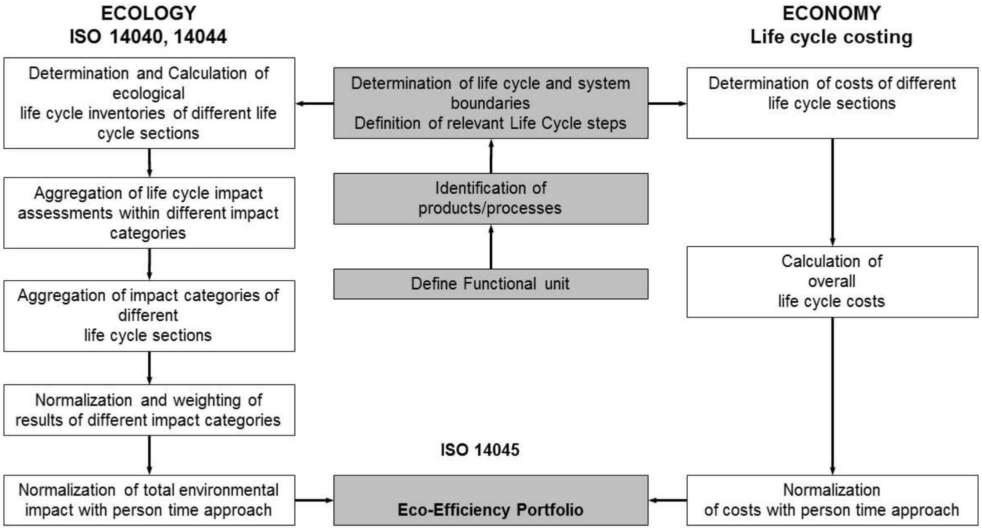


Figure 1. BASF flow diagram for the preparation of an EEA study

4. Study Goals, Context and Target Audience

4.1. Study Goals:

The specific goal defined for the Cape Seal Eco-Efficiency Analysis was to quantify the differences in life cycle environmental impacts and total life cycle costs of asphalt pavement preservation technologies in the United States.

The study specifically compares two different pavement preservation technologies for roads: (1) a hot mix technology: mill and fill (1 ½ -inch thin hot mix overlay) and (2) cape seal technologies. A cape seal is a chip seal covered with a slurry or micro-surfacing treatment. For this study, a micro surfacing treatment is assumed. The benefits from using a cape seal include a very smooth surface with an increased durability by sealing the subbase. Cape seals are typically applied to rural and urban highways and utilized when the roads are distressed and a simple micro surfacing treatment is not sufficient.

The study considered application of these technologies in two unique regions of the United States: California (West coast) and the Southeast. This allowed for the modeling of the regional variations in the chip seal technologies applied as the subbase of the cape seal. Specific data related to product formulations, durability and costs for each region were developed and provided by industry experts knowledgeable in the technologies. The hot mix overlay and micro surfacing technologies were consistent throughout all regions, thus average national data was used for key study input parameters such as expected durability, material compositions, costs etc.

It is well documented that the major factor influencing the lifetime environmental and cost impact of the road is how the profile and condition of the road influences the performance (fuel efficiency) of the traffic on the road[5]. The general findings of the Joint EAPA / Eurobitume Task Group on Fuel Efficiency[5] after a review of several relevant studies was that the differences in pavement types did not play a significant role in effecting the energy consumption of the traffic on the road. A more important factor influencing the fuel efficiency of the traffic was whether the pavements were in good condition with good surface characteristics (texture and roughness). Optimal maintenance and pavement preservation of the roads is therefore the key means to limit fuel consumption, greenhouse gas emissions and reduce the overall environmental impact of roads. Consistent with these findings, this study focused on two major maintenance technologies and assumed that these pavement preservation technologies were applied at a frequency and quality that the underlying performance and profile of the road remained the same for each alternative and thus no significant effect on the relative fuel efficiencies of the traffic was realized and thus did not need to be considered in the analysis as it was an identical impact for both alternatives.

Study results will be used as the basis to guide product development and manufacturing decisions that will result in more sustainable pavement preservation technologies as well as provide the necessary information to allow a clear comparison between the life cycle environmental and total cost impacts and benefits of specific pavement preservation technologies. It will also facilitate the clear communications of these results as well to key stakeholders in the transportation industry who are challenged with evaluating and making strategic decisions related to the environmental and total costs trade-offs associated with different pavement preservation technologies.

4.2. Design Criteria:

The context of this EEA study compared the environmental and cost impacts for pavement preservation technologies, specifically cape seal pavement preservation technologies and mill and fill (thin hot mix asphalt overlays) for distressed rural or urban roads on a regional level over the road's defined life cycle. The study was technology driven and required supplier and customer engagement. The study goals, target audience, and context for decision criteria used in this study are displayed in Figure 2.

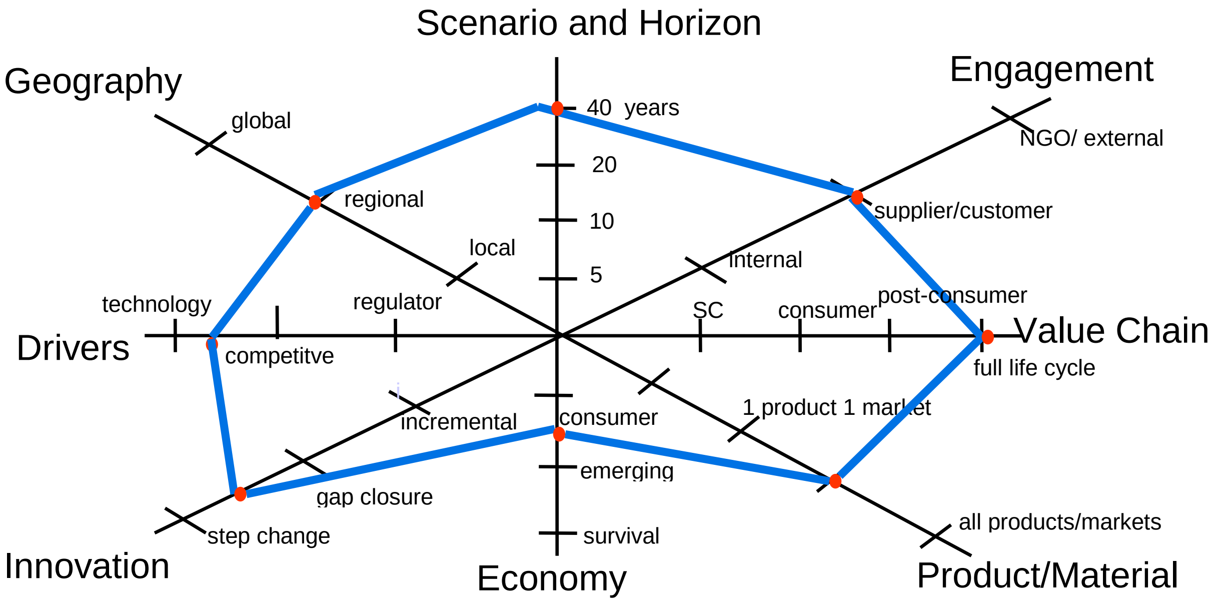


Figure 2: Study Goals, Target Audience and Context for Design Criteria for Cape Seal Eco-Efficiency Analysis

4.3. Target Audience:

The target audience for the study has been defined as state and federal government agencies (e.g. DOT, Department of Transportation), customers and trade associations. It is planned to communicate study results in marketing materials and at trade conferences.

4.4. Allocation Method:

Except where noted in section 6, Input Parameters and Assumptions, allocation procedures recommended by ISO 14040 were followed.

5. Customer Benefit, Alternatives, System Boundaries and Relevance Check

5.1. Customer Benefit:

The Federal Highway Administration (FHWA) defines the standard lane width for rural and urban roads as 12 feet resulting in a 24-foot travelled way (2 12-foot lanes) [32]. Thus, assessing the impacts for one lane (12 feet) will provide representative results for the entire road and study results could be easily extrapolated if impacts for the entire road were desired. The Customer Benefit (identified also as CB) applied to all alternatives for the base case analysis for this study is the preventive maintenance of a 1 mile stretch of a 12-foot lane of an urban or rural road to a similar profile and performance using best engineering practices over a 40-year period. With regards to the life span to consider, the FHWA's (Federal Highway Association) LCCA Policy statement[6] states that an analysis period of at least 35 years be considered for pavement projects. Though this was specific to life cycle cost analyses, the same philosophy should apply to an eco-efficiency analysis.

5.2. Alternatives:

The pavement preservation alternatives compared under this EEA study are unique to two regions of the country (1) California (West Coast) and (2) the Southeast. The alternatives defined for each region are as follows:

a. California (West coast):

1. Cape Seal Technology I (asphalt rubber (AR) chip seal + micro surfacing)
2. Cape Seal Technology II (SBR polymer modified emulsion chip seal + micro surfacing)
3. Hot Mix Asphalt (HMA) (1.5" thin hot mix overlay)

b. Southeast:

1. Cape Seal Technology I (ground tire rubber (GTR) chip seal + micro surfacing)
2. Cape Seal Technology II (SBR polymer modified emulsion chip seal + micro surfacing)
3. Hot Mix Asphalt (HMA) (1.5" thin hit mix overlay)

5.3. System Boundaries:

The system boundaries define the specific elements of the production, use, and disposal phases that are considered as part of the analysis. The system boundaries for the various alternatives evaluated in this study are shown in Figures 3 through 6. Sections identified in gray were excluded from the analysis as they represented identical impacts for both alternatives (e.g. fuel efficiency of traffic on the road).

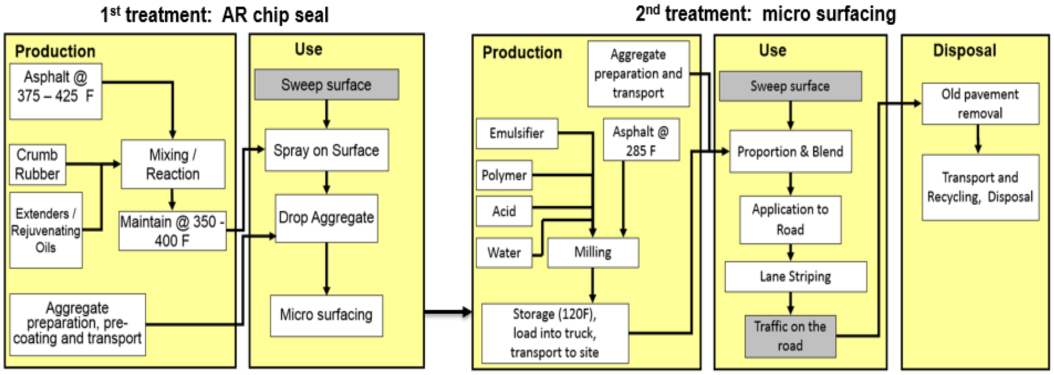


Figure 3. System diagram for generic life cycle of Cape Seal I (AR chip seal + micro surfacing) - California (West Coast)

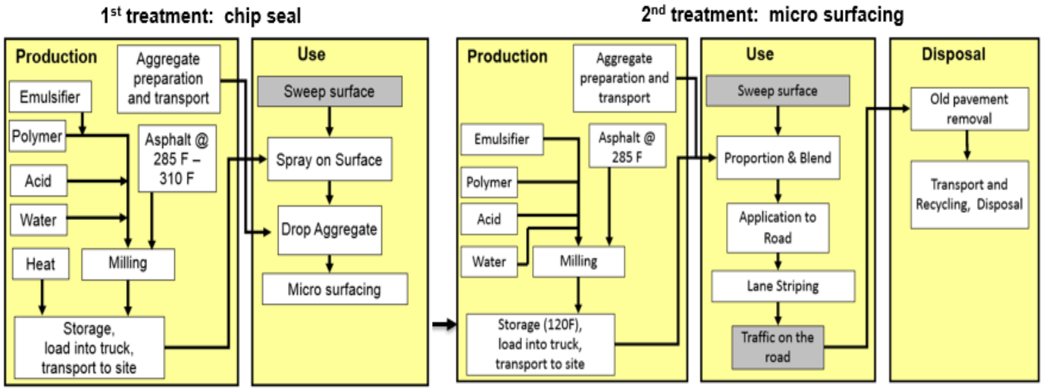


Figure 4. System diagram for generic life cycle of Cape Seal II (polymer modified emulsion chip seal + micro surfacing)

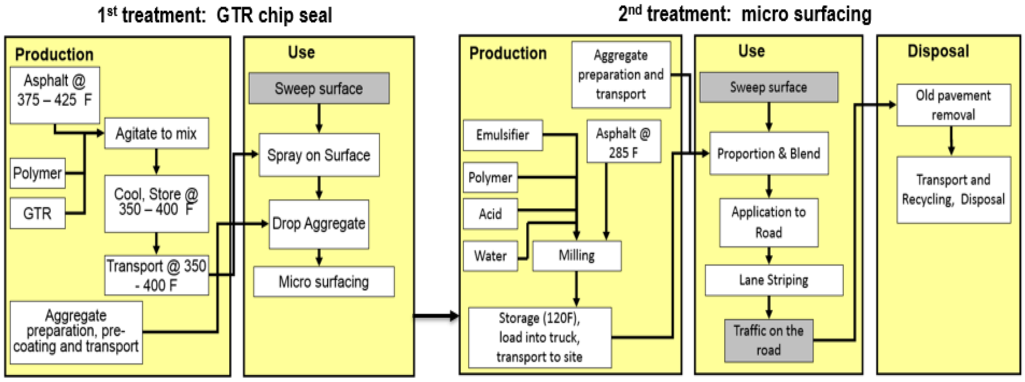


Figure 5. System diagram for generic life cycle of Cape Seal I (GTR Chip Seal + Micro surfacing) – Southeast

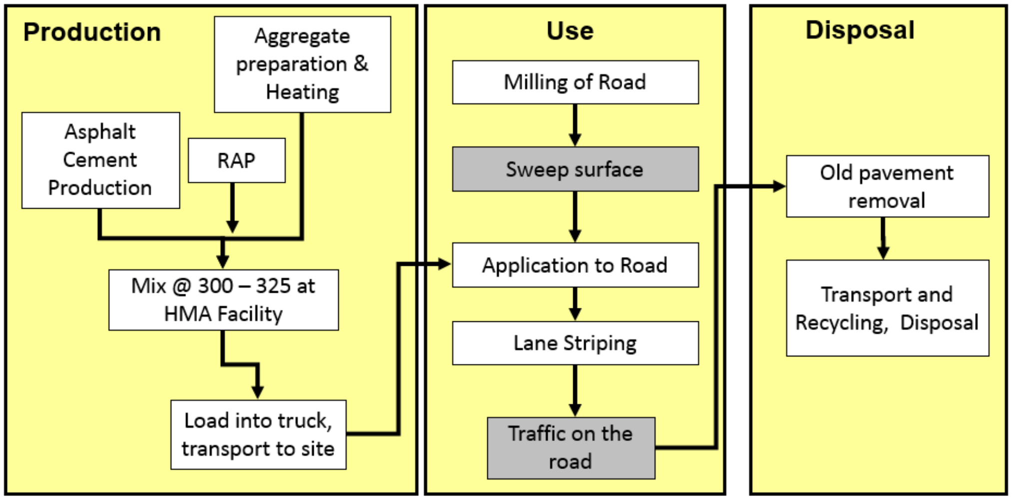


Figure 6. System Diagram for generic life cycle of Hot Mix Overlay

5.4. Scenario Analyses:

In addition to the base case analysis, several additional scenarios were evaluated to determine the sensitivity of the study's final conclusions and results to key input parameters as well as to help focus the interpretation of the study results. Results will be presented and discussed in section 10.

5.4.1. Scenario #1:

Increased durability of hot mix overlay (Mill and Fill).

5.4.2. Scenario #2:

Incremental reductions in thin hot mix overlay mix and placement temperatures

a. 10% energy savings vs. base case
b. 20% energy savings vs. base case
c. 30% energy savings vs. base case
d. 40% energy savings vs. base case
e. 50% energy savings vs. base case

5.4.3. Scenario #3

Incremental reductions in thin hot mix overlay mix and placement temperatures (Scenario #2) and increase allotment of RAP by 10%.

a. 10% energy savings vs. base case + 10% additional RAP
b. 20% energy savings vs. base case + 10% additional RAP
c. 30% energy savings vs. base case + 10% additional RAP
d. 40% energy savings vs. base case + 10% additional RAP
e. 50% energy savings vs. base case + 10% additional RAP

5.5. Relevance Check

As defined in section 3.2.1 Environmental Burdens, a relevance check is done for each analysis to determine the appropriate level of environmental metrics that need to be considered (i.e. EEA6, EEA10). Relevance checks were completed for each separate analysis (1) Cape Seal California (West Coast) and (2) Cape Seal - Southeast. The relevance check summary for analysis 1 (California) is shown in Figure 7 while the relevance check for analysis 2 Southeast is shown in Figure 8.

