LIFE CYCLE ASSESSMENT OF STYRENE-BUTADIENE-STYRENE BLOCK COPOLYMER

ASPHALT INSTITUTE

JUNE 2022

WAP SUSTAINABILITY CONSULTING

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DOCUMENT SUMMARY

The following table identifies the relevant details of the life cycle assessment (LCA).

COMMISSIONER	Asphalt Institute 2696 Research Park Dr. Lexington, KY, 40511
PRODUCT	Styrene-butadiene-styrene block copolymer (SBS)
DECLARED UNIT	1 kg of SBS used as an additive to liquid asphalt for pavement and roofing applications
REFERENCE STANDARDS	☒ ISO 14040 ☒ ISO 14044
LCA SCOPE	Cradle-to-Gate
LCA STUDY DETAILS	Completed: June 2022 LCA Practitioners: Maggie Wildnauer & Lydia Schreiber, WAP Sustainability Consulting, LLC
YEAR OF PRIMARY DATA	2020
LCA SOFTWARE	GaBi 10.6.135
LCA DATABASE	GaBi Database Service Pack 2022.1
LCIA METHODOLOGY	IPCC, TRACI 2.1, CML2001 (Aug 2016)
APPLICABLE REGION(S)	North America

Important Note: Results presented in this report are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

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ACRONYMS

ADPE	Abiotic depletion potential for non-fossil resources (elements)
ADPF	Abiotic depletion potential for fossil resources
AI	Asphalt Institute
AP	Acidification potential of soil and water
CML	Centrum voor Milieukunde Leiden
COD	Chemical oxygen demand
CRU	Components for reuse
DOT	Department of transportation
EP	Eutrophication potential
EPD	Environmental product declaration
FW	Net use of fresh water
GWP	Global warming potential
HLRW	High-level radioactive waste
HWD	Hazardous waste disposed
ILLRW	Intermediate- and low-level radioactive waste, conditioned, to final repository
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
MER	Materials for energy recovery
MFR	Materials for recycling
NHWD	Non-hazardous waste disposed
NMVOC	Non-methane volatile organic compound
NRPRE	Use of non-renewable primary energy
NRPRM	Use of non-renewable primary energy as materials
NRPRT	Total use of non-renewable primary energy resources
NRSF	Non-renewable secondary fuels
ODP	Ozone depletion potential

PM	Particulate matter
POCP	Photochemical ozone creation potential
RE	Recovered energy
RPRE	Use of renewable primary energy
RPRM	Use of renewable primary energy as materials
RPRT	Total use of renewable primary energy resources
RSF	Renewable secondary fuels
SBR	Styrene butadiene rubber
SBS	Styrene butadiene styrene
SFP	Smog formation potential
SM	Secondary materials
TRACI	Tool for the Reduction and Assessment of Chemical and Other Env. Impacts

EXECUTIVE SUMMARY

Current trends in corporate sustainability emphasize transparency and the evaluation of environmental and social impacts throughout a product's entire value chain. Thus, life cycle assessment (LCA) is considered an important delivery tool of transparent market communication. The Asphalt Institute commissioned this study to increase the availability of high-quality life cycle inventory datasets used to develop environmental product declarations (EPDs). Increasingly, EPDs are being requested by customers purchasing asphalt products, including state departments of transportation (DOTs).

For this cradle-to-gate study, the declared unit is 1 kg of styrene-butadiene-styrene (SBS) manufactured during calendar year 2020, used in liquid asphalt modification for paving and roofing applications. The results represent an industry average for SBS sold to the North American market. The study includes different grades of SBS polymers that may have somewhat different performance characteristics in asphalt modification. The industry average was created using a weighted average based on sales to North America provided by the four participating companies. Though not required, a critical review was conducted to ensure that the LCA has met all relevant standards and that the methodology and results are reasonable.

Key inputs evaluated in the study include electrical and thermal energy consumption, transportation, and sourcing of raw materials.

The industry-average results reveal that raw materials inputs are the main driver of impacts in all assessed categories. This is because the raw materials, styrene and butadiene, are made from petrochemicals. The second largest source of impacts is thermal energy (i.e., steam), which is powered by fossil fuels. The results of this study are presented in Table 1, with impact drivers highlighted in Figure 1.

Table 1: Impact assessment, SBS, per kg

Impact Category	Value	Unit
IPCC AR5		
GWP	2.89E+00	kg CO_2 eq
IPCC AR6		
GWP	2.88E+00	kg CO_2 eq
TRACI 2.1		
AP	3.92E-03	kg SO_2 eq
EP	3.08E-04	kg N eq
ODP	8.09E-09	kg CFC 11 eq
Resources	1.20E+01	MJ, surplus energy
SFP	9.44E-02	kg O_3 eq

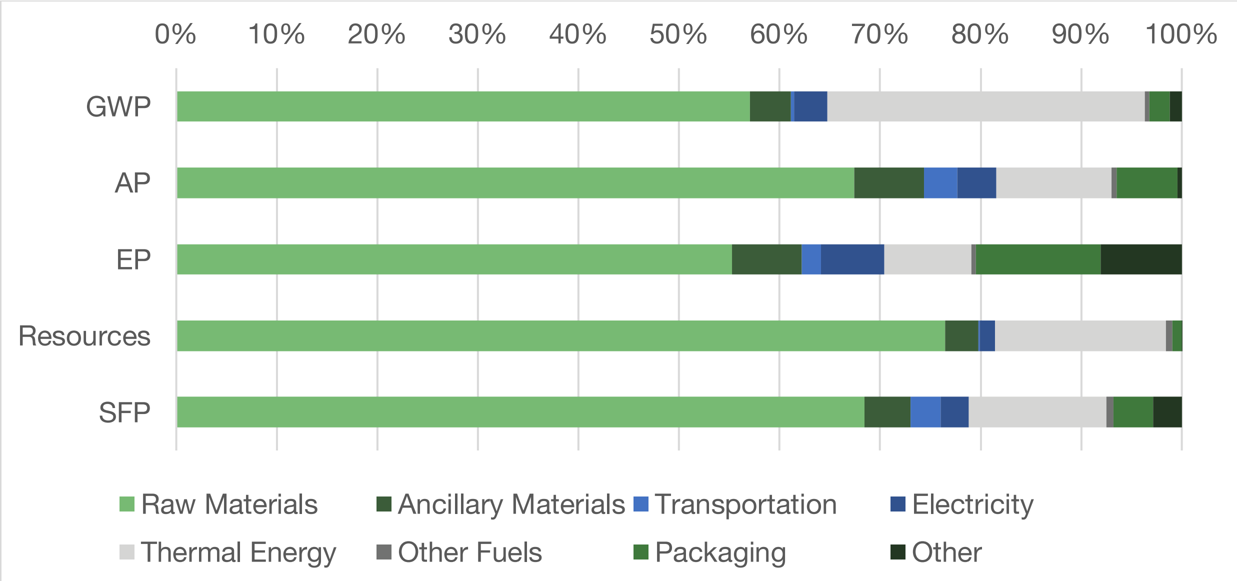

Figure 1: Overview of Product Impacts

Sensitivity analysis results were conducted on transportation of the SBS to a US warehouse as well as the source for upstream production of butadiene. It was found that AP, EP, and SFP were most significantly affected. The current results are considered to accurately represent the present state of SBS used in North American asphalt modification; however, LCA practitioners should keep these sensitivity results in mind when using the results of this study.

1 GOAL

The Asphalt Institute (AI) commissioned this life cycle assessment on styrene-butadiene-styrene (SBS), used as an additive to liquid asphalt (also referred to as bitumen) for pavement and roofing applications in North America, with the support of four affiliate members: Dynasol Group, Kraton Corporation, LCY Group, and TSRC.

The Asphalt Institute is the international trade association of petroleum asphalt producers, manufacturers, and affiliated businesses. Through education, engineering, technical development, environmental stewardship and marketing leadership, the Asphalt Institute promotes the safe use, benefits, and quality performance of petroleum asphalts in a unified voice for their membership. Following AI's previously commissioned LCA study on asphalt binder, member organizations saw an opportunity for data quality improvement in life cycle inventories (LCIs) of SBS used in the previous study by replacing proxy datasets with product-specific datasets for SBS (thinkstep AG, 2019).

This industry-wide cradle-to-gate LCA was conducted for the development of a life cycle inventory (LCI) dataset for SBS, used primarily in liquid asphalt modification. The resulting dataset will be made publicly available to the larger LCA community via digital format. The intended audience includes the LCA critical reviewer, the asphalt industry, and the LCA community. The LCA community may use this LCI dataset in LCAs for the development of environmental product declarations (EPDs). EPDs are public-facing documents used to transparently communicate environmental information for products. Increasingly, EPDs are being requested by customers purchasing construction products, including state departments of transportation (DOTs).

The LCA has been conducted in conformance with ISO14040/44 (ISO, 2006; ISO, 2006). To ensure the study supports users of the resulting dataset in developing ISO 21930-conformant EPDs, this LCA uses ISO 21930 as a guide. This means this study follows the requirements defined by the ISO 21930 standard for life cycle scope, methodological framework for LCA modeling, criteria for inclusion and exclusion for inputs and outputs, selection of data and data quality requirements, use of SI units, data collection, calculation procedures, principles for allocation, and declaration of additional environmental indicators. Within an ISO 21930 conformant EPD this dataset would fall under module A1 (Production: Extraction and upstream production). A critical review has been conducted to verify conformance.

Primary data were provided by the participating affiliate members. WAP Sustainability Consulting was contracted to develop the LCA model and complete this background report. Maggie Wildnauer of WAP Sustainability served as the project manager and lead LCA practitioner with support from Lydia Schreiber, also of WAP Sustainability.

This study was not completed with the intent that comparative assertions with external objects or general public disclosures (i.e., comparative marketing claims) would be made.

2 SCOPE OF THE STUDY

2.1 LCA METHODOLOGICAL FRAMEWORK

The LCA follows an attributional approach.

2.2 PRODUCT DESCRIPTION

This life cycle assessment report covers SBS, used as an additive to liquid asphalt for pavement and roofing applications in North America. The study includes different grades of SBS polymers that may have somewhat different performance characteristics in liquid asphalt modifications.

SBS is a styrenic thermoplastic elastomer commonly used in the modification of asphalt binder. Thermoplastic elastomers are copolymers with rubbery characteristics produced rapidly using thermoplastic processing methods. SBS has hard polystyrene end segments that form spherical domains distributed throughout the continuous, rubbery butadiene phase. The polystyrene segments act as crosslinks, tying together the elastomeric butadiene (Holden, 2011). This study applies to all the basic types of SBS polymer with approximately 30% styrene content. This includes linear, radial and diblock SBS polymers. Refer to section 2.4.2 for details on specific grades.

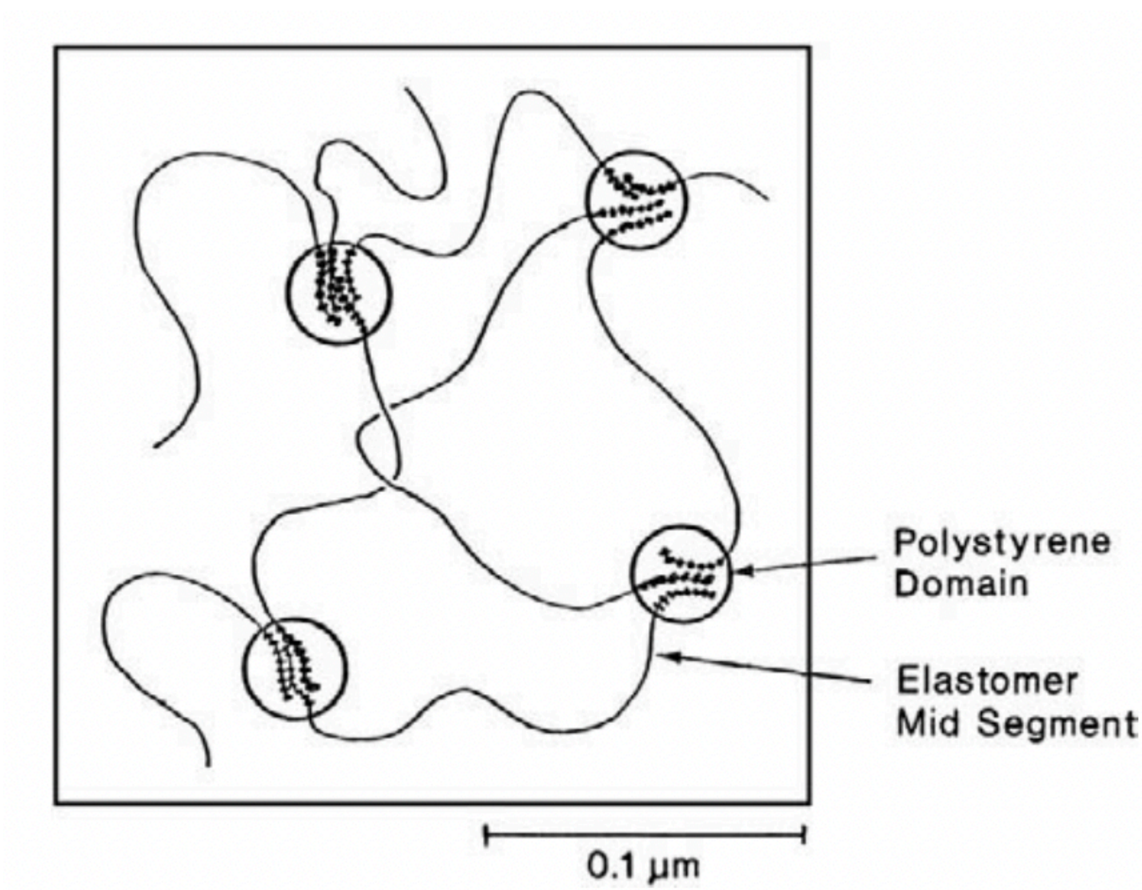

Figure 2: Morphology of styrenic block copolymers (Holden, 2011).