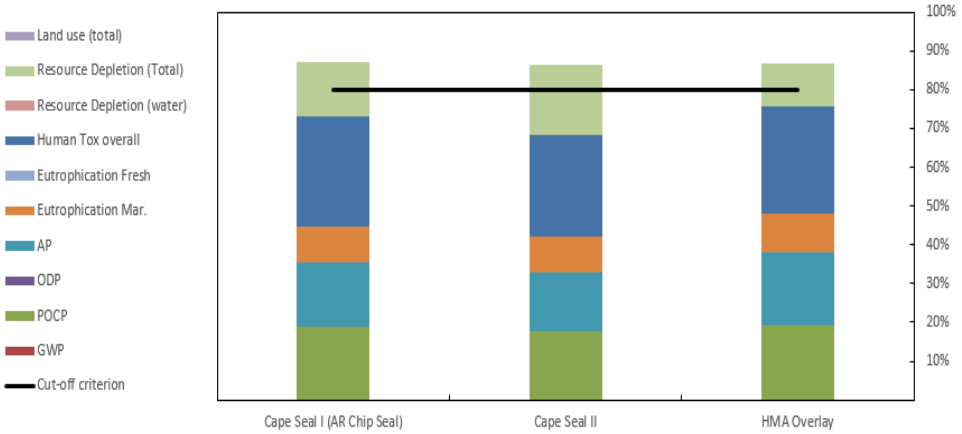


Figure 7. Relevance Check Cape Seal California (West Coast)

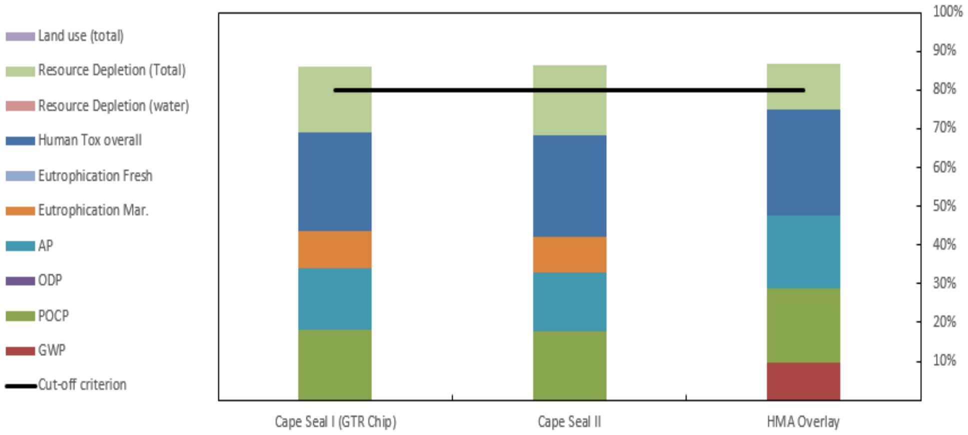


Figure 8. Relevance Check Cape Seal - Southeast

As evident in both figures, there was over 85% coverage of environmental burden for each alternative using the EEA6 parameters which is well above the minimum cut-off criterion of 80% coverage (solid black bar in Figure 8) in order to insure adequate coverage of environmental impact. In addition, the standard six (6) environmental categories identified in EEA6 contributed to the > 80% score. Therefore, the EEA6 impact parameters identified in Table 1 were utilized in this eco-efficiency analysis.

6. Input Parameters and Assumptions

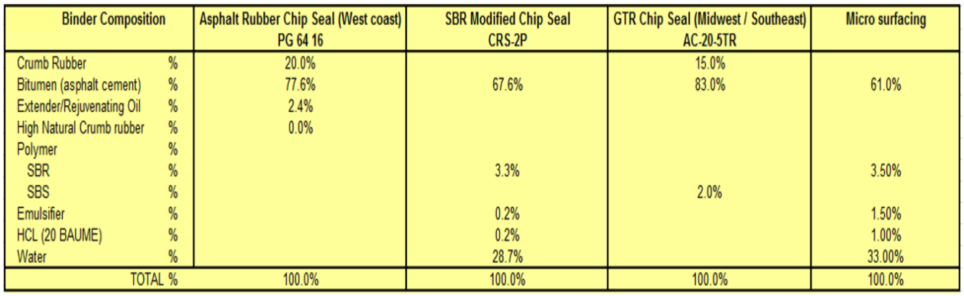
6.1. Input Parameters:

A comprehensive list of input parameters was included for this study and considered all relevant material and operational characteristics for the pavement preservation technologies assessed. Absolute input values as opposed to relative values were used.

6.1.1. Binder – Tack Coat Parameters

a. Cape Seal

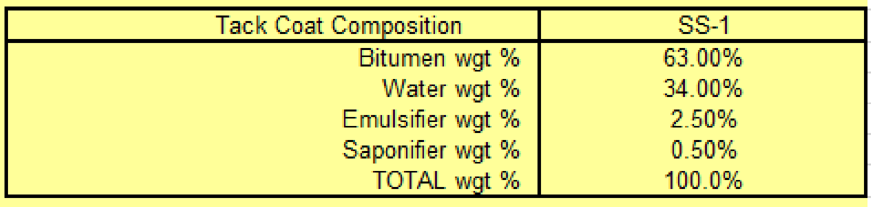
The compositional data for the cape seal binders are based on representative compositions for the industry and shown below in Table 2. The chip seal binder compositions shown below were vendor supplied[7,8] and reflect an average composition and are within the industry recommendations. The micro surfacing binder composition shown below was vendor supplied[7] and reflects an average composition and is within the recommendations provided in the ISSA (International Slurry Surfacing Association) A143 mix design guideline for micro surfacing[9]. The tack coat was based on an SS-1, anionic grade emulsion and was also based on manufacturer's data[10] and is shown in Table 3.



Binder Composition		Asphalt Rubber Chip Seal (West coast) PG 64 16	SBR Modified Chip Seal CRS-2P	GTR Chip Seal (Midwest / Southeast) AC-20-5TR	Micro surfacing
Crumb Rubber	%	20.0%		15.0%	
Bitumen (asphalt cement)	%	77.6%	67.6%	83.0%	61.0%
Extender/Rejuvenating Oil	%	2.4%			
High Natural Crumb rubber	%	0.0%			
Polymer	%				
SBR	%		3.3%		3.50%
SBS	%			2.0%	
Emulsifier	%		0.2%		1.50%
HCL (20 BAUME)	%		0.2%		1.00%
Water	%		28.7%		33.00%
TOTAL	%	100.0%	100.0%	100.0%	100.0%

Table 2. General Product Formulation – Cape Seal Technologies

b. Tack Coat



Tack Coat Composition	SS-1
Bitumen wgt %	63.00%
Water wgt %	34.00%
Emulsifier wgt %	2.50%
Saponifier wgt %	0.50%
TOTAL wgt %	100.0%

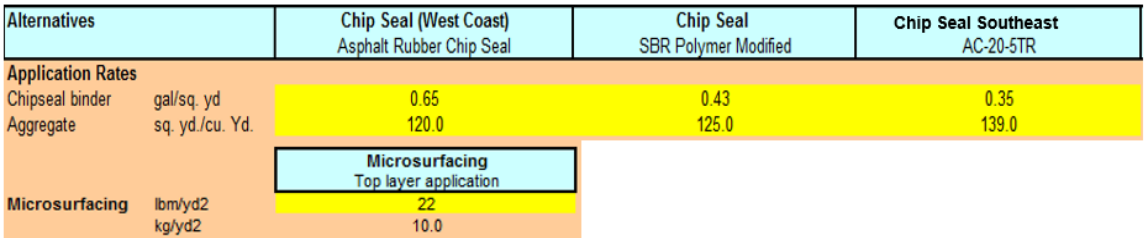
Table 3. General Product Formulation – Tack Coat

6.1.2. Production and Application Parameters

As the processing steps and temperatures required for the manufacture and application of the various alternatives are drastically different (see Figures 4 - 7) it is essential that these impacts are considered. Energy requirements to produce crumb rubber / ground tire rubber from tires were based on industry report data.[11] Energy impacts related to the production and storage of the binder prior to application were provided by asphalt manufacturers[12]. Impacts related to mixing and pre-coating energies for the hot mix asphalt alternatives were taken from Table 4.2.38.1 of the Life Cycle Assessment (LCA) report prepared for the Swedish National Road Administration by the IVL - Swedish Environmental Research Institute.[13] For the chip seal application, pre-coating aggregate helps improve the adhesion or binding properties between the aggregate and the binder. Most asphalt cement binders are used with pre-coated aggregate while emulsion based binders are not.

Application (laying) energies for all the alternatives were taken from Annex II of the lifecycle assessment report by Colas.[14] Energy related to the storage of the binder and mix materials was only considered for the chip seal technology as the hot mix overlay and micro surfacing technologies are usually applied shortly after manufacture. Due to similarities between the binder (CRS-2P) for the micro surfacing treatment and for the tack coat (SS-1), the energy requirement for the tack coat was estimated to be 10% higher than the CRS-2P binder because of the slightly higher temperature requirement (150 ^{O}F).

The application amounts of binder and aggregate for the chip seal were taken from typical DOT combination rates[16] and were confirmed by customers to be still representative of industry practice. Values varied between technologies and regions assessed and are reflected in Table 4.



Alternatives		Chip Seal (West Coast) Asphalt Rubber Chip Seal	Chip Seal SBR Polymer Modified	Chip Seal Southeast AC-20-5TR
Application Rates				
Chipseal binder	gal/sq. yd	0.65	0.43	0.35
Aggregate	sq. yd./cu. Yd.	120.0	125.0	139.0
		Microsurfacing Top layer application		
Microsurfacing	lbm/yd2	22		
	kg/yd2	10.0		

Table 4. Application rates Cape Seal

For the thin hot mix overlay (Mill & Fill) a 1.5" application (which includes compaction) was assumed.

6.1.3. RAP (Recycled Asphalt Pavement)

Reclaimed asphalt pavement was included in the hot mix overlay alternative. By reutilizing RAP, the hot mix asphalt alternative can introduce existing aggregate and bitumen materials into the mix formula with virgin material and thus reduce the environmental and economic impact of producing additional virgin material. However, to maintain the same performance characteristics on the road and to eliminate any additional issues related to surface durability and quality control, many state agencies have limitations on the amount of RAP that can be utilized on the wear coarse of roads. For this study, the maximum amount of RAP allowed in the base case hot mix asphalt overlay was 15% for the California (West Coast) model and 20% for the Southeast model. At these RAP concentrations, no change in the performance grade of the binder was required. It was also assumed that while RAP will be reutilized, it must first be taken off-site for processing prior to being introduced back into the hot mix asphalt.

6.1.4. Crumb Rubber / Ground Tire Rubber

Crumb rubber or ground tire rubber (GTR) can be blended with asphalt to beneficially modify the properties of the asphalt in highway construction. Per the US EPA, asphalt rubber is the largest single market for ground rubber, consuming an estimated 220 million pounds, or approximately 12 million tires. Energy usage to convert the recycled tires into GTR or crumb rubber was included in the analysis and was calculated from manufacturer data as well as equipment energy consumption. No previous environmental impacts were burdened to the rubber, only the energy required to shred and granulate the tires and energy related to transport. In addition, credit was given to the rubber modified alternatives for diverting waste from the landfill and a small energy credit for steel recovery. For the California (West Coast) asphalt rubber chip seal, the rubber component was selected as 20% based on customer specification[8]. For the Southeast GTR chip seal, a 15% composition was deemed representative of industry practice.

6.1.5. Transportation - Logistics

Maintaining an asphalt road over 40 years requires a significant quantity of material. Thus, the environmental and cost impacts associated with transporting the materials to and from the job site are significant and are thus included in this analysis. The following assumptions were used when considering transportation:

- 75 km distance for binder, tack coat, striping material and aggregate
- 100 km for distance to landfill or recycling location

6.2. Life Cycle Costs

6.2.1. Life cycle costing

The long term economic impacts of the pavement preservation technologies evaluated were considered by conducting a life cycle cost analysis. Thus, in addition to initial costs (e.g. material and labor), all relevant future cost impacts are considered as well. Consistent with the guidance provided by the US DOT FHWA, constant dollars and real discount rates were considered[6]. For this study, both a financial discount rate and a social discount rate[17] were used. See Section 6.2.3 for the justification for the specific rates used.

6.2.2. User Costs

User costs were evaluated for each alternative. User costs are defined as excess costs incurred by drivers on the road due to non-standard travel delays caused by agency (e.g. DOT) maintenance and construction activities which disrupt the normal flow of traffic. This approach is basically a way of placing a value on people's time that is impacted or disrupted by traffic delays. The FHWA normally groups user costs as vehicle operating costs (VOC), user delay costs and crash costs. Guidance for these costs was obtained from LCA literature published by Hicks and Epps[18]. Specific to this study, as most pavements on the National Highway System (NHS) have similar VOCs, they were not considered for this study. In addition, crash costs were not considered. Consistent with the strategy proposed by Hicks and Epps, delay costs were accounted for by utilizing a simpler approach: lane rental fees. Research[19] conducted on lane rental fees indicate that this value can vary significantly based on factors such as the time of the day and region of the country. The value utilized for this study reflecting a moderately traveled rural road was estimated at $5,000 lane-mile/day[18].

6.2.3. Discount Rates

As previously described, comprehensive life cycle costing for roads needs to consider both the actual costs incurred as well as the intangible costs associated with user costs. As both costs are distinctly different, a single discount rate cannot be applied. Thus, both a financial discount rate (FDR) and a social discount rate (SDR) need to be used.

Latest guidance[17] on the financial discount rate has it linked to the 30-year nominal treasury rate which for calendar year 2017 was 2.8%[20].

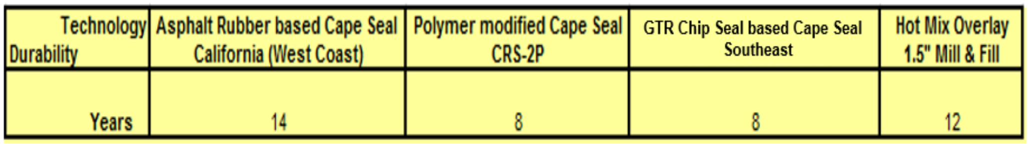
Literature[17] documents the social discount rate (SDR) between 4 - 8%. Following a weighted average rule implies that an SDR of about 7 percent is appropriate for use in government benefit-cost analysis. This is consistent with current Office of Management and Budget (OMB) guidelines, which recommend a 7 percent "base case" SDR. Thus, for this assessment, 2.8% was used for the FDR and 7% for the SDR.

6.3. Durability

The durability or life expectancy of the pavement preservation technology will have a significant impact in determining the overall eco-efficiency of the alternatives. Durability will vary depending on the region of the country and climate, level and type of traffic usage, and the condition of the underlying pavement.

Literature reports expected performance data for thin (hot mix) overlays between 8 – 11 years (FHWA, Federal Highway Association)[24] and specific to states in the Southeast (e.g. Georgia, Florida) as between 10 – 12 years[24,33]. Thus a conservative value of 12 years was selected for the HMA alternatives. For standard cape seal application, research by the Cornell University Local Roads Program sites the US National Park Service as achieving a life extension of asphalt pavements between 6 – 8 years but for polymer modifications (applicable to this analysis) up to 10 years. An average of 8 years was selected. The Asphalt Rubber based cape seal alternative for California is unique in that the crumb rubber content is higher than the standard alternative (20% vs 15%) and the chip seal application rate is significantly higher than the standard chip seal application (0.65 gal/yd^2 vs. 0.35 gal/yd^2). These will lead to improved life extensions. Regional expertise for California applications set the asphalt pavement extension at 14 years which is also at the average of the figures reported by another regional manufacturer[34].

Based upon reported data and the expert judgment and experiences of the team, the following base case durability values were established for the various technologies:



Technology Durability	Asphalt Rubber based Cape Seal California (West Coast)	Polymer modified Cape Seal CRS-2P	GTR Chip Seal based Cape Seal Southeast	Hot Mix Overlay 1.5" Mill & Fill
Years	14	8	8	12

Table 5. Durability for pavement preservation technologies

6.4. Lane Striping

The study assumed that each time a surface treatment was applied, new lane striping was applied. The striping material was based on an epoxy resin based thermoplastic (ETP) with glass beads. Material composition was obtained from a DOT standard[21]. Specific costs and application rates were provided by a vendor[7]. Study assumption was for the application of four (4) stripes per road.

6.5. Disposal – End of Life

It was also assumed that 99.5% of the road surface materials will be recycled in some capacity and thus will not be sent directly to the landfill. However, the logistical impacts of transporting the materials to their final end-of-life destination were considered (e.g. recycling for inclusion as RAP in future roads). Values for the Cape Seal California (West Coast) model was established at \$45/ton[22] and tipping fee for the Southeast model was established at \$42/ton[22].

7. Data Sources

7.1. Environmental:

The environmental impacts for the production, use, and disposal of the various alternatives were calculated from eco-profiles (e.g. life cycle inventories) for the individual system components, for energy consumption (fuel and electricity), and for material transport and disposal. Life cycle inventory data for these eco-profiles were from several data sources, including BASF, GaBi ts[23] and ecoinvent databases as well as customer specific manufacturing data. Overall, the quality of the data was considered medium to high. Over 98% of the total mass and energy inputs of each alternative was covered. None of the eco-profiles data was considered to be of low data quality. A summary of the eco-profiles is provided in Table 6.

As you will note from Table 6, several profiles are greater than 10 years old. Each of these eco-profiles were individually assessed to determine their representativeness for the study and whether the level of effort required to close any data gaps could be supported or was prohibitive.

Profiles for mineral filler (Portland cement) and rejuvenating oil (petroleum distillate) though greater than 10 years old were still deemed to be representative of standard, current industrial processes. In addition, each material contributes less than 0.5% to the total mass of the final cape seal alternative and thus further refinement of the profiles would not impact the overall results and conclusions of the study.

BASF manufacturing data for the SBR polymer and emulsifier were deemed to not have significantly changed in the last decade and thus were of sufficient data quality.

The SBS polymer profile which is only relevant for the Cape Seal I alternative for the Southeast analysis contributes about 0.1% to the overall mass of the alternative and thus was deemed of sufficient data quality based on its impact on the overall study results and conclusions for the Cape Seal I alternative.

Finally, the effort to update the saponifier profile, which contributes about 0.5% to the mass of the tack coat, was deemed not justifiable based on the level of effort to update the profile vs. its insignificant impact on the overall impact of the environmental footprint of the tack coat / HMA alternative.

Eco-Profile	Source, Year	Comments
Binder / Tack Coat		
SBS polymer	ChemSystems PERP report, 2003	
SBR Polymer	BASF, 2004	BASF site manufacturing data
Emulsifier	BASF, 2008	BASF site manufacturing data
Hydrochloric Acid	GaBi ts[23], 2016	production mix at plant
Saponifier	GaBi ts[23], 2005	ECOSOL study of the European surfactant industry
Bitumen	GaBi ts[23], 2016	US Bitumen, at refinery
Mineral Filler	GaBi ts[23], 2004	portland cement at plant
Extender / Rejuvenating Oil	GaBi ts[23], 2003	petroleum refining coproduct
Aggregate	GaBi ts[23], 2016	gravel; wet and dry quarry. Production mix at plant
Water	GaBi ts[23], 2016	
Natural Gas	GaBi ts[23], 2016	US: Thermal energy from natural gas
Electricity - West	GaBi ts[23], 2012	US_ Electricity grid mix (production mix) West
Electricity - Southeast	GaBi ts[23], 2012	US_ Electricity grid mix (production mix) SRSO
Heavy Fuel Oil	GaBi ts[23], 2016	US Thermal energy from heavy fuel oil (HFO) (West) technology mix
Diesel Use - US	GaBi ts[23], 2016	Diesel, combusted in industrial equipment
Material to Landfill	GaBi ts[23], 2016	US landfilling of waste, treatment of leachate
Disposal Asphalt	ecoinvent, 2016	disposal asphalt sanitary landfill
Lane Striping	GaBi ts[23], 2009	Dept. of Transportation[21]
Truck Transport	GaBi ts[23], 2016	global transport, combination truck, diesel powered
BASF data sources are internal data, while the others are external to BASF. Internal data is confidential to BASF; however, full disclosure was provided to NSF International for verification purposes.		

Table 6. Eco-profile Data Sources

8. Eco-Efficiency Analysis Results and Discussion

8.1. Environmental Impact Results:

The environmental impact results for the Cape Seal Eco-Efficiency analysis were generated as defined in Section 6 of the BASF EEA methodology. The results discussed in Section 8.1.1 through 8.1.6 are for the Base Case only and do not represent any of the scenarios. They will be presented in section 8.4.

8.1.1. Resource Depletion – mineral, fossil:

Environmental Relevance: **HIGH** – Contributes between 11% - 18% to the overall environmental impact. See Table 14 for summary of environmental impact relevance / significance factors.

This impact category looks at the depletion of abiotic resources, namely the use of non-renewable resources. All resources are characterized separately based on their extraction rates and reserves. Thus, more scarce resources are weighted more heavily. As clearly seen in the figures below, for both the California (West Coast) analysis and the Southeast analysis, the predominate impact on resource depletion is the road markings, specifically the pigment materials. Alternatives that have longer durability will require less frequent lane striping and thus perform better in this category. The asphalt rubber based cape seal in the California (West Coast) analysis achieved the lowest overall impact, while in the Southeast study the HMA Overlay had the lowest impact.

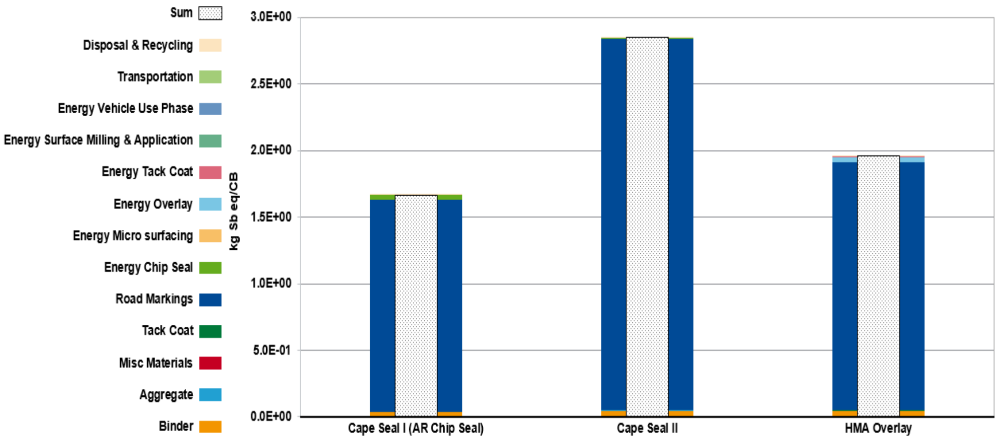


Figure 9. Resource Depletion – California (West Coast)

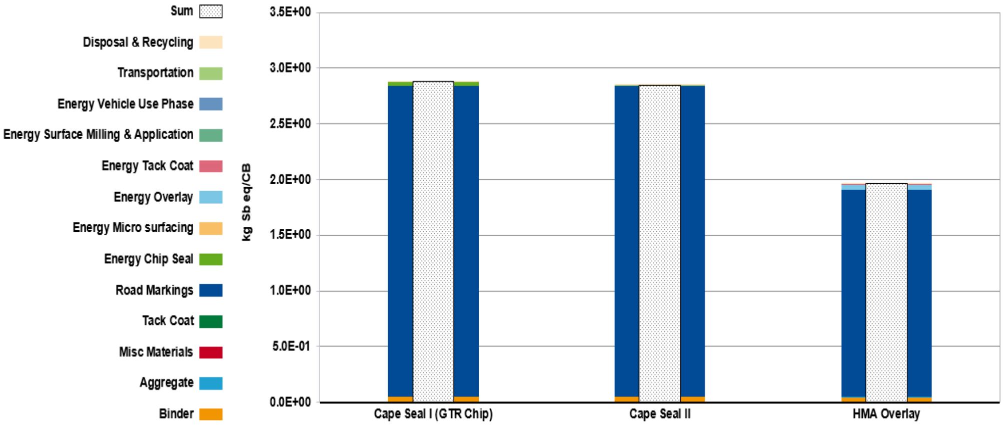


Figure 10. Resource Depletion – Southeast

8.1.2. Air Emissions:

8.1.2.1. Global Warming Potential (GWP):

Environmental Relevance: **Medium** – Contributes between 8% - 10% to the overall environmental impact. See Table 14 for summary of environmental impact relevance / significance.

Figures 11 and 12 show the GWP / GHG emissions / Carbon Footprint for the two analyses. Contributions to CO_2 emissions come from both material use (e.g. binder and striping material) and energy consumption during manufacturing and transport. For the California (West Coast) analysis, both cape seal technologies had lower GWP than the hot mix asphalt (HMA) overlay. Between the cape seal technologies, the asphalt rubber based cape seal had a GWP about 10% less than the polymer modified emulsion based cape seal. The AR based cape seal compensated for having much higher chip seal manufacturing energy and application rates by having 75% longer durability (14 yrs. vs. 8 yrs.). The main contributor to the hot mix overlay was the large amount of energy required during the production, storage and application of the asphalt. Finally, the lane striping material contributed significantly to each alternative's carbon footprint due to the emissions relate to the manufacturing of the epoxy resin.

For the Southeast analysis, the polymer modified emulsion based cape seal (Cape Seal II) had the lowest carbon footprint: 20% lower than the GTR chip seal based cape seal and 30% lower than the hot mix overlay. The Southeast rubber modified cape seal alternative did not perform as well as in the California (West Coast) model due to its much lower durability (8 yrs. vs. 14 yrs.)

For both analyses the binder contribution to GWP for all alternatives was roughly the same.

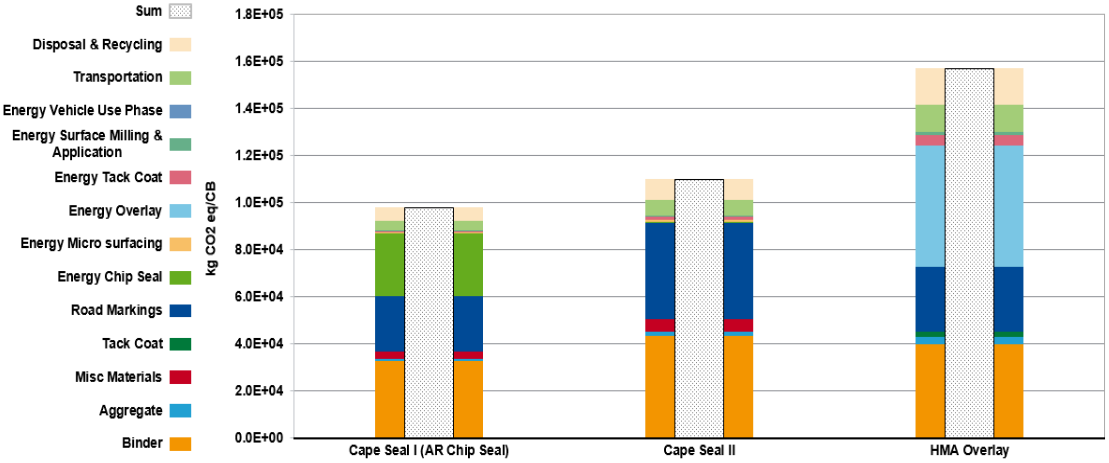


Figure 11. Global warming potential (GWP) – California (West Coast)

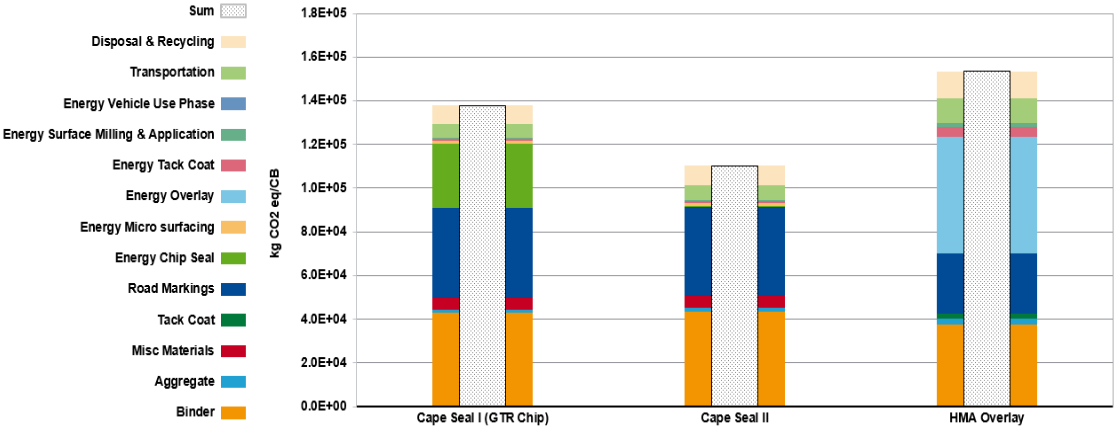


Figure 12. Global warming potential (GWP) – Southeast

8.1.2.2. Photochemical ozone creation potential (POCP, summer smog):

Environmental Relevance: **HIGH** – Contributes between 18% - 19% to the overall environmental impact. See Table 14 for summary of environmental impact relevance / significance.

The lowest emissions for ground level ozone creation potential (summer smog) for the California (West Coast) analysis was the Cape Seal I (AR Chip Seal) alternative (Figure 13). Mainly due to its durability advantage, the AR based cape seal technology had POCP emissions reductions of 20% and 35% respectively when compared to the Cape Seal II and HMA overlay alternatives. Main contributors to this impact category were the methane and non-methane VOCs emitted during the manufacturing of the binder and lane striping material and the combustion of fossil fuels for energy production and transportation.

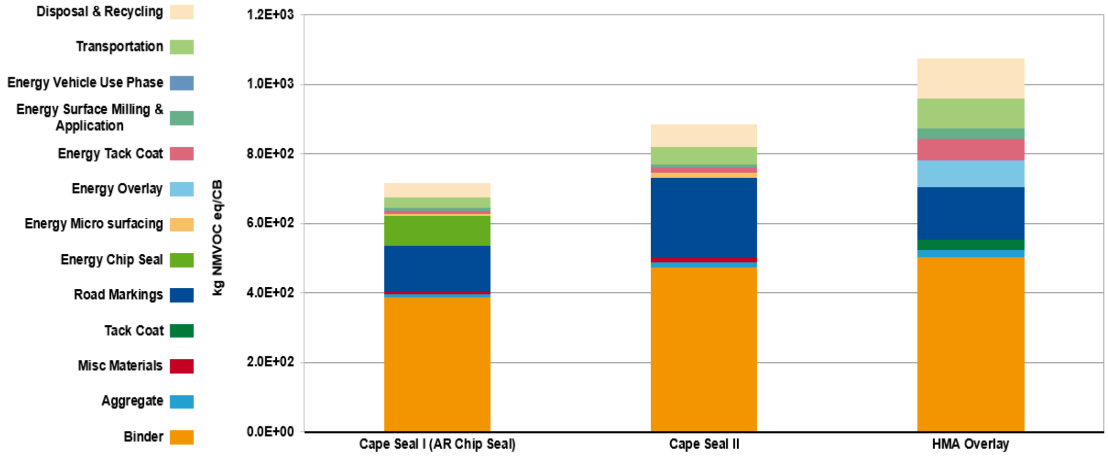


Figure 13. Photochemical Ozone Creation Potential (POCP) – California (West Coast)

For the Southeast analysis (Figure 14), the Cape Seal II alternative had the lowest POCP, approximately 10% lower than Cape Seal I and 15% lower than the HMA overlay alternative.

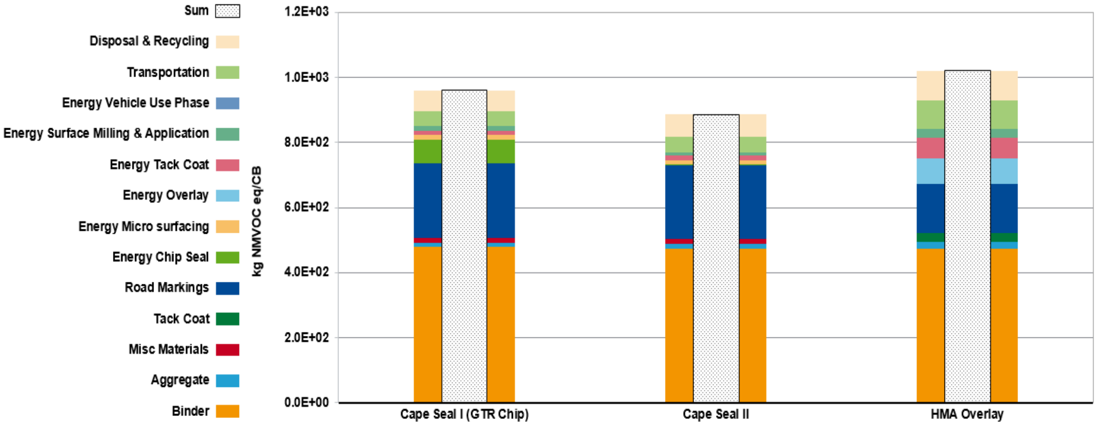


Figure 14. Photochemical Ozone Creation Potential (POCP) – Southeast

8.1.2.3. Acidification potential (AP):

Environmental Relevance: **HIGH** – Contributes almost 15% - 19% to the overall environmental impact. See Table 14 for summary of environmental impact relevance / significance.

Similar to the other air emissions categories (GWP, POCP), the AR chip seal based cape seal scored the lowest in acidification potential for the West Coast analysis reducing AP emissions relative to the worst performing alternative (HMA overlay) by over 40%. Acidification potential primarily results from NO_x and SO_x generated during the use and burning of fossil fuels.

For the Southeast analysis where both cape seal alternatives have the same durability (8 years) the polymer modified cape seal (Cape Seal II) had 10% lower AP when compared to the GTR based cape seal and 25% lower AP when compared to the HMA overlay.