For paving applications, SBS polymer modification improves resistance to both rutting and cracking, more commonly used for higher traffic loads and/or slow or static traffic. SBS polymer modification is used for both hot mix asphalt and emulsion applications. Also, it is useful for climatic regions with more extreme temperature ranges. Consequently, it is used throughout North America and globally. For roofing applications, SBS polymer modification is used for low slope modified bitumen roll roofing products. For steep slope applications it is used in self-adhering underlayments. For asphalt shingles SBS modified asphalt is used to improve adhesion for tab adhesives and for laminating adhesives for architectural shingles. It is also used in modification of the body of the shingle to improve impact resistance.

The range of SBS polymer modification for asphalt paving applications varies from about 1% to about 8% based on performance-related specification requirements. For asphalt roofing applications, the SBS polymer content may be up to 12% or higher.

The results of this LCA study are for an industry average of SBS produced by four (4) AI member companies at six (6) sites in Europe, Mexico, and the United States. The participating companies and sites are listed in Table 2 below.

Table 2: Participating sites

Company	Facilities
Dynasol	Cantabria, ES Altamira, MX
Kraton	Berre, FR Wesseling, DE
TSRC	Plaquemine, LA, USA
LCY	Baytown, TX, USA

Participants and sites were selected based on willingness to participate. Products from the six cited production facilities comprise greater than 50% of SBS polymer for roofing and paving applications in North America.

2.3 DECLARED UNIT

The declared unit is 1 kg of SBS, used as an additive to liquid asphalt for pavement and roofing applications.

2.4 SYSTEM BOUNDARY

This LCA is a Cradle-to-Gate study, where the gate is defined as the gate of the factory. An overview of the system boundary is shown in Figure 3.

Figure 3: System Boundary Summary

The system boundary includes raw material extraction, inbound transportation of raw materials to facilities, and manufacturing requirements. Inclusions and exclusions from the system boundary are presented in Table 3.

Table 3: Items Included in System Boundary

Included	Excluded
Extraction and processing of raw materials and packaging	Creation of supplier facilities
Transportation of materials and packaging to the manufacturing location	Manufacturing of supplier operational equipment or transport vehicles
Manufacturing of products, including energy, water, material usage, direct emissions, and water disposal	

Transportation from manufacturing facility to customer was excluded from the system boundary. This stage is considered variable because there is a mix of customers purchasing SBS directly from the manufacturing facility or purchasing from a distributor warehouse. A sensitivity analysis examining the effects of including this life cycle stage in the system boundary is presented in Section 5.2.

2.4.1 Time Coverage

The data represents production of SBS in calendar year 2020 and, as such, data was provided by AI member companies for 12 consecutive months during 2020.

2.4.2 Technical Coverage

The study is intended to represent the industry average SBS production technology. More specifically, the grades included are for use as modifiers in asphalt. Table 4 shows the technical properties of the range of SBS grades included in the assessment.

Table 4: Technical Specifications

Specifications	Value	Unit	Standard
Specific gravity	0.94	-	ASTM D 792
Volatile Matter	<1.0	%	ASTM D 5668
Ash Content	Typically <1.0, dependent on method of supply (i.e., pellets, powder)	%	ASTM D 5667
Bound Styrene	23-35	%	-

Table 5 lists the grades of SBS represented in the study.

Table 5: Represented SBS Grades

Company	SBS Grade
Dynasol	Calprene 401 Calprene 411 Calprene 480X Calprene 500 Calprene 501 Calprene 580
Kraton	D1101 A D1192 E
TSRC	Vector 2336A Vector 2411A Vector 2518A Vector 2518ALD
LCY	Globalprene 3411 Globalprene 3412 Globalprene 3501 Globalprene 3520 Globalprene 3522 Globalprene 3537 Globalprene 3566 Globalprene 3710 Globalprene 3741

2.4.3 Geographical Coverage

This study is intended to represent the AI member companies' products sold in the North America market, produced by facilities in North America and Europe. Background data are intended to represent the respective countries or regions of production (USA, Mexico, Spain, France, Germany) and raw material sourcing (Europe, North America).

2.5 CUT-OFF CRITERIA

Material inputs greater than 1% (based on total mass of the final product) were included within the scope of analysis. Material inputs less than 1% were included if sufficient data was available to warrant inclusion and/or the material input was thought to have significant environmental impact. No inputs or outputs were knowingly excluded from the scope of analysis.

Some material inputs may have been excluded within the GaBi datasets used for this project. All GaBi datasets have been critically reviewed and conform to the exclusion requirement of ISO 14040/44.

2.6 ALLOCATION PROCEDURES

General principles of allocation were based on ISO 14040/44. There are no products other than the product under study that are produced as part of the manufacturing processes. Since there are no co-products, no allocation based on co-products is required.

To derive a per-unit value for manufacturing inputs such as electricity, thermal energy, and water, allocation based on total production by mass was adopted. As a default, secondary GaBi datasets use a physical mass basis for allocation.

2.7 SELECTION OF LCIA METHODOLOGY AND IMPACT CATEGORIES

Environmental Impacts were calculated using the GaBi software platform. Impact results have been calculated using IPCC AR5 (IPCC, 2013), IPCC AR6 (IPCC, 2021), TRACI 2.1 (US EPA, 2012), and CML 2001-Jan 2016 (CML - Department of Industrial Ecology, 2016) characterization factors. Results for indicators required by ISO 21930 for EPDs are also included (ISO, 2017). Results presented in this report are relative expressions and do not predict impacts on category endpoints, the exceeding of thresholds, safety margins, or risks.

These impact categories were selected in alignment with the goal of the study. The primary intended use for this data is in the development of EPDs for production and purchase in North America, leading to the selection of IPCC, TRACI, and ISO 21930 indicators. Both IPCC AR5 and AR6 indicators are included for completeness. To provide more information for member companies that manufacture SBS in Europe and to add completeness to the results, results for CML 2001 indicators are also presented.