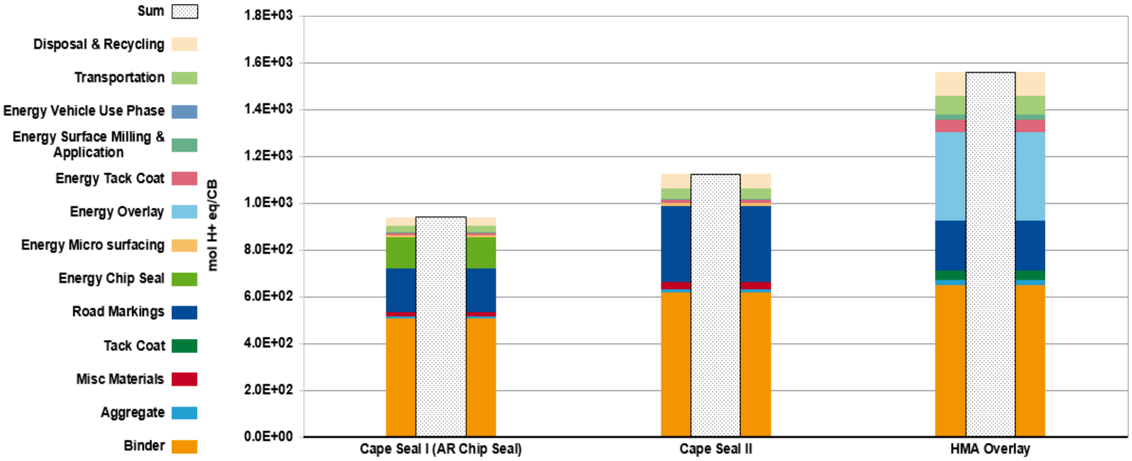


Figure 15. Acidification Potential (AP) – California (West Coast)

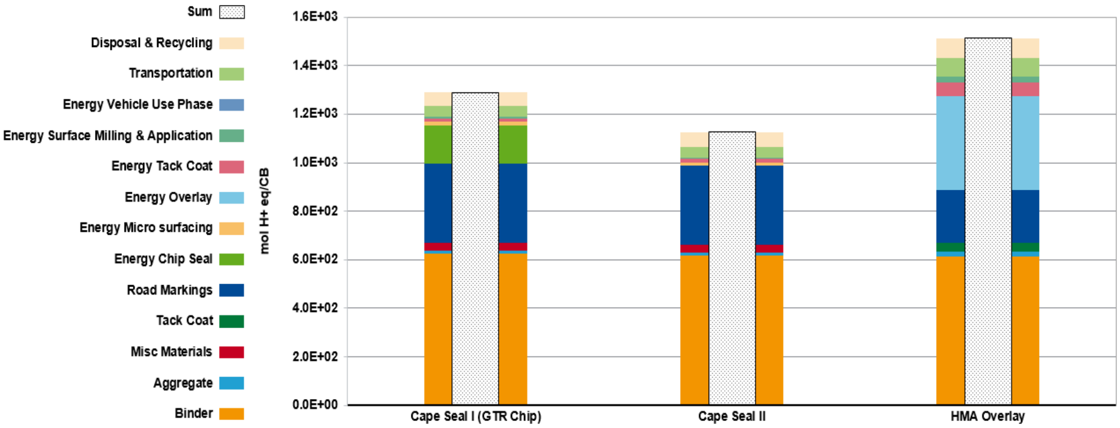


Figure 16. Acidification Potential (AP) – Southeast

8.1.3. Eutrophication

8.1.3.1. Eutrophication (fresh water)

Environmental Relevance: **LOW** – Contributes less than 1% to the overall environmental impact. See Table 14 for summary of environmental impact relevance / significance.

For both Cape Seal analyses the two main contributors to fresh water eutrophication are the binder materials and the lane striping materials. Both cape seal technologies which utilize crumb rubber / GTR to modify the chip seal benefit from the eutrophication benefits of avoiding sending tires to landfill. The Cape Seal I technology (West Coast) benefits the most due to its higher concentration of crumb rubber. The polymer modified cape seal technology (Cape Seal II) has additional fresh water impacts due to the manufacturing of the emulsion. For the West Coast analysis, the Cape Seal I (AR modified Chip Seal) has the lowest fresh water eutrophication while for the Southeast analysis, the Cape Seal I (GTR chip seal) technology and HMA overlay scored the lowest.

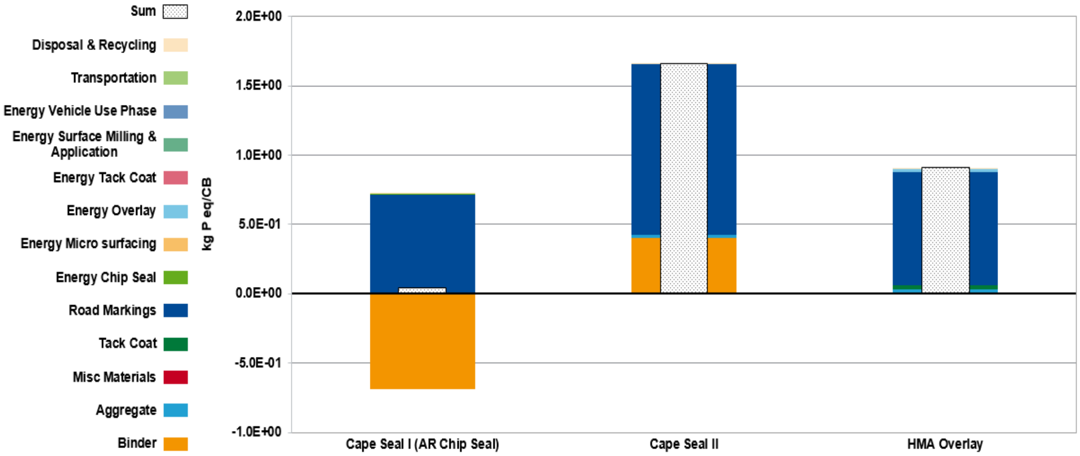


Figure 17. Eutrophication – fresh water – California (West Coast)

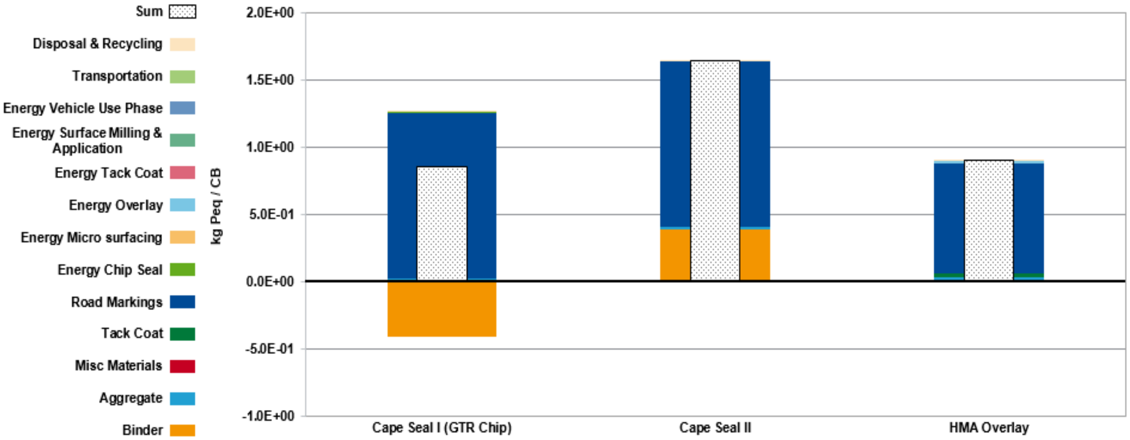


Figure 18. Eutrophication – fresh water - Southeast

8.1.3.2. Eutrophication (marine):

Environmental Relevance: **MEDIUM** – Contributes 9% - 10% to the overall environmental impact. See Table 14 for summary of environmental impact relevance / significance.

Contributions to marine eutrophication are a lot more diverse than for fresh water eutrophication though the main contributors are still the binder and striping materials. As you can see from Figure 19, the Cape Seal I (AR Chip Seal) scored the lowest for the California (West Coast) analysis about 35% less than the worst scoring alternative, the HMA overlay. The HMA thin overlay scored high due to high impacts in energy consumption and transportation. For the Southeast analysis, the Cape Seal II alternative (polymer modified emulsion based) scored 10% - 15% lower in marine eutrophication than the other alternatives.

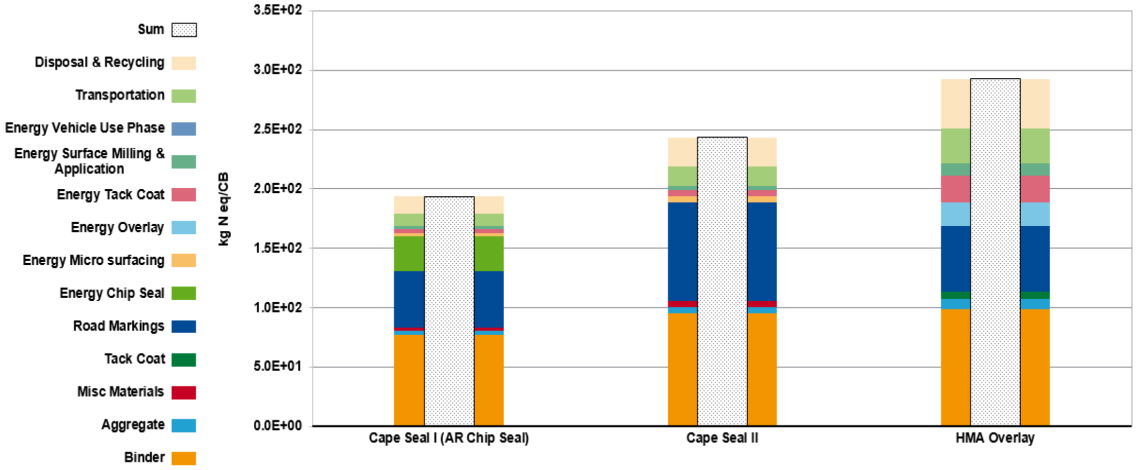


Figure 19. Eutrophication – marine water – California (West Coast)

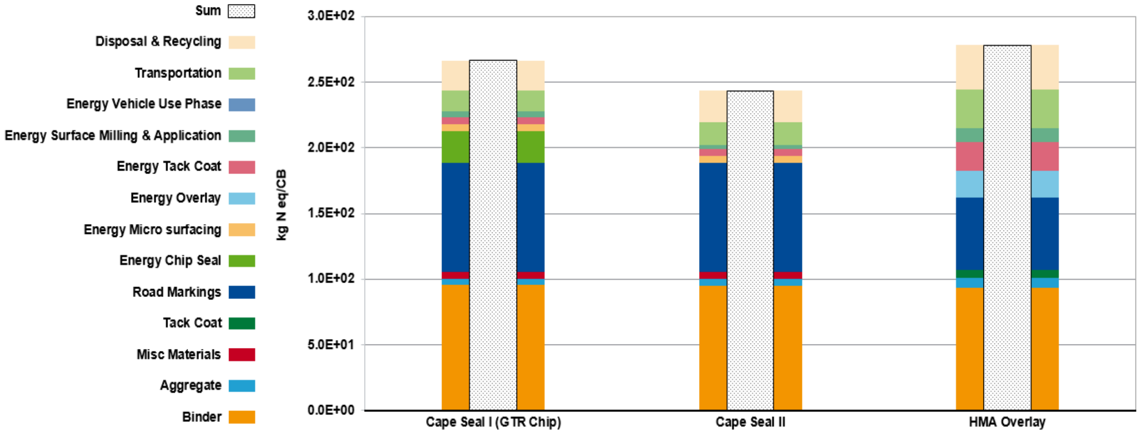


Figure 20. Eutrophication – marine - Southeast

8.1.4. Toxicity potential:

Environmental Relevance: **HIGH** – Contributes 25% - 28% to the overall environmental impact. See Table 14 for summary of environmental impact relevance / significance.

The toxicity potential of the various materials and components required to produce the cape seal and hot mix asphalt (HMA) thin overlay alternatives as well as any associated activities with their use, maintenance and disposal/recycling were analyzed for each stage of their respective life cycles. A full analysis of the entire pre-chain of chemicals and raw/recycled materials required during their manufacture and transport was also considered. Toxicity potential at the end of life considered impacts from disposal, recycling and the associated logistics.

Nanoparticles were not included in the chemical inputs of any of the alternatives and were not evaluated in this study.

Inventories of all relevant materials were quantified for each alternative and assessed consistent with BASF's EEA Methodology's for assessing the human health impact potential of materials (ref. Section 6.4 of Part A Submittal). Figure 21 (California – West Coast) and Figure 22 (Southeast) show how each life cycle module contributed to the overall toxicity potential score for each alternative.

The highest contributor to toxicity potential for the California (West Coast) analysis was the binder (bitumen). Thus, alternatives that applied more binder, scored the highest. Based on application rates and durability data, the AR modified cape seal scored the lowest due to its 14-year durability, more than compensating for the higher chip seal application rate when compared to the polymer modified cape seal alternative. The HMA overlay scored the highest overall.

For the Southeast analysis, both Cape Seal technologies scored the lowest and were within 5% of one another due to their identical durability and similar application rates. Though its binder (bitumen) usage was similar to the two cape seal technologies, the impact of the fossil fuel usage required to produce and apply the hotter thin hot mix overlay caused the HMA alternative to score about 15% higher in toxicity potential.

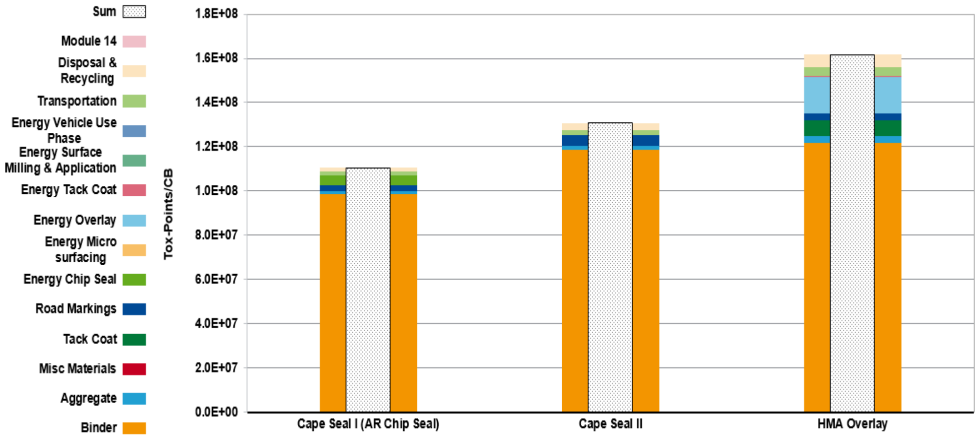


Figure 21. Toxicity Potential (human) – California (West Coast)

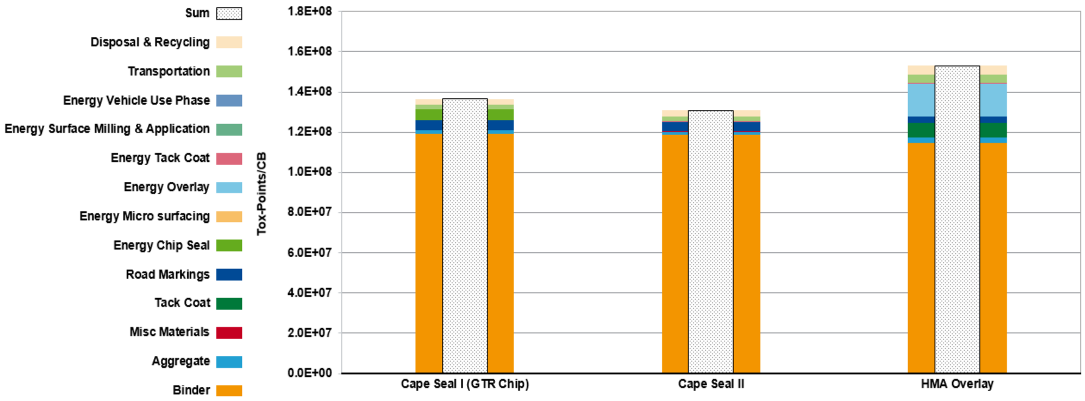


Figure 22. Toxicity Potential (human) – Southeast

8.1.5. Cumulative Energy demand (CED)

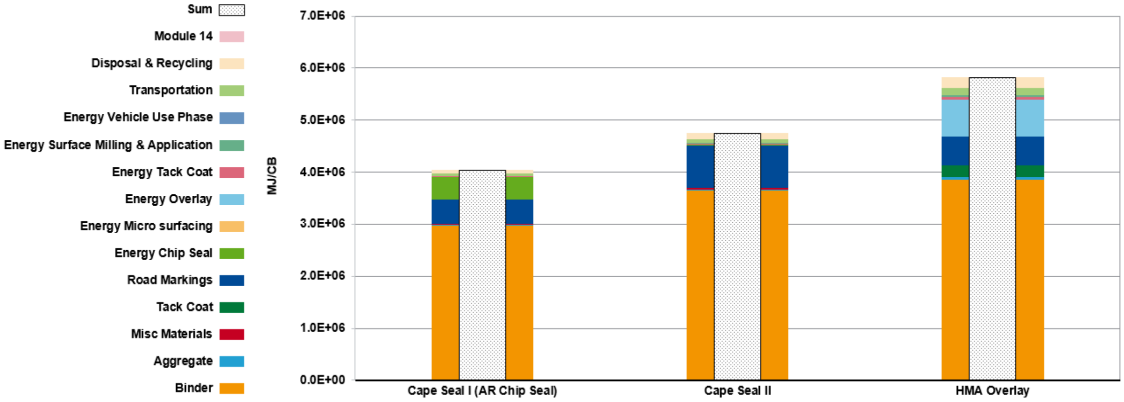


Figure 23. Cumulative energy demand (CED) – California (West Coast)

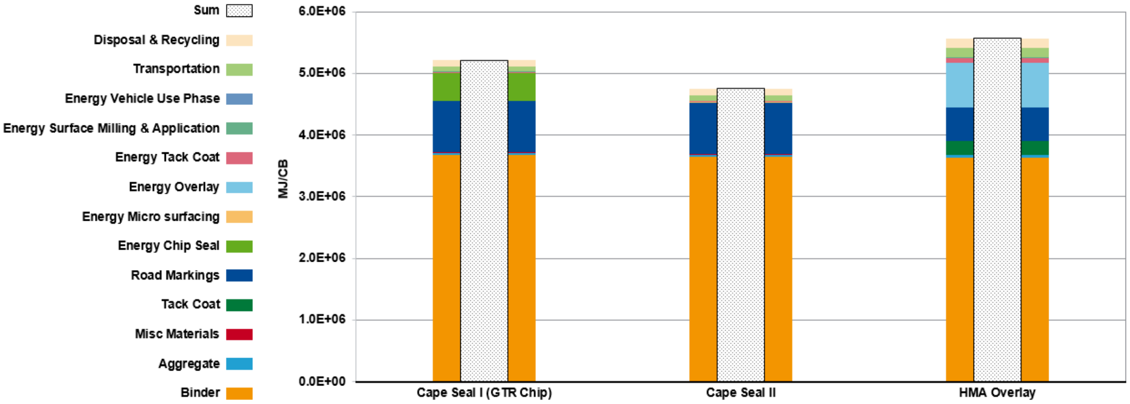


Figure 24. Cumulative energy demand (CED) – Southeast

Though not a true environmental impact category, cumulative energy can be a useful indicator for assessing the environmental impact of an alternative. The Cumulative Energy Demand (CED) of an alternative assess the direct and indirect energy use throughout the life cycle including the energy used during the extraction, manufacturing, use and disposal of the raw and auxiliary materials.