Table 6: LCIA Indicators

Abbreviation	Parameter	Unit
	IPCC AR5	
GWP	GWP 100, excluding biogenic CO_2	kg CO_2 eq
	IPCC AR6	
GWP	GWP 100, excluding biogenic CO_2	kg CO_2 eq
	TRACI 2.1	
AP	Acidification potential of soil and water	kg SO_2 eq
EP	Eutrophication potential	kg Phosphate eq
ODP	Ozone depletion of air	kg O_3 eq
Resources	Use of fossil fuel resources	MJ, surplus energy
SFP	Smog formation potential	kg O_3 eq.
	CML 2001-Jan 2016	
AP	Acidification potential of soil and water	kg SO_2 eq
EP	Eutrophication potential	kg Phosphate eq
ODP	Depletion of stratospheric ozone layer	kg CFC 11 eq
ADPE	Abiotic depletion potential for non-fossil resources	kg Sb eq
ADPF	Abiotic depletion potential for fossil resources	MJ, net calorific value
POCP	Photochemical ozone creation potential	kg Ethene eq
	Resource Use	
RPR_E	Use of renewable primary energy	MJ
RPR_M	Use of renewable primary energy as materials	MJ

Abbreviation	Parameter	Unit
RPR_T	Total use of renewable primary energy resources	MJ
$NRPR_E$	Use of non-renewable primary energy	MJ
$NRPR_M$	Use of non-renewable primary energy as materials	MJ
$NRPR_T$	Total use of non-renewable primary energy resources	MJ
SM	Secondary materials	kg
RSF	Renewable secondary fuels	MJ
NRSF	Non-renewable secondary fuels	MJ
RE	Recovered energy	MJ
FW	Net use of fresh water	m^3
Waste Categories and Output Flows		
HWD	Hazardous waste disposed	kg
NHWD	Non-hazardous waste disposed	kg
HLRW	High-level radioactive waste	kg
ILLRW	Intermediate- and low-level radioactive waste, conditioned, to final repository	kg
CRU	Components for reuse	kg
MFR	Materials for recycling	kg
MER	Materials for energy recovery	kg

Greenhouse gas emissions from land use change are not significant and therefore have been excluded.

2.8 INTERPRETATION TO BE USED

The results of the LCI and LCIA were interpreted in accordance with this study's Goal and Scope. The interpretation identifies key findings, including the major contributors (e.g., process steps, inputs, emissions) to the overall results. It also includes an evaluation of the completeness, sensitivity, and consistency of the study to justify any data excluded from the system boundary as well as use of proxy data. Finally, the interpretation presents conclusions, limitations, and recommendations of the study.

2.9 DATA QUALITY REQUIREMENTS

Creation of the inventory model prioritizes data that is as precise, consistent, and as representative as possible in accordance with the Goal and Scope of the study given the constraints of time and budget. When choosing data used in the model, the goal is to achieve very good data quality, as defined in the below pedigree matrix (Ciroth, Muller, & Weidema, 2016).

Table 7: Data quality pedigree matrix (Ciroth, Muller, & Weidema, 2016)

	Further technological correlation	Temporal correlation	Geographical correlation	Completeness	Reliability
Very Good	Data from enterprises, processes, and materials under study	Less than 3 years of difference to the time period of the dataset	Data from area under study	Representative data from all sites relevant for the market considered, over an adequate period to even out normal fluctuations	Verified data based on measurements

	Further technological correlation	Temporal correlation	Geographical correlation	Completeness	Reliability
Good	Data from processes and materials under study (i.e., identical technology) but from different enterprises	Less than 6 years of difference of the time period of the dataset	Average data from larger area in which the area under study is included	Representative data from >50 % of the sites relevant for the market considered, over an adequate period to even out normal fluctuations	Verified data partly based on assumptions OR non-verified data based on measurements
Fair	Data from processes and materials under study from different technology	Less than 10 years of difference to the time period of the dataset	Data from area with similar production conditions	Representative data from only some sited (≪50 %) relevant for the market considered or >50 % of sites but from shorter periods	Non-verified data partly based on qualified estimates
Poor	Data on related processes or materials	Less than 15 years of difference to the time period of the dataset	Data from area with slightly similar production conditions	Representative data from only one site relevant for the market considered or some sites but from shorter periods	Qualified estimate (e.g., by industrial expert); data derived from theoretical information (stoichiometry, enthalpy, etc.)
Very Poor	Data on related processes on laboratory scale or from different technology	Age of data unknown or more than 15 years of difference to the time period of the dataset	Data from unknown or distinctly different area (North America instead of Middle East, OECD-Europe instead of Russia)	Representativeness unknown or data from a small number of sites and from shorter periods	Non-qualified estimate

In Section 5.3, the quality of the data used in this study is assessed against these requirements. Topics of missing data treatment, reproducibility, and uncertainty are also discussed within the data quality assessment.

2.10 TYPE AND FORMAT OF REPORT

This report attempts to present results and conclusions of the LCA completely, accurately, and without bias to the intended audience in accordance with ISO 14040/14044 requirements. To allow the audience to interpret results and use results consistently with the goal and scope, this study presents the results, data, methods, assumptions and limitations with transparency and sufficient detail.

2.11 SOFTWARE AND DATABASE

The products were modeled utilizing data from the GaBi 2022.1 LCA software system to produce the potential environmental impacts over their lifetime. For any materials unavailable in the GaBi database, appropriate proxies were used. Specific descriptions of secondary unit processes can be viewed through the GaBi dataset documentation online at https://gabi.sphera.com/america/databases/gabi-data-search/.

2.12 CRITICAL REVIEW

A critical review by an independent third party is not required for an LCI dataset, but one has been conducted by Thomas P. Gloria, Ph.D., Managing Director of Industrial Ecology Consultants, to ensure that the LCA has met all relevant standards and that the methodology applied and results are reasonable. The critical review does not ensure that the results can be compared to the results of other LCA studies, but it does provide credibility for LCA results developed by users of the LCI dataset.

3 LIFE CYCLE INVENTORY ANALYSIS

3.1 DATA COLLECTION PROCESS

All primary data was collected from participating AI member companies using a customized data collection template. Data was collected at the plant and process levels.

Data was reviewed for accuracy as it was collected. Any inconsistencies in data were resolved through email and telephone communication with technical associates at the manufacturer.

The industry-wide average results were calculated as a production-weighted average using the sales volumes to the North American market from the six (6) facilities owned by the four (4) participating AI member companies. Results were aggregated using a vertical average approach, i.e., each site was modeled separately, and a production-weighted average was calculated only at the final product level.

3.2 PRODUCT COMPOSITION

The composition of the product is represented in Table 8.

Table 8: Material Composition per Functional Unit

	SBS
Styrene	30%
Butadiene	70%

3.3 MANUFACTURING

This stage includes raw material extraction, supplier processing, and delivery of the materials to the manufacturing site, as summarized in Table 3.

SBS is manufactured by anionic polymerization. In this process, monomers of styrene and butadiene are sequentially polymerized into polymer segments. An alkyl-lithium initiator reacts with styrene and monomers to form a “living polymer,” which can initiate further polymerization, Next, butadiene reacts with the initiator to also form a living polymer. These steps are repeated and block copolymers with multiple alternating blocks are formed. SBS may also be produced sequentially with styrene polymerized, then butadiene and then styrene again. These reactions take place in an inert hydrocarbon solvent in the absence of water, oxygen, or CO_2 (Holden, 2011).

The raw materials for the product are obtained from Europe or North America. Either bills of materials were obtained from the participating companies, or annual use of raw materials for CY2020 was provided and then divided by production volume to derive a material use-per-production unit for use in the LCA.

Total energy, water consumption, and waste generation were provided for CY 2020 and divided by production volume during this period to derive per-production unit values for use in the LCA. The materials are delivered to the manufacturing facility via a combination of truck, ship, rail, and pipeline, which is accounted for in the model. The distances were modeled by material and were calculated using the supplier location and the location of manufacturing. Where supplier location data were not available, it was assumed inbound ancillary materials are transported 500 miles (805 km) to facilities in North America, and 100 miles (161 km) to facilities in Europe. No assumptions had to be made on the inbound distances of styrene and butadiene.

Energy resources used in the manufacturing process are accounted for in the model. The electricity is either sourced from the power grid or generated from neighboring industrial co-generation facilities. Electricity production datasets from GaBi, which represent eGRID subregions, national average grid mixes, and electricity from specified fuel sources are used to assess the generation, distribution, and transmission of electricity. Steam is either generated on-site or purchased from neighboring industrial co-generation facilities. GaBi datasets for steam produced from natural gas or heavy fuel oil were used as appropriate for the co-generation facilities. Secondary datasets for other fuels, ancillary materials, packaging, and waste treatment were utilized from the GaBi database. Packaging materials, as provided by the participating companies, are also included in this stage. These details are summarized in the industry-average unit process data in Table 9. To protect proprietary information, unit process details are not reported here when they are not reported by at least three (3) manufacturing facilities. Note that direct emissions reported here are only those measured and reported by the facilities. Combustion emissions are calculated using secondary data.

Table 9: Manufacturing Inputs and Outputs per Declared Unit (1 kg) of SBS

Manufacturing Data	Value	Unit
Energy and Fuels		
Electricity	3.11E-01	kWh
Steam (mix of natural gas and heavy fuel oil)	1.14E+01	MJ
Diesel	1.16E-02	MJ
LPG	8.00E-03	MJ
Propane	7.33E-02	MJ
Gasoline	6.50E-04	MJ
Natural Gas	2.58E-01	MJ
Ancillary Materials		
Antioxidant	5.35E-03	kg
Coupling Agent	6.04E-04	kg
Dusting Anti-Blocking agent	4.76E-03	kg
Initiator	3.58E-03	kg
Solvent	3.03E-02	kg
Other Ancillary Materials	1.61E-03	kg
Other Manufacturing Inputs		
Refrigerant	1.57E-07	kg

Manufacturing Data	Value	Unit
Water	1.21E+00	m^3
Waste		
Non-Hazardous Waste to Landfill	6.91E-03	kg
Hazardous Waste to Landfill	7.76E-05	kg
Non-Hazardous Waste to Incineration	1.36E-03	kg
Hazardous Waste to Incineration	2.11E-03	kg
Non-Hazardous Waste to Recycling	1.24E-03	kg
Hazardous Waste to Recycling	1.81E-03	kg
Wastewater	1.05E+00	m^3
Packaging		
Cardboard Boxes	1.10E-02	kg
Paper Bags	3.93E-03	kg
Polyethylene Bags	1.20E-03	kg
Polypropylene Bags	3.78E-03	kg
Wooden Pallets	1.74E-02	kg
Facility Reported Emissions to Air		
Carbon Dioxide (CO_2)	3.42E-02	kg
Carbon Monoxide (CO)	8.29E-05	kg
Nitrogen Oxides (NO_x)	2.37E-05	kg
Nitrous Oxide (N_2O)	1.40E-07	kg
Non-methane Volatile Organic Compounds (NMVOC)	7.86E-04	kg
Particulate Matter ≤10 µm (PM_{10})	5.46E-05	kg
Particulate Matter ≤2.5 µm ($PM_{2.5}$)	7.80E-05	kg
Refrigerant-22 (R-22)	1.57E-07	kg
Sulfur Dioxide (SO_2)	1.12E-06	kg
Emissions to Water		
Chemical Oxygen Demand (COD)	4.50E-04	kg

4 LIFE CYCLE IMPACT ASSESSMENT

The results from the study are shown below. All results are given per the declared unit of 1 kg.

4.1 OVERALL RESULTS

Table 10 presents the impact assessment results for all IPCC, TRACI, and CML impact methods.

Table 10: Impact assessment, SBS, per kg

Impact Category	Value	Unit
IPCC AR5		
GWP	2.89E+00	kg CO_2 eq
IPCC AR6		
GWP	2.88E+00	kg CO_2 eq
TRACI 2.1		
AP	3.92E-03	kg SO_2 eq
EP	3.08E-04	kg N eq
ODP	8.09E-09	kg CFC 11 eq
Resources	1.20E+01	MJ, surplus energy
SFP	9.44E-02	kg O_3 eq
CML 2001-Aug 2016		
AP	3.36E-03	kg SO_2 eq
EP	6.74E-04	kg Phosphate eq
ODP	8.09E-09	kg CFC 11 eq
ADPE	1.61E-06	kg Sb eq
ADPF	8.39E+01	MJ, net calorific value
POCP	7.52E-04	kg Ethene eq

Results for ISO 21930 resource use indicators are presented in Table 11.

Table 11: Resource use, SBS, per kg

Indicator	Value	Unit
RPR_E	2.03E+00	MJ
RPR_M	4.68E-01	MJ
RPR_T	2.50E+00	MJ
$NRPR_E$	3.99E+01	MJ
$NRPR_M$	4.54E+01	MJ
$NRPR_T$	8.53E+01	MJ
SM	-	kg
RSF	-	MJ
NRSF	-	MJ
RE	-	MJ
FW	1.14E-02	m^3

Results for ISO 21930 waste and output flow indicators are presented in Table 12.

Table 12: Waste and output indicators, SBS, per kg

Indicator	Value	Unit
HLRW	3.13E-07	kg

Indicator	Value	Unit
ILLRW	4.30E-04	kg
HWD	5.66E-06	kg
NHWD	3.32E-02	kg
CRU	-	kg
MFR	-	kg
MER	-	kg

4.2 DETAILED RESULTS

To understand the main contributors to environmental burdens in the production of SBS, the industry-average results are presented using the following groupings: raw materials, ancillary materials, transportation of raw materials, manufacturing electricity, thermal energy, other fuels, packaging, and other. The raw materials grouping only includes styrene and butadiene, while the ancillary materials include any materials consumed in the manufacturing of SBS that do not become part of the final product. Thermal energy is any energy source used for production of process steam. The group "other fuels" contains energy sources for operations other than steam production, such as gasoline for internal transport. The group "other" includes direct emissions to water and air from manufacturing processes that the AI member companies report, as well as water and waste treatment.

Figure 4 presents the impacts for SBS by relative contribution to each impact category. The results presented here use IPCC AR6 and TRACI 2.1 indicators.