Figure 23 shows the CED for the California (West Coast) analysis. The asphalt rubber (AR) modified cape seal had the lowest overall CED. It was 30% lower than the worst performing HMA overlay. Longer durability was the leading contributor to this advantage.

Figure 24 shows the CED for the Southeast assessment. All alternatives generally had the same impact due to binder (bitumen) usage. The GTR cape seal had additional energy usage for crumb rubber manufacturing while the HMA overlay had higher energy usage associated with the higher production and application temperatures. The HMA overlay, due to its longer durability (12 yrs. vs. 8 yrs.) did save energy related to road markings. Overall, the lowest energy user was the polymer modified, emulsion based Cape Seal II alternative. The Cape Seal II energy usage was about 10% lower than the GTR modified cape seal and 15% lower than the HMA overlay.

8.1.6. Environmental Fingerprint:

Following normalization, the relative impact for all seven of the main environmental categories (EEA6 has two eutrophication categories) for each alternative is shown in the environmental fingerprint, Figure 25. A value of "1.0" represents the alternative with the highest impact in the referenced category; all other alternatives are normalized against this value and given a normalized value less than 1.0. Positions closer to the center of the fingerprint reflect lower impact in that specific environmental category.

As presented in the previous discussions of the individual impact categories and depicted in the environmental fingerprint, the asphalt rubber (AR) modified cape seal technology demonstrated reduced overall environmental impacts in all environmental categories for the base case California – West Coast analysis. The key factor influencing the reduced overall environmental impact is the technology's longer durability and reduced resource consumption.

Comparing the other alternatives in Figure 25 you will see that there are trade-offs. The Cape Seal II alternative performs better in air emissions, toxicity potential and marine eutrophication than the HMA overlay but scored higher in resource consumption and fresh water eutrophication. To better assess the alternatives a bar graph (Figure 26) was developed to show the normalized environmental impacts for each alternative. Using the normalized results (person years), you can still see that the AR cape seal scored the lowest, followed by the Cape Seal II alternative. The HMA overlay had the highest overall environmental impact.

As presented previously, the most significant environmental impact categories were toxicity potential, acidification, photochemical ozone creation potential and resource depletion.

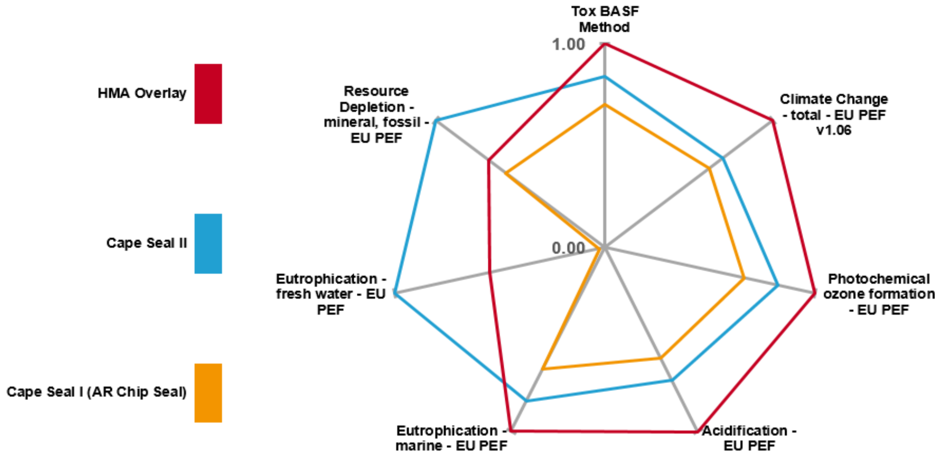


Figure 25. Environmental fingerprint – California (West Coast)

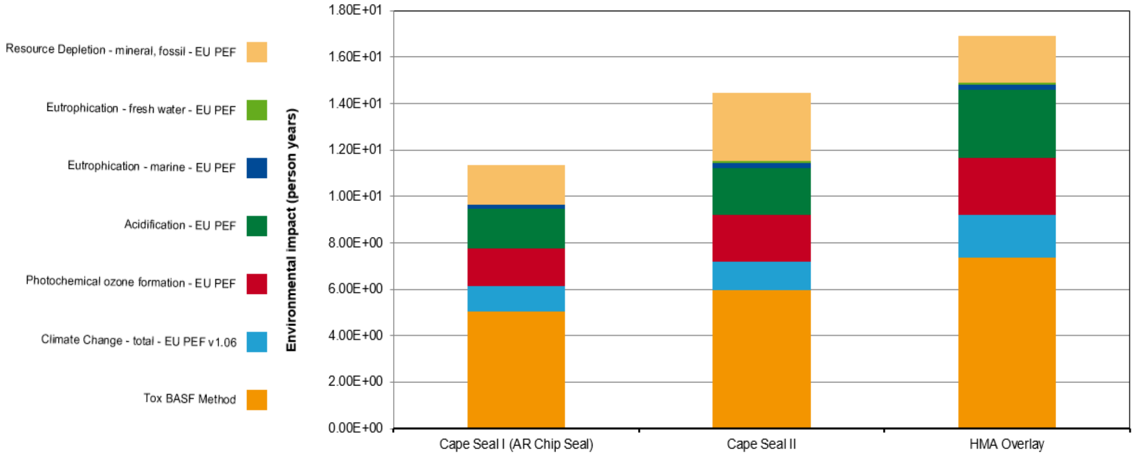


Figure 26. Environmental contributions diagram – California (West Coast)

Similarly, normalized results for the main environmental categories (EEA6 has two eutrophication categories) for each alternative in the Southeast analysis is shown in the environmental fingerprint, Figure 27.

Excluding resource depletion and fresh water eutrophication, the Cape Seal II (polymer modified emulsion based cape seal) alternative scored the lowest in each category followed by the GTR modified cape seal and then the hot mix overlay (HMA). Specific to resource depletion, the HMA overlay scored the best while the cape seal technologies had about 30% higher impact. The Cape Seal II technology had the highest impact in fresh water eutrophication.

The normalized environmental impacts for each alternative is shown in Figure 28. Using the normalized results (person years), you can see that the polymer modified emulsion based cape seal (Cape Seal II) scored the lowest, followed by the Cape Seal I (GTR modified) alternative. The HMA overlay had the highest overall environmental impact.

As presented previously, the most significant environmental impact categories were toxicity potential, acidification, photochemical ozone creation potential and resource depletion.

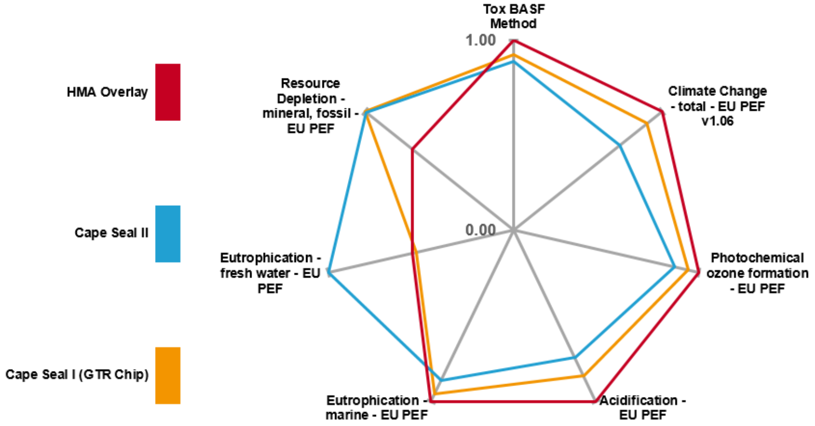


Figure 27. Environmental fingerprint – Southeast

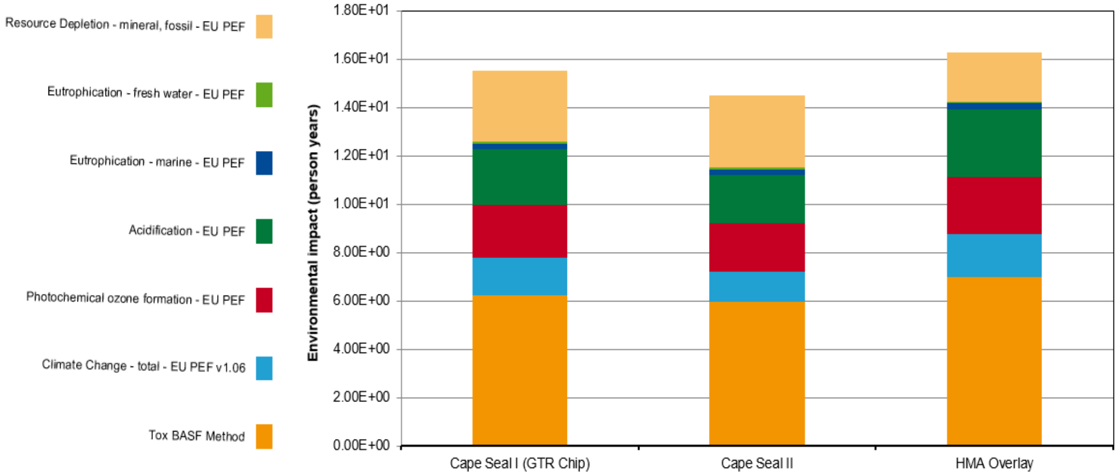
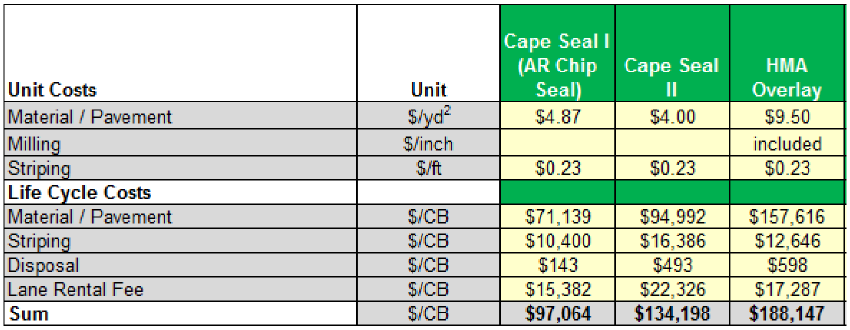


Figure 28. Environmental contributions diagram – Southeast

8.2. Economic Cost Results:

The life cycle costs for the California (West Coast) cape seal analysis are shown in Table 7 and for the Southeast analysis in Table 8. Material unit costs were provided by customers[7,8]. The pricing data was recent (2017) from multiple sources and specific to the region assessed and deemed representative of standard industry pricing.

Due to its low material costs and high durability, the AR based cape seal was the least expensive alternative, about 50% less expensive than the most expensive alternative, the HMA overlay. The Cape Seal II alternative was about 30% less expensive than the HMA overlay.

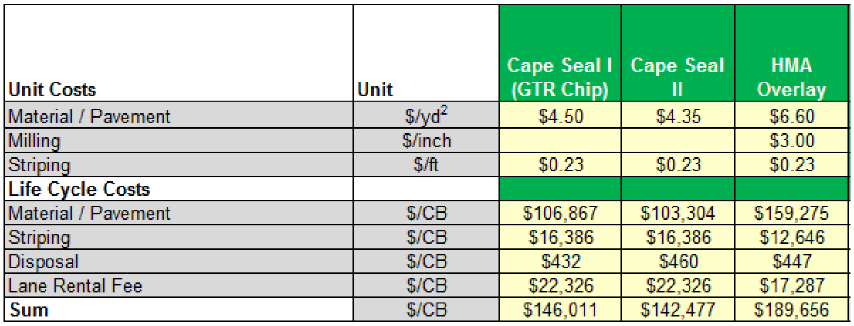


Unit Costs	**Unit**	**Cape Seal I (AR Chip Seal)**	**Cape Seal II**	**HMA Overlay**
Material / Pavement	$/yd^2	$4.87	$4.00	$9.50
Milling	$/inch			included
Striping	$/ft	$0.23	$0.23	$0.23
Life Cycle Costs				
Material / Pavement	$/CB	$71,139	$94,992	$157,616
Striping	$/CB	$10,400	$16,386	$12,646
Disposal	$/CB	$143	$493	$598
Lane Rental Fee	$/CB	$15,382	$22,326	$17,287
Sum	$/CB	**$97,064**	**$134,198**	**$188,147**

Table 7. Life cycle costs – California (West Coast)

The life cycle costs for the Southeast cape seal analysis are shown in Table 8. Material unit costs were provided by customers[7,8]. The pricing data was recent (2017) from multiple sources and specific to the region assessed and deemed representative of standard industry pricing.

Due to their identical durability and low material costs, both cape seal alternatives were the least expensive alternatives, about 25% less expensive than the most expensive alternative, the HMA overlay.



Unit Costs	**Unit**	**Cape Seal I (GTR Chip)**	**Cape Seal II**	**HMA Overlay**
Material / Pavement	$/yd^2	$4.50	$4.35	$6.60
Milling	$/inch			$3.00
Striping	$/ft	$0.23	$0.23	$0.23
Life Cycle Costs				
Material / Pavement	$/CB	$106,867	$103,304	$159,275
Striping	$/CB	$16,386	$16,386	$12,646
Disposal	$/CB	$432	$460	$447
Lane Rental Fee	$/CB	$22,326	$22,326	$17,287
Sum	$/CB	$146,011	$142,477	$189,656

Table 8. Life cycle costs – Southeast

8.3. Eco-Efficiency Analysis Portfolio:

The eco-efficiency analysis portfolio for the Cape Seal EEA has been generated as defined in Section 9.5 of the BASF EEA methodology. Utilizing weighting factors, the relative importance of each of the individual environmental impact categories are used to determine and translate the fingerprint results to the position on the environmental axis for each alternative shown. For clearer understanding of how weighting and normalization is determined and applied please reference Section 9 of BASF's Part A submittal to P-352. Default normalization factors were utilized for the environmental impact categories while the weighting factors applied to this study were for North America, as this was the intended target market for the use of the materials. The environmental weighting factors were last updated in 2014 by TNS[35] an external, qualified third-party organization.

Figure 29 displays the eco-efficiency portfolio for the base case analysis California (West Coast) and shows the results when all seven individual environmental categories are combined into a single environmental score and combined with its respective life cycle cost. Because environmental impact and cost are equally important, the most eco-efficient alternative is the one closest to the upper right-hand quadrant. Combining both the lowest life cycle cost as well as the lowest overall environmental impact, the asphalt rubber (AR) modified cape seal alternative (Cape Seal I) was the most eco-efficient alternative, over 30% better than the least eco-efficient alternative, the HMA overlay. The polymer modified, emulsion based cape seal (Cape Seal II) trailed the AR modified cape seal but was still about 15% more eco-efficient than the HMA thin hot mix overlay.

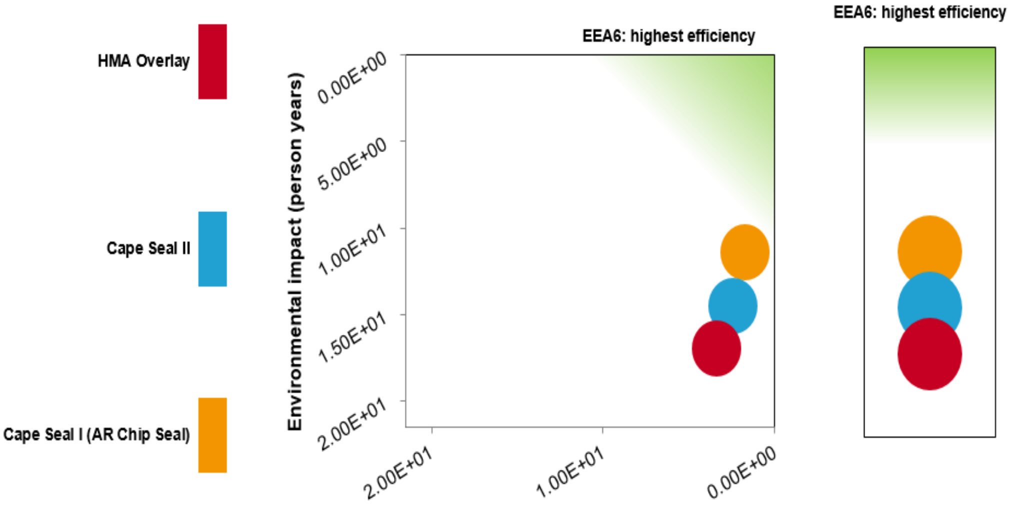


Figure 29. Eco-efficency portfolio base case analysis – California (West Coast)

For the Southeast analysis, due to their slightly better performance in both the environmental and economic assessments, the cape seal alternatives were the more eco-efficient alternatives when compared to the HMA overlay. Both cape seal technologies scored an eco-efficiency index score within 10% of one another and thus were deemed of similar eco-efficiencies. The Cape Seal II (polymer modified, emulsion based) alternative combined the lowest overall environmental impact and lowest life cycle cost giving it a 11.5% eco-efficiency advantage over the HMA overlay (worst performing alternative) and around a 5% advantage over the GTR modified cape seal.

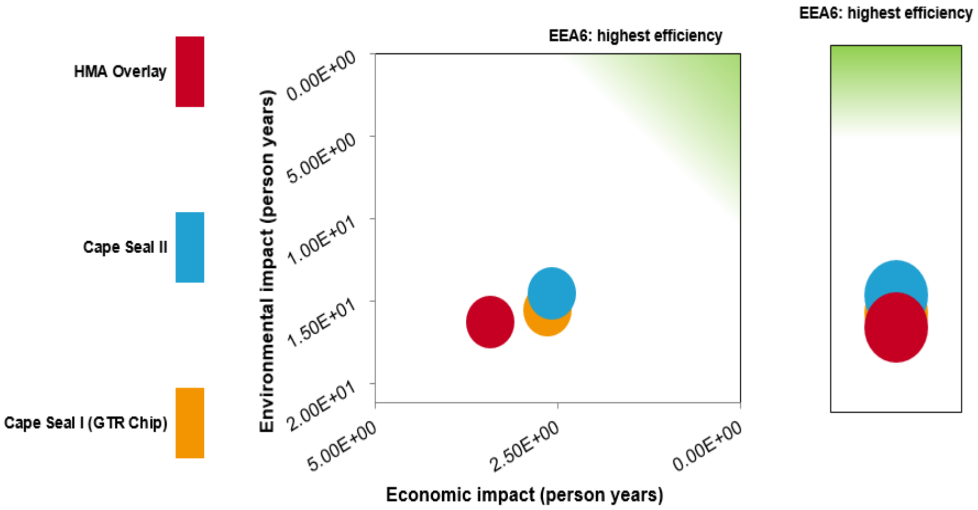


Figure 30. Eco-efficency portfolio base case analysis – Southeast

8.4. Scenario Analysis:

8.4.1. Scenario 1: Influence of durability on HMA asphalt (thin hot mix overlay)

This scenario looks at the impact of product durability on the hot mix asphalt overlay alternative. As discussed in the results, the durability of the pavement preservation technology is the key factor influencing the eco-efficiency of the design. For both the California (West Coast) and Southeast assessments, the durability assumption for HMA overlay was 12 years. This was a very fair assessment as literature[24,25] generally assigns a durability range between 7 -12 years. Thus, a sensitivity analysis was done for each analysis to determine at what durability does the HMA overlay become as eco-efficient as the leading alternative. Increasing durability, reduces both the environmental and economic impacts associated with an alternative.

For the California (West Coast) analysis and assuming the only variable modified was the durability of the HMA overlay, the HMA overlay would need to achieve a durability of 18 years to have the same eco-efficiency as the asphalt rubber (AR) modified cape seal. Conversely, a durability reduction to 11 years would make the AR modified cape seal equivalent to the polymer emulsion based cape seal and a durability reduction to just over 9 years would make the alternative equivalent to the HMA overlay.

Using the same basis, for the Southeast analysis, the HMA overlay would need to achieve a durability of over 13 years to have the same eco-efficiency as the leading alternative, the polymer modified, emulsion based cape seal (Cape Seal II). Conversely, a durability reduction to 7 years for the cape seal technologies would make them equivalent to the HMA overlay technology.

8.4.2. Scenario 2: Reduced HMA overlay temperatures (10% - 50% energy savings)

As detailed above in the results of the eco-efficiency analysis, a large contributor to the environmental footprint of the hot mix asphalt overlay technology is the large energy (fossil resource) requirement to achieve the desired production and application temperatures, normally between 280 °F – 325 °F. If technologies or chemistries could be developed that would reduce this temperature without compromising any technical or performance characteristic of the final product, a reduction of the product's environmental footprint could be achieved.

"*Warm mix asphalt (WMA) is a group of diverse technologies that allow a reduction in the temperatures at which the asphalt mixes are produced and applied. The goal of WMA is to produce mixtures with similar strength, durability, and performance characteristics as HMA using substantially reduced production temperatures. There are important environmental and health benefits associated with reduced production temperatures including lower greenhouse gas emissions, lower fuel consumption, and reduced exposure of workers to asphalt fumes. Lower production temperatures can also potentially improve pavement performance by reducing binder aging, providing added time for mixture compaction, and allowing improved compaction during cold weather paving*"[26].

Recent research shows that the usage of WMA is steadily increasing[27]. Many different warm mix technologies exist[27]: chemical additives or surfactants; foaming processes; organic additives etc. The intent of this scenario analysis is to not directly assess the individual WMA technologies, rather to assess the benefits of WMA technology relative to the established HMA technology. As mentioned previously the key benefit of WMA is the reduction of the asphalt production temperatures. Figure 31 represents a summary of the reported fuel savings based on literature reviewed as part of a NCHRP research project. Temperature decreases were reported in the range of 30 °F to 115 °F, with resulting savings falling generally between 10% - 50%.

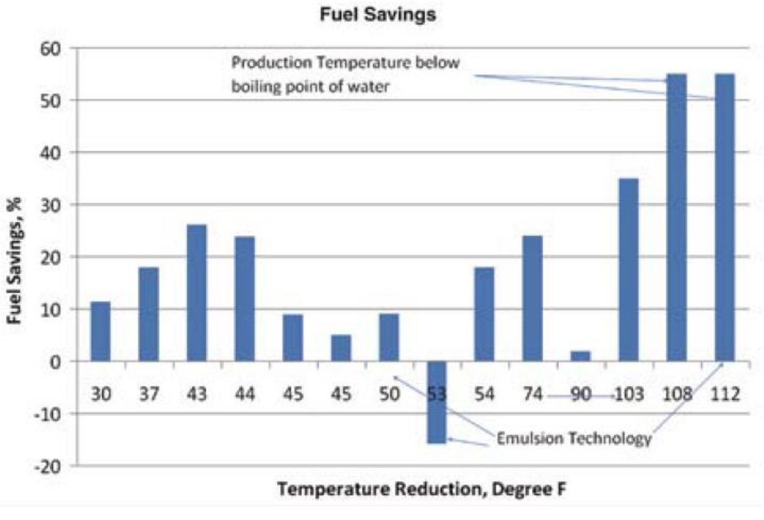


Figure 31. Summary of WMA fuel (energy) savings relative to HMA[27]

“*WMA technologies reduce the viscosity (thickness) of the asphalt binder so that asphalt aggregates can be coated at lower temperatures. The key is the addition of additives (e.g. water based, organic, chemical or hybrids) to the asphalt mix. The additives allow the asphalt binders and asphalt aggregates to be mixed at the lower temperatures*”.[31]

WMA additives (excluding pure water or water components) are generally in the range of 2-%-3% of bitumen weight[29]. Conservatively, this could add another 0.2% to the overall weight of an asphalt mix. Literature notes that manufacturing impacts for additives are similar to bitumen[29]. Thus, for this scenario to model the WMA additives, the aggregate weight was reduced by 0.2% while increasing bitumen by a corresponding 0.2%.

No other changes were made to the HMA assumptions (e.g. change in binder grade; RAP %; durability). Thus, 5 (five) new alternatives were assessed to represent the impact on the environmental profile of HMA (thin hot mix overlay) through production temperature decreases made possible through warm mix technologies. The following alternatives were evaluated for both the California (West Coast) and Southeast analyses.

a. 10% energy savings vs. base case
b. 20% energy savings vs. base case
c. 30% energy savings vs. base case
d. 40% energy savings vs. base case
e. 50% energy savings vs. base case

The results of scenario analysis #2 are shown below in Figures 32-35 for the California (West Coast) model and Figures 36-39 for the Southeast case study. As shown in Figure 32, the lower temperatures translated directly into CO$_2$ emissions reductions. Though not the only contributor to GHG emissions, the lowering of the production / mix temperatures led to carbon footprint reductions between 3% (10% energy savings) and 16% (50% energy savings).

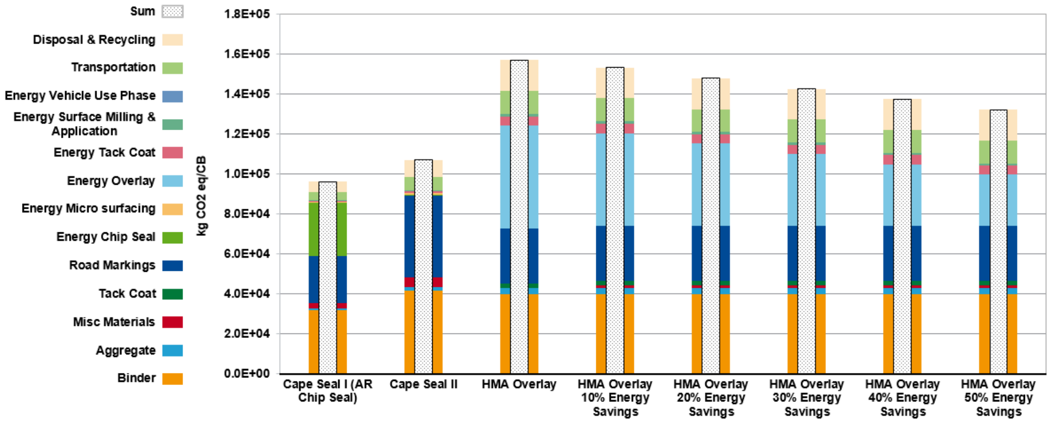


Figure 32. Scenario analysis 2 California (West Coast): HMA lower production temperatures (Energy Savings:10% - 50%) – Global Warming Potential

The environmental fingerprint in Figure 33 and contribution diagram in Figure 34 also show a steadily reducing overall environmental impact with the reduction in the HMA production temperatures.

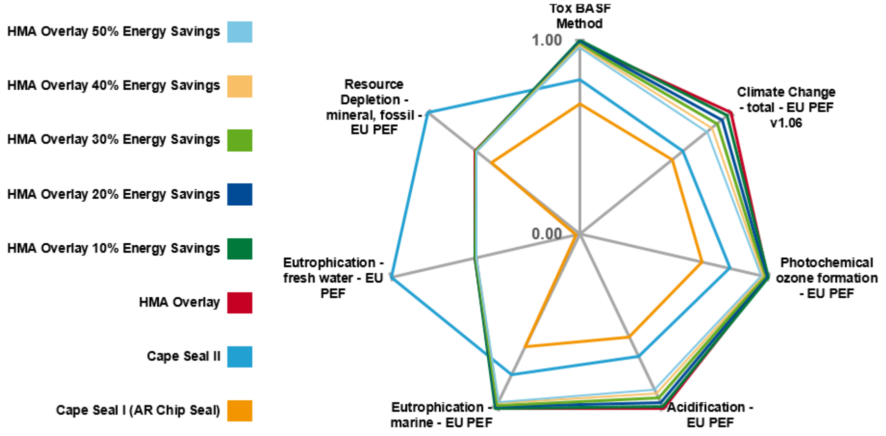


Figure 33. Scenario analysis 2 California (West Coast) : HMA lower production temperatures (Energy Savings:10% - 50%) – Environmental Fingerprint

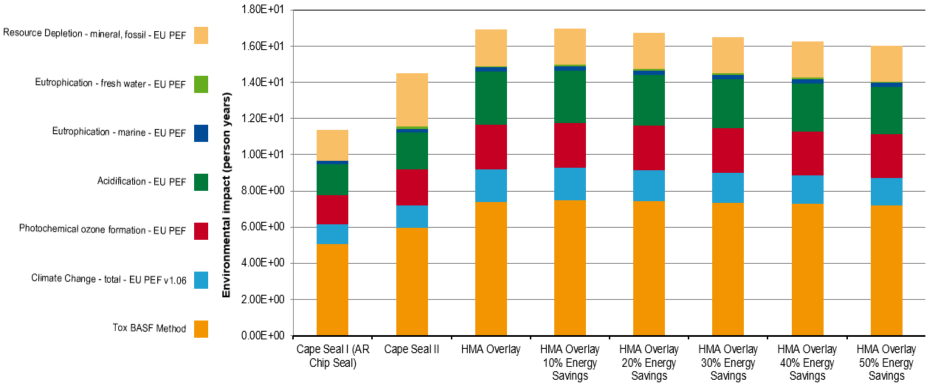


Figure 34. Scenario analysis 2 California (West Coast) : HMA lower production temperatures (Energy Savings:10% - 50%) – Environmental Contributions Diagram

For this scenario no adjustments were made to the economic assessments for the alternatives. The updated eco-efficiency portfolio for scenario analysis #2 California (West Coast) is shown in Figure 35.

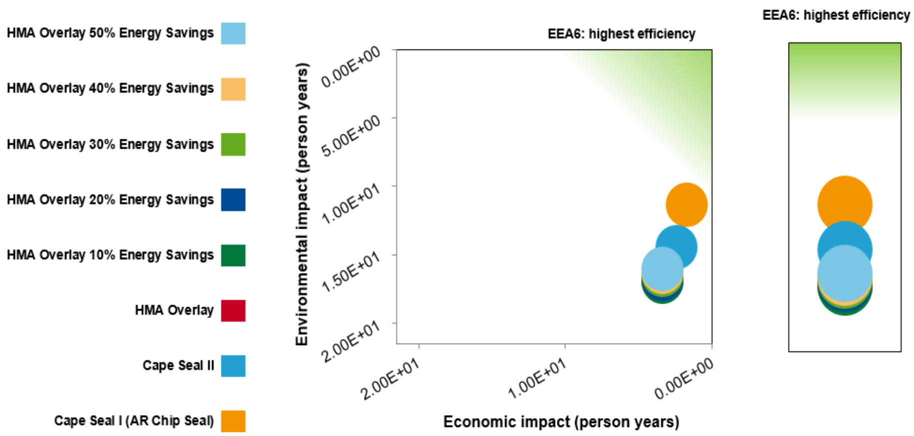


Figure 35. Scenario analysis 2 California (West Coast): HMA lower production temperatures (Energy Savings:10% - 50%) – Eco-Efficiency Portfolio

As expected, lower production temperatures for the HMA saves energy and thus reduces the overall environmental impact. Table 9 depicts the significance of the impact to the overall environmental impact and eco-efficiency score for each HMA alternative. Even with the improved scores, the HMA overlay technologies still trail both cape seal technologies.

Scenario #2 California (West Coast)	Cape Seal I (AR Chip Seal)	Cape Seal II	HMA Overlay	HMA Overlay 10% Energy Savings	HMA Overlay 20% Energy Savings	HMA Overlay 30% Energy Savings	HMA Overlay 40% Energy Savings	HMA Overlay 50% Energy Savings
Economic impact (person)	1.756	2.428	3.404	3.404	3.404	3.404	3.404	3.404
Environmental impact (person)	11.375	14.484	16.921	16.988	16.746	16.508	16.269	16.031
Environmental improvement vs HMA overlay	33%	14%		0%	1%	2%	4%	5%
Eco-Efficiency index	11.51	14.69	17.26	17.33	17.09	16.85	16.62	16.39
Eco-Efficiency advantage vs. HMA overlay	33%	15%		0%	1%	2%	4%	5%

Table 9. Scenario analysis #2 California (West Coast): envionmental impact and EEA index score

As shown in Figure 36 below, the lower HMA temperatures (energy consumption) led to carbon footprint reductions between 3% (10% energy savings) and 17% (50% energy savings) in the Southeast analysis.