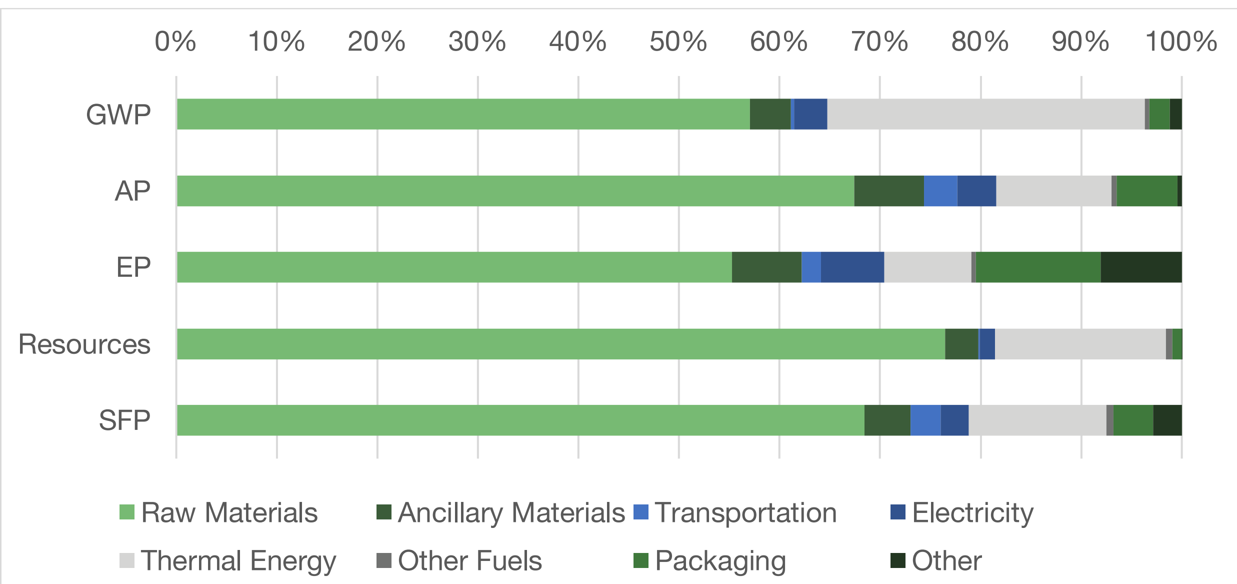

Figure 4: Detailed Results for Impacts of SBS [IPCC AR6 and TRACI 2.1]

The main contributor for burdens in all impact categories is the group "raw materials," generally contributing to more than 55% of the potential impacts in each category. The next greatest contributor is thermal energy, contributing 9% or more in all impact categories, reaching up to 32% of potential impacts.

For GWP, raw materials contribute 57% of the total burden. Thermal energy contributes 32% of the total GWP. The remaining groups each contribute less than 5% to the overall GWP.

AP impacts were driven mainly by raw materials, contributing 67% of total AP. Thermal energy contributes about 12%. The remaining categories each contributed less than 7% to total GWP.

Raw materials contributed to 55% of total EP. Packaging contributes 12% of total potential EP, followed by thermal energy with 9% and “other” with 8%. The remaining categories each contribute less than 7%.

Fossil fuel resource consumption is dominated by raw materials (76%), with thermal energy contributing 17%.

Finally, the SFP contribution from raw materials is 69%, and 14% for thermal energy.

5 INTERPRETATION

Within this section, the results of the life cycle assessment are interpreted according to the goal and scope of the study. This interpretation includes key findings, a sensitivity analysis, and a data quality assessment, before providing conclusions based on the LCA.

5.1 KEY FINDINGS

The primary driver of all potential environmental impacts is raw materials. This is because styrene and butadiene are made from petrochemicals. Following raw materials, the highest contributor in the manufacturing process for all impact categories is thermal energy. This is due to the production of steam using fossil-based energy sources such as natural gas and heavy fuel oil. Packaging shows some relevance in EP mainly due to the use of wooden pallets, assumed to be single-use with each shipment of SBS.

5.2 SENSITIVITY ANALYSIS

A sensitivity analysis is performed within life cycle assessment to determine how the results of an LCA are affected by the assumptions the LCA practitioner made during the course of the study, or, in this case, how changes in material sourcing or system boundary could affect the results. Of relevance to this model are the exclusion of the distribution from the facility to a warehouse and the region of sourcing of the butadiene.

5.2.1 Warehouse Distribution

As this study is intended to represent use of SBS within North America, it was debated whether transportation from overseas facilities to North American warehouses should be included within the LCI. Ultimately, it was determined that the decision on transportation distance of SBS should be made by the downstream users of this SBS LCI dataset. However, it was of interest to the participating companies to determine the sensitivity of LCIA results to the transportation distance of SBS to a warehouse (e.g., Houston, TX, assumed in this study), as compared to the impact of manufacturing the SBS. Two scenarios are explored here: one is transport via container ship from Europe (assumed to be Marseille, FR) to Houston, TX and another is from China (assumed to be Shanghai, CN) to Houston, TX, also via container ship. Though no Asian facilities participated in the study, the Asphalt Institute's LCA of polymer-modified binder (thinkstep AG, 2019) showed inbound transport distances that indicated sourcing could be from Asia. For greater understanding, this scenario is explored as well. A total of 50 miles (80 km) of trucking is also included to account for transport to or from the ports. Note that this is only for distribution to North America, not to the final customer. Table 13 shows the results as a percent difference from the baseline results previously shared. Values less than +/- 10% are grayed out to indicate insignificance.

Table 13: Warehouse distribution sensitivity results, as absolute values and a percentage increase to the baseline

Phase	Unit	Methodology	Distribution EU to US	% Increase to baseline	Distribution CN to US	% Increase to baseline
GWP	kg CO_2 eq	IPCC AR5	3.59E-02	1%	6.22E-02	2%
GWP	kg CO_2 eq	IPCC AR6	3.56E-02	1%	6.17E-02	2%
AP	kg SO_2 eq	TRACI 2.1	6.13E-04	15%	1.15E-03	29%
EP	kg N eq	TRACI 2.1	3.44E-05	11%	6.38E-05	20%
Resources	MJ, surplus energy	TRACI 2.1	6.31E-02	1%	1.09E-01	1%
SFP	kg O_3 eq	TRACI 2.1	1.85E-02	19%	3.49E-02	36%

It can be seen that AP, EP, and SFP are all significantly affected, which is unsurprising given that these are the impact categories most influenced by transportation emissions. This indicates the importance of downstream stakeholders accurately capturing the inbound transport distance of raw materials, particularly with larger inputs of SBS.

5.2.2 Butadiene Source

While the geographical representativeness of the upstream butadiene datasets for the sites modeled is excellent, given the high contribution of raw materials (and more specifically butadiene as the largest fraction of the composition) to the overall impacts, it is of interest to understand the potential range of impacts that could be seen if butadiene were to be sourced from different regions and/or technologies. Three regions were assessed based on background dataset availability: Germany, Italy, and the United States. Differences in datasets are most likely due the mix of feedstocks used (natural gas and naphtha). The differences in these feedstocks could be due to the cracking, refining, and/or extraction technologies used. Table 14 shows the results as a percent difference from the baseline results previously shared. Values less than +/- 10% are grayed out to indicate insignificance.

Table 14: Butadiene sensitivity analysis results, as a percentage difference from the baseline

Phase	Unit	Methodology	Maximum Decrease from Baseline	Maximum Increase from Baseline
GWP	kg CO_2 eq	IPCC AR5	-8%	4%
GWP	kg CO_2 eq	IPCC AR6	-8%	4%
AP	kg SO_2 eq	TRACI 2.1	-16%	6%
EP	kg N eq	TRACI 2.1	-10%	5%
Resources	MJ, surplus energy	TRACI 2.1	-3%	1%
SFP	kg O_3 eq	TRACI 2.1	-23%	14%

The results indicate that GWP and Resources are not as sensitive to the upstream butadiene production as AP, EP, and SFP. When compared side by side, the US butadiene dataset shows a significantly higher SFP result and slightly higher AP result (Italy also shows a higher AP result, as compared to the German dataset). The US dataset, and associated upstream datasets, do not provide enough documentation to understand the reasons for this difference.

These results indicate that the source for butadiene can alter some of the results significantly; however, it should be noted that increased inbound transportation distance was not included in this assessment which could offset some of the benefits associated with switching sources. SBS producers should work to understand their supply chain before making any changes.

5.3 BENCHMARKING

As mentioned previously, one of the goals of this study was to ensure SBS data was available so proxy data would not have to be used. Figure 5 benchmarks the results of this assessment against possible current proxy datasets in the Sphera LCI database, as well as the SBS proxy data that was previously used in the 2019 Asphalt Institute assessment on asphalt binder (thinkstep AG, 2019). The US: E-SBR[1] and US: S-SBR[2] are current Sphera datasets for styrene butadiene rubber, produced via emulsion or suspension polymerization. The US: SBR Sphera (2016) is the outdated dataset used in the asphalt binder LCA which represented suspension polymerization SBR.

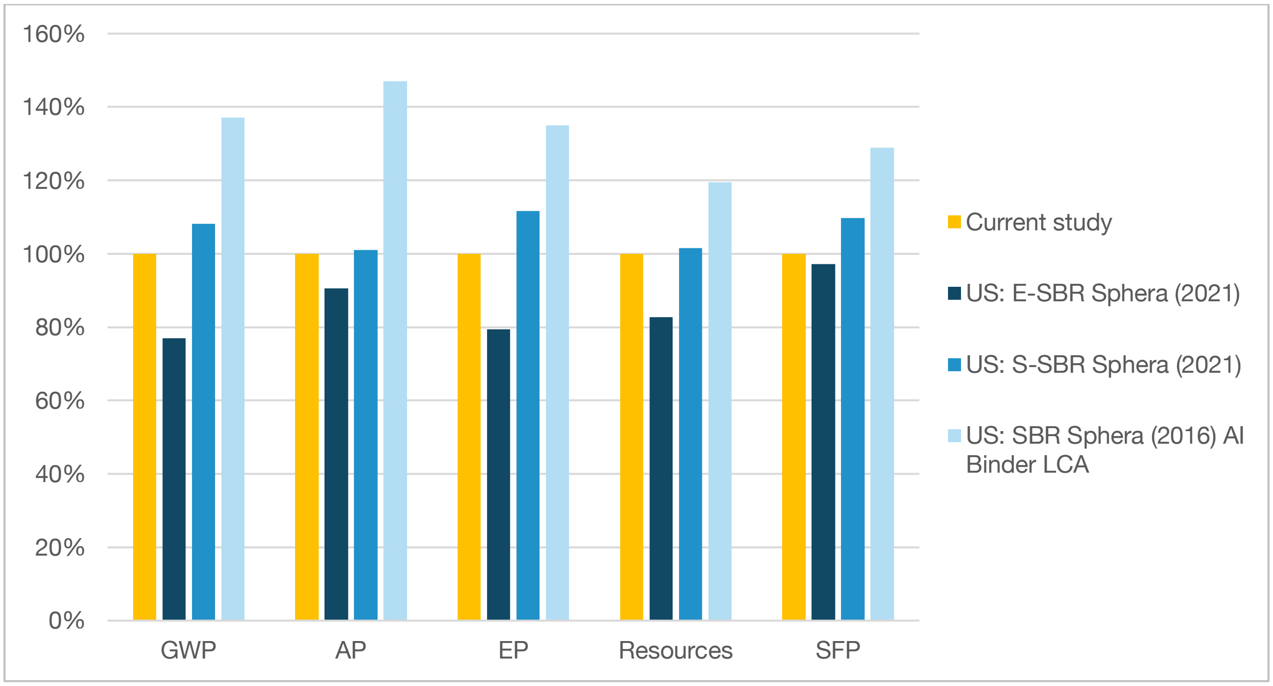

Figure 5: LCIA results benchmark

Results have decreased significantly in comparison to the old dataset. Much of this can likely be attributed to the general "greening" of the electricity grid, which filters through all Sphera LCI datasets. This study's results are comparable to those of S-SBR and higher than those of E-SBR. However, the Sphera LCI datasets represent theoretical production for US based facilities and are

[1] http://gabi-documentation-2022.gabi-software.com/xml-data/processes/62d61706-5d47-47c6-baff-a4586cfe30a3.xml

[2] http://gabi-documentation-2022.gabi-software.com/xml-data/processes/4e3ad9ed-1dfb-445c-b09a-e34adf27bee4.xml

not representative of primary data from facilities actually supplying to the US market. Using primary data has ensured that this study is accurate and representative.

5.4 DATA QUALITY ASSESSMENT

The assessed data quality for the data utilized is covered in the following sections. Overall data quality is considered very good. Improvements can be made through the modification of datasets to incorporate more regional specificity, both in terms of energy and technology. However, the data was considered appropriate in relation to the goal, scope, and budget of the project.

5.4.1 Geographic Coverage

The geographical scope of the manufacturing portion of the life cycle is Europe and North America. All primary data were collected from the manufacturers. The final average was calculated based on sales to North America. The geographic coverage of primary data is considered very good.

The geographical scope of the raw material acquisition is also Europe and North America.

In selecting secondary data (i.e., GaBi Datasets), priority was given to the accuracy and representativeness of the data. When available and deemed of significant quality, country-specific data was used. However, priority was given to technological relevance and accuracy in selecting secondary data. This often led to the substitution of regional and/or global data for country-specific data. Overall geographic data quality is considered good.

5.4.2 Time Coverage

Primary data were provided by the manufacturers and represent all information for calendar year 2020. Time coverage of this primary data is considered very good.

Data necessary to model cradle-to-gate unit processes were sourced from Sphera LCI datasets. Time coverage of the GaBi datasets varies from 2018 to present, with the exception of two datasets from 2011 and 2012. All datasets rely on at least one 1-year average data. Overall time coverage of the datasets is within a 10-year period, with the vast majority within a 3-year period, therefore the overall temporal coverage is considered good.