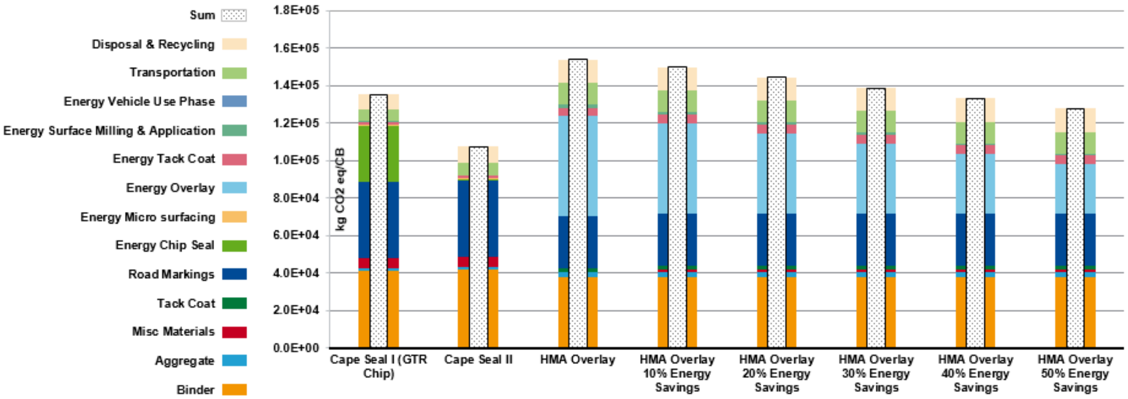


Figure 36. Scenario analysis 2 - Southeast: HMA lower production temperatures (Energy Savings:10% - 50%) – Global Warming Potential

Similar to the California (West Coast) model, the environmental fingerprint in Figure 37 and contribution diagram in Figure 38 show a steadily reducing overall environmental impact with the reduction in the HMA production temperatures for the Southeast analysis.

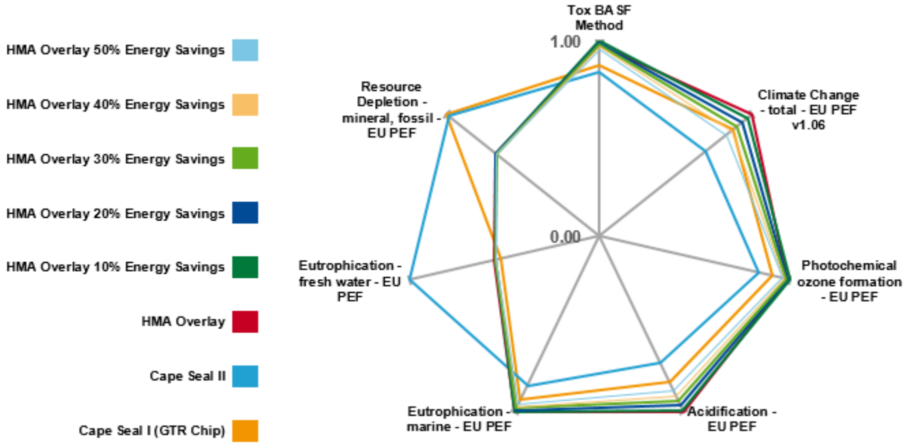


Figure 37. Scenario analysis 2 - Southeast: HMA lower production temperatures (Energy Savings:10% - 50%) – Environmental Fingerprint

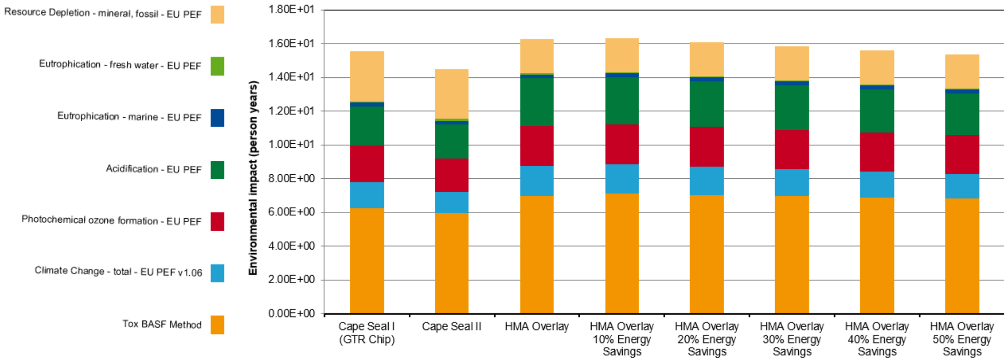


Figure 38. Scenario analysis 2 - Southeast: HMA lower production temperatures (Energy Savings:10% - 50%) – Environmental Contributions Diagram

For the Midewest / Southeast scenario no adjustments were made to the economic assessments for the alternatives. The updated eco-efficiency portfolio for scenario analysis #2 is shown below in Figure 39.

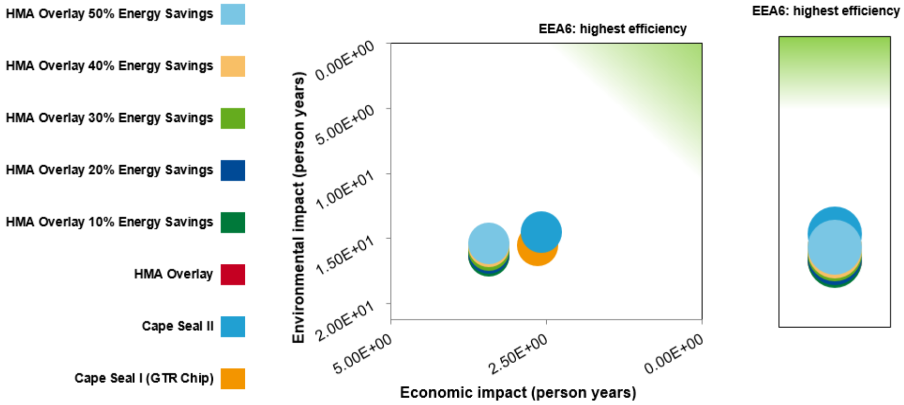


Figure 39. Scenario analysis 2 - Southeast: HMA lower production temperatures (Energy Savings:10% - 50%) – Eco-Efficiency Portfolio

As expected, lower the production temperature of the HMA does save energy and thus reduce overall environmental impact. Table 10 depicts the significance of the impact to the overall environmental impact and eco-efficiency score for each HMA alternative. At a 50% energy savings, the HMA thin overlay has a lower environmental impact than the GTR chip seal based cape seal technology and an equivalent eco-efficiency score. The polymer modified emulsion based cape seal still holds over a 5% advantage over the best performing HMA overlay alternative.

Scenario #2 Midwest / Southeast	Cape Seal I (GTR Chip Seal)	Cape Seal II	HMA Overlay	HMA Overlay 10% Energy Savings	HMA Overlay 20% Energy Savings	HMA Overlay 30% Energy Savings	HMA Overlay 40% Energy Savings	HMA Overlay 50% Energy Savings
Economic impact (person)	2.642	2.578	3.432	3.432	3.432	3.432	3.432	3.432
Environmental impact (person)	15.547	14.487	16.272	16.332	16.088	15.845	15.601	15.358
Environmental improvement vs HMA overlay	4%	11%		0%	1%	3%	4%	6%
Eco-Efficiency index	15.77	14.71	16.63	16.69	16.45	16.21	15.97	15.74
Eco-Efficiency advantage vs. HMA overlay	9%	15%		3%	5%	6%	7%	9%

Table 10. Scenario analysis #2 - Southeast: envionmental impact and EEA index score

8.4.3. Scenario 3: Reduced HMA overlay temperatures (10% - 50%) energy savings plus increase in RAP by 10%.

As cited in NAPA's Quality Improvement Publication 125 (Warm Mix Asphalt Best Practices)[28], typical WMA temperature reductions of approximately 50 °F (28 °C) can reduce the aging of virgin binder which in turn could allow for increases in the allowable amount of RAP. The NCHRP (National Cooperative Highway Research Program) 9-43 team estimates that improving the low temperature properties of the virgin binder by 0.6 °C will allow for 10% additional RAP binder to be added to the mixture without having to change the virgin binder grade[30]. The inclusion of additional RAP benefits the HMA alternative by reducing requirements for virgin aggregate and bitumen (in the binder).

This scenario thus builds upon the assumptions of scenario #2 and evaluates the impacts of incremental reductions in hot mix overlay mix and placement temperatures (Scenario #2) with an increase allotment of RAP by 10%.

a. 10% energy savings vs. base case + 10% additional RAP

b. 20% energy savings vs. base case + 10% additional RAP
c. 30% energy savings vs. base case + 10% additional RAP
d. 40% energy savings vs. base case + 10% additional RAP
e. 50% energy savings vs. base case + 10% additional RAP

As shown in Figure 40 (California (West Coast)), the increase in RAP by 10% contributed significantly to a further reduction in the CO_2 emissions for the HMA alternatives. Overall reductions were between 6% (10% energy savings & 10% additional RAP) and 19% (50% energy savings & 10% additional RAP). About an additional 3% GHG emissions reduction for each HMA alternative relative to scenario #2 California (West Coast).

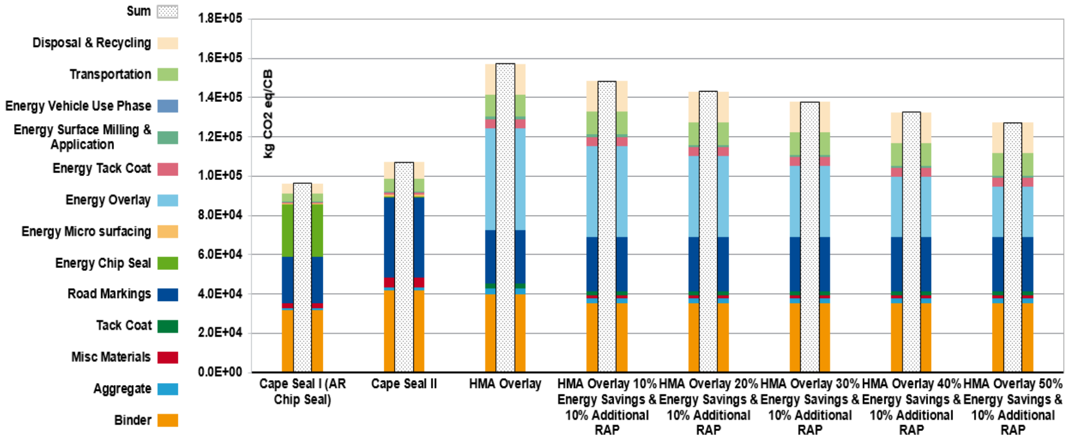


Figure 40. Scenario analysis 3 California (West Coast): HMA lower production temperatures (Energy Savings:10% - 50%) & 10% additional RAP – Global Warming Potential

The environmental fingerprint in Figure 41 and contribution diagram in Figure 42 show a steadily reducing overall environmental impact with the combined reduction in the HMA production temperatures and increase in RAP percentage.

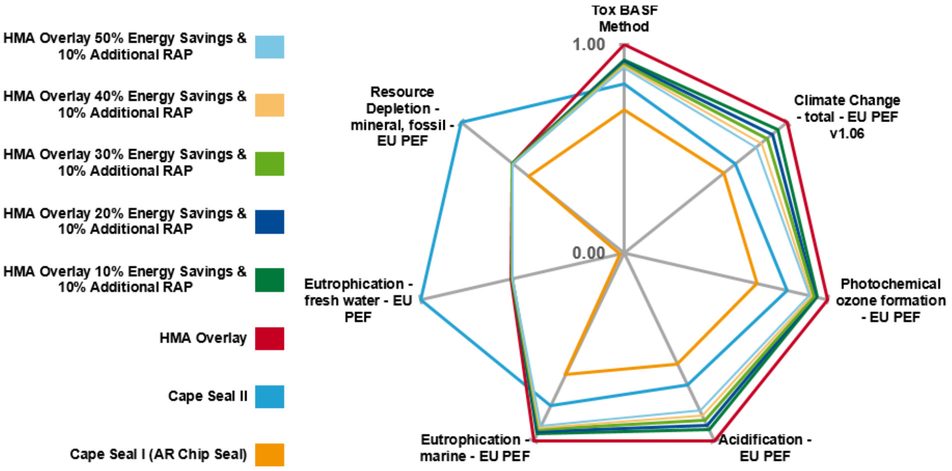


Figure 41. Scenario analysis 3 California (West Coast) : HMA lower production temperatures (Energy Savings:10% - 50%) & 10% additional RAP – Environmental Fingerprint

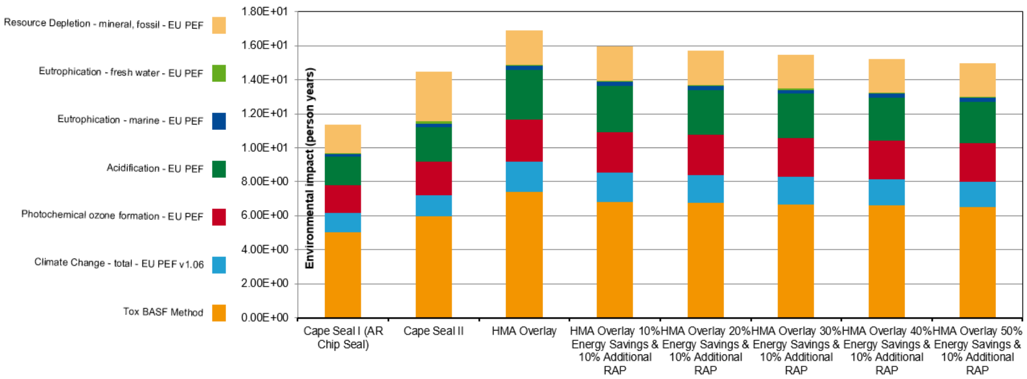


Figure 42. Scenario analysis 3 California (West Coast) : HMA lower production temperatures (Energy Savings:10% - 50%) & 10% additional RAP – Environmental Contributions Diagram

As was the case for scenario #2, no adjustments were made to the economic assessments for the alternatives. The updated eco-efficiency portfolio for scenario analysis #3 California (West Coast) is shown in Figure 43.

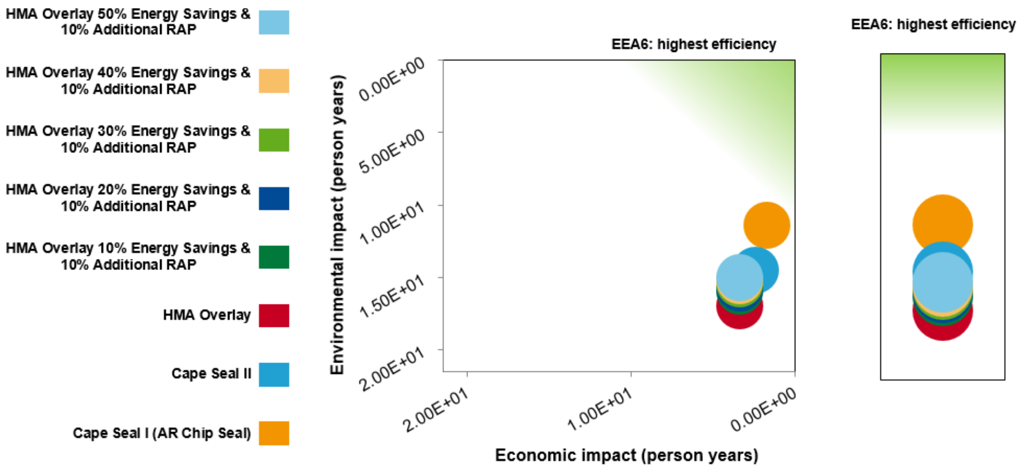
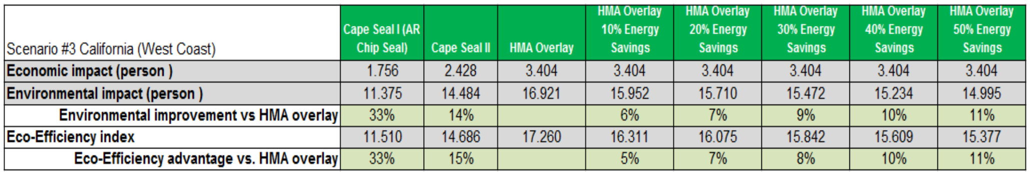


Figure 43. Scenario analysis 3 California (West Coast): HMA lower production temperatures (Energy Savings:10% - 50%) & 10% additional RAP – Eco-Efficiency Portfolio

Table 11 depicts the significance of the impact to the overall environmental impact and eco-efficiency score for each HMA alternative based on the scenario #3 revisions. At a 50% energy reduction and 10% additional RAP, the HMA thin overlay has improved its environmental and eco-efficiency performance by around 11% when compared to the base case HMA. Even with only a 10% energy savings, the 10% additional RAP reduces environmental impact by around 6%. Even with this marketable improvement, the AR modified chip seal alternative is still the most eco-efficient alternative. The polymer modified emulsion based cape seal has only a 4% advantage over the best performing HMA overlay alternative.



Scenario #3 California (West Coast)	Cape Seal I (AR Chip Seal)	Cape Seal II	HMA Overlay	HMA Overlay 10% Energy Savings	HMA Overlay 20% Energy Savings	HMA Overlay 30% Energy Savings	HMA Overlay 40% Energy Savings	HMA Overlay 50% Energy Savings
Economic impact (person)	1.756	2.428	3.404	3.404	3.404	3.404	3.404	3.404
Environmental impact (person)	11.375	14.484	16.921	15.952	15.710	15.472	15.234	14.995
Environmental improvement vs HMA overlay	33%	14%		6%	7%	9%	10%	11%
Eco-Efficiency index	11.510	14.686	17.260	16.311	16.075	15.842	15.609	15.377
Eco-Efficiency advantage vs. HMA overlay	33%	15%		5%	7%	8%	10%	11%

Table 11. Scenario analysis #3 California (West Coast): envionmental impact and EEA index score

As shown in Figure 44, the increase in RAP by 10% contributed significantly to a further reduction in the CO_2 emissions for the HMA alternatives in scenario #3, Southeast. Overall reductions were between 7% (10% energy savings & 10% additional RAP) and 21% (50% energy savings & 10% additional RAP). About an additional 4% GHG emissions reduction for each HMA alternative relative to scenario #2.

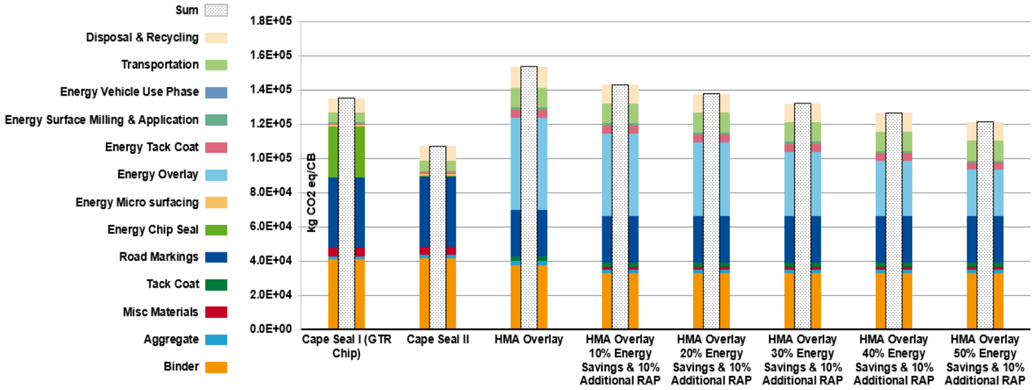


Figure 44. Scenario analysis 3 - Southeast: HMA lower production temperatures (Energy Savings:10% - 50%) & 10% additional RAP – Global Warming Potential

The environmental fingerprint in Figure 45 and contribution diagram in Figure 46 show a steadily reducing overall environmental impact with the combined reduction in the HMA production temperatures and increase in RAP percentage by 10%.

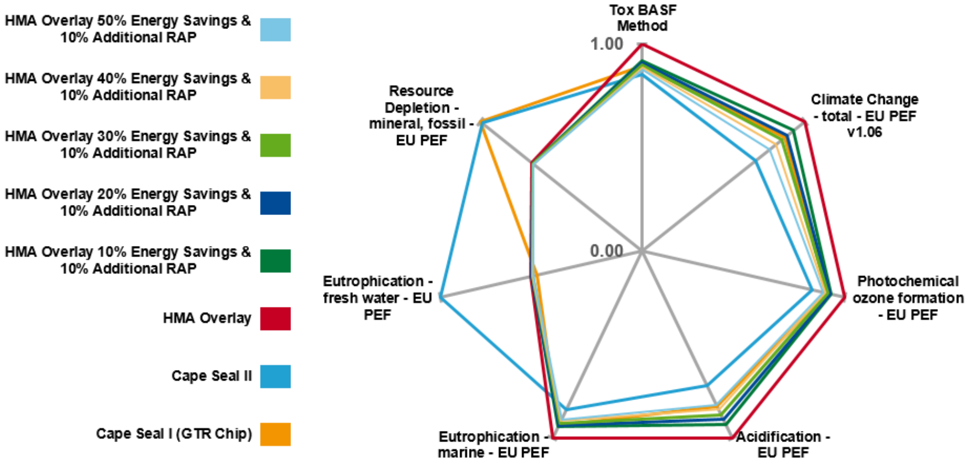


Figure 45. Scenario analysis 3 - Southeast: HMA lower production temperatures (Energy Savings:10% - 50%) & 10% additional RAP – Environmental Fingerprint

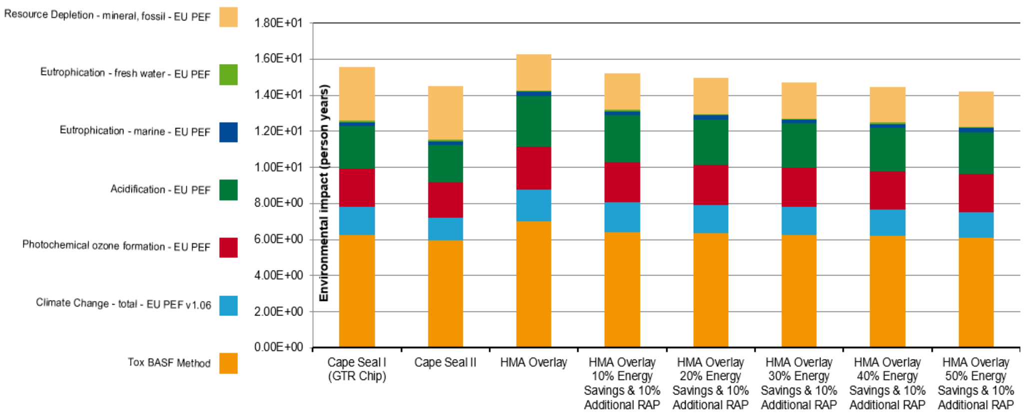


Figure 46. Scenario analysis 3 - Southeast: HMA lower production temperatures (Energy Savings:10% - 50%) & 10% additional RAP – Environmental Contributions Diagram

No adjustments were made to the economic assessments for the alternatives. The updated eco-efficiency portfolio for scenario analysis #3 Southeast is shown in Figure 47.

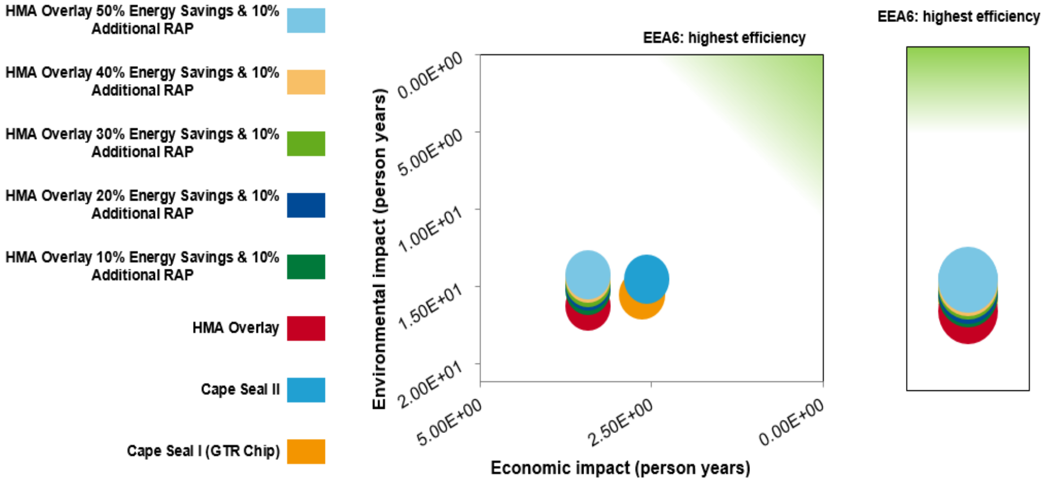
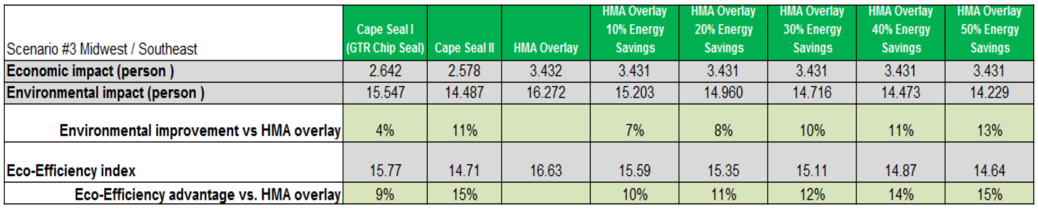


Figure 47. Scenario analysis 3 - Southeast: HMA lower production temperatures (Energy Savings:10% - 50%) & 10% additional RAP – Eco-Efficiency Portfolio

Table 12 depicts the significance of the impact to the overall environmental impact and eco-efficiency score for each HMA alternative based on the scenario #3 revisions. At a 50% energy reduction and 10% additional RAP, the HMA thin overlay has improved its environmental and eco-efficiency performance by 13% and 15% respectively when compared to the base case HMA. At 10% energy savings and 10% addditional RAP, the HMA overlay technology is more eco-efficient than the GTR modified cape seal alternative. The HMA overlay technolgy for the Southeast analysis becomes as eco-efficient as the leading alternative (polymer modified emulsion based cape seal) when energy savings are > 40% and 10% additional RAP are achieved.



Scenario #3 Midwest / Southeast	Cape Seal I (GTR Chip Seal)	Cape Seal II	HMA Overlay	HMA Overlay 10% Energy Savings	HMA Overlay 20% Energy Savings	HMA Overlay 30% Energy Savings	HMA Overlay 40% Energy Savings	HMA Overlay 50% Energy Savings
Economic impact (person)	2.642	2.578	3.432	3.431	3.431	3.431	3.431	3.431
Environmental impact (person)	15.547	14.487	16.272	15.203	14.960	14.716	14.473	14.229
Environmental improvement vs HMA overlay	4%	11%		7%	8%	10%	11%	13%
Eco-Efficiency index	15.77	14.71	16.63	15.59	15.35	15.11	14.87	14.64
Eco-Efficiency advantage vs. HMA overlay	9%	15%		10%	11%	12%	14%	15%

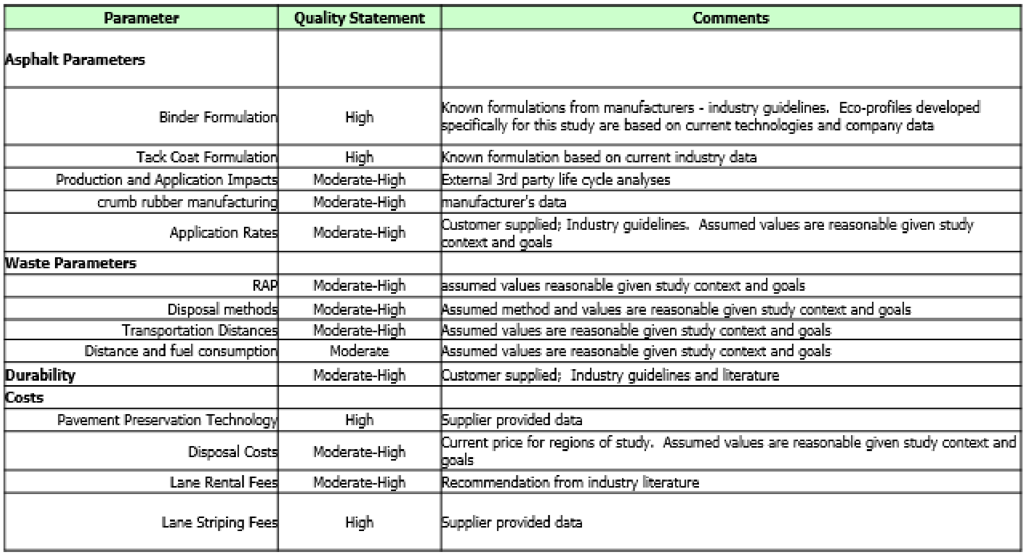
Table 12. Scenario analysis #3 - Southeast: envionmental impact and EEA index score

Overall, scenario #3 shows the potential benefits of technologies which reduce operating temperatures of hot mix asphalt and enable the use of additional recycle content (i.e. RAP) without compromising the performance characteristics or costs.

9. Data Quality Assessment

9.1. Data Quality Statement:

The data used for parameterization of the EEA was sufficient with most parameters of medium to high data quality. Moderate data is where industry average values or assumptions pre-dominate the value. No critical uncertainties or significant data gaps were identified within the parameters and assumptions that could have a significant effect on the results and conclusions. Table 13 provides a summary of the data quality for the EEA.



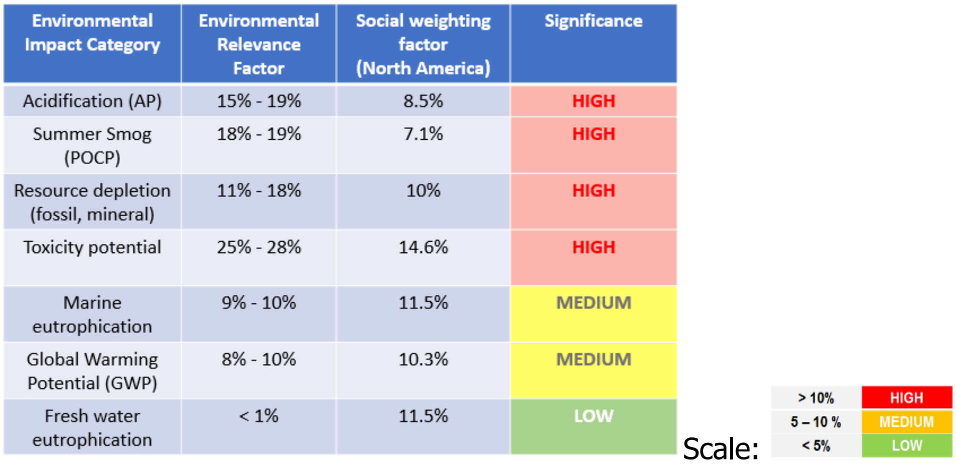
Parameter	Quality Statement	Comments
Asphalt Parameters		
Binder Formulation	High	Known formulations from manufacturers - industry guidelines. Eco-profiles developed specifically for this study are based on current technologies and company data
Tack Coat Formulation	High	Known formulation based on current industry data
Production and Application Impacts	Moderate-High	External 3rd party life cycle analyses
crumb rubber manufacturing	Moderate-High	manufacturer's data
Application Rates	Moderate-High	Customer supplied; Industry guidelines. Assumed values are reasonable given study context and goals
Waste Parameters		
RAP	Moderate-High	assumed values reasonable given study context and goals
Disposal methods	Moderate-High	Assumed method and values are reasonable given study context and goals
Transportation Distances	Moderate-High	Assumed values are reasonable given study context and goals
Distance and fuel consumption	Moderate	Assumed values are reasonable given study context and goals
Durability	Moderate-High	Customer supplied; Industry guidelines and literature
Costs		
Pavement Preservation Technology	High	Supplier provided data
Disposal Costs	Moderate-High	Current price for regions of study. Assumed values are reasonable given study context and goals
Lane Rental Fees	Moderate-High	Recommendation from industry literature
Lane Striping Fees	High	Supplier provided data

Table 13. Data quality evaluation for EEA parameters

10. Sensitivity and Uncertainty Analysis

10.1. Sensitivity and Uncertainty Considerations:

A sensitivity analysis of the final results indicates that the environmental impacts were more influential or relevant in determining the final relative eco-efficiency positions of the alternatives. This conclusion is supported by reviewing the normalized person time equivalents for both the economic and environmental impacts and noting that the environmental impacts are around 5x – 6x higher. As the data quality related to the environmental life cycle inventories (Table 6) and the study parameters (Table 13) are at least medium to high quality, we were confident in the final conclusions indicated by the study.   Table 14 summarizes the environmental relevance factors and societal weighting factors utilized for the cape seal eco-efficiency analysis.



Environmental Impact Category	Environmental Relevance Factor	Social weighting factor (North America)	Significance
Acidification (AP)	15% - 19%	8.5%	HIGH
Summer Smog (POCP)	18% - 19%	7.1%	HIGH
Resource depletion (fossil, mineral)	11% - 18%	10%	HIGH
Toxicity potential	25% - 28%	14.6%	HIGH
Marine eutrophication	9% - 10%	11.5%	MEDIUM
Global Warming Potential (GWP)	8% - 10%	10.3%	MEDIUM
Fresh water eutrophication	< 1%	11.5%	LOW

Scale:

> 10%	HIGH
5 – 10 %	MEDIUM
< 5%	LOW

Table 14. Environmental relevance factors, social weighting factors, and significance used in the sensitivity and uncertainty analysis

10.2. Critical Uncertainties:

There were no significant critical uncertainties from this study that would limit the findings or interpretations of this study. The data quality, relevance, and sensitivity of the study support the use of the input parameters and assumptions as appropriate and justified.

11. Limitations of EEA Study Results

11.1. Limitations:

The eco-efficiency analysis results and the conclusions are based on the specific comparison of the production, use, and disposal phases, for the described customer benefit, alternatives, system boundaries and specific study assumptions. Transfer of these results and conclusions to other production methods or products is expressly prohibited. In particular, partial results may not be communicated so as to alter the meaning, nor may arbitrary generalizations be made regarding the results and conclusions.

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