5.4.3 Technological Coverage

Primary data provided by the manufacturer are specific to the technology the participating companies use in manufacturing SBS. It is site-specific and considered of very good quality.

Data necessary to model cradle-to-gate unit processes were sourced from GaBi LCI datasets. Technological coverage of the datasets is considered very good relative to the actual supply chain of the manufacturers. While improved life cycle data from each facility's suppliers would improve technological coverage, the use of lower-precision generic datasets does meet the goal of this LCA.

5.4.4 Completeness

The LCA model included all known material and energy flows, primary data has been collected over 12 months, and participating companies represent much of the market for SBS sales for liquid asphalt modification (though no quantifiable fraction of the market is available). Completeness of the study is considered good.

5.4.5 Reliability

The reliability of the data is considered very good. Company and/or site representatives provided detailed material and utilities data for the manufacturing facilities. The raw material transportation distances were calculated based on the distances and supplier locations provided by the participating companies.

5.4.6 Treatment of Missing Data

Primary data were used for all manufacturing processes. When primary data did not exist, the value from another site operated by the same manufacturer was used to fill in the data gap. No gaps had to be filled for parameters that significantly affected final results.

5.4.7 Reproducibility

This study is considered reproducible. Descriptions of the data and assumptions through this report would allow a practitioner to utilize the LCA tool to generate generic results for the product. The input of confidential and/or proprietary information, including but not limited to the production volumes of each company, prevents the exact results from being recreated by a practitioner.

5.4.8 Uncertainty

Uncertainty for the secondary datasets is discussed in the documentation published by Sphera. Uncertainty of the primary data comes primarily from the utility data allocated to each product. The yearly total energy use changes over time due to more efficient operations, warmer or cooler seasons and other factors. Because energy data typically comes directly from utility bills, the uncertainty is mainly based on the accuracy of the utility meters.

5.5 ASSUMPTIONS AND LIMITATIONS

Throughout this report, value choices and judgements that may have affected the LCA have been described. Additional decisions are summarized below:

- In some cases, inclusion of facility-level energy, water, emission, and waste data was determined appropriate due to the inability to sub-meter or isolate process-level data from facility-level data. Some companies were able to provide more specific data.
- In cases where water consumption data was not available for a facility, water output data from that facility was used to estimate make-up water inputs.
- Packaging was assumed to be single-use.
- The use and selection of secondary datasets from GaBi – The selection of which generic dataset to use to represent an aspect of a supply chain is a significant value choice. Collaboration between the LCA practitioner, the manufacturer, and GaBi data experts was valuable in determining best-case scenarios in the selection of data. However, no generic

data can be a perfect fit. Improved supply chain specific data would improve the accuracy of results, however budgetary and time constraints must be taken into account.

Some limitations to the study have been identified as follows:

- This study only represents production of SBS in North America and Europe for use in the North American asphalt modification market.
- Only emissions to air and water measured and reported by the participating companies are included.
- Availability of geographically more accurate and/or supplier-specific datasets would have improved the accuracy of the study.
- Only known and quantifiable environmental impacts are considered.
- Due to the assumptions and value choices listed above, these do not reflect real-life scenarios and hence they cannot assess actual and exact impacts, but only potential environmental impacts.

5.6 CONCLUSION

This study presents the results for the cradle-to-gate production of SBS. Raw materials inputs were revealed as the primary driver for potential environmental impacts, followed by thermal energy. Their contribution to environmental impacts – especially to the categories GWP, EP, and AP – is due to use of fossil derived materials and energy inputs in their production. Packaging was shown to be a somewhat relevant contributor to EP, due to the shipping of product on pallets.

SBS manufacturers should consider alternative sources for thermal energy if possible. Additionally, engagement with the supply chain may lead to opportunities for upstream impact reductions.

The Asphalt Institute, and participating companies, can improve the precision of future assessments by collecting more detailed data on the production data of their raw materials styrene and butadiene. These results are considered high quality and accurate, but any improvements with supplier-specific data would improve this study and increase precision of results.

The representativeness of this study could be improved in a future assessment with the inclusion of additional companies and more facilities from the Asphalt Institute. The inclusion of companies with manufacturing facilities in additional regions (e.g., Asia) would broaden the geographical representativeness.

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APPENDIX A SECONDARY DATASETS

The table below lists the background datasets used, excluding datasets for inputs or outputs used by fewer than 3 companies. These datasets were made available to the critical reviewer for transparency but are not shared with participants of the study to protect proprietary information.

Dataset	Source	Year of Last Update	Time Coverage	Geographical Coverage	Technological Coverage	Overall Representatives	Description
Bulk commodity carrier, 5,000 to 200,000 dwt payload capacity, ocean going	Sphera	2021	Within 10-year period	GLO	Appropriate technology	Good. Appropriate technology. Not specific geography, GLO is only dataset available.	Transportation of raw materials from supplier to manufacturing facility in EU and North America.
Butanediol from propylene oxide (PO chlorohydrine)	Sphera	2021	Within 10-year period	US	Proxy technology.	Good. Proxy technology. Correct geography.	Ancillary materials used in production of SBS in North America.
C16-18 fatty alcohol from beef tallow (No. 21 - Matrix)	ERASM	2011	Within 10-year period	EU-28	Proxy technology.	Poor. Proxy technology. Not specific geography for EU facilities but is only dataset available. EU used as proxy for North America due to unavailability of region-specific datasets.	Ancillary materials used in production of SBS in EU and North America.
C4 cut (butadiene)	Sphera	2021	Within 10-year period	DE	Appropriate technology	Very good.	Production of raw materials for SBS made in EU.
C4 cut (butadiene)	Sphera	2021	Within 10-year period	IT	Appropriate technology	Good. Appropriate technology. Incorrect geography. IT used as proxy for EU sites due to unavailability of region-specific datasets.	Production of raw materials for SBS made in EU.
C4 cut (butadiene)	Sphera	2021	Within 10-year period	US	Appropriate technology	Very good.	Production of raw materials for SBS made in North America.
Chlorodifluoromethane (R22, HCFC-22) (approximation)	Sphera	2021	Within 10-year period	US	Appropriate technology	Very good.	Refrigerant used at North America facilities.
Corrugated product	Sphera/ AF&PA	2012	Within 10-year period	US	Appropriate technology	Good. Appropriate technology. Correct geography for US sites, but incorrect geography for EU sites. US used as proxy for EU sites due to unavailability of region-specific datasets.	Packaging for final product made in EU and North America.
Cyclohexane	Sphera	2021	Within 10-year period	DE	Appropriate technology	Very good.	Ancillary materials used in production of SBS in EU.

Dataset	Source	Year of Last Update	Time Coverage	Geographical Coverage	Technological Coverage	Overall Representatives	Description
Cyclohexane	Sphera	2021	Within 10-year period	US	Appropriate technology	Very good.	Ancillary materials used in production of SBS in North America.
Diesel mix at filling station	Sphera	2018	Within 10-year period	US	Appropriate technology	Good. Appropriate technology. Correct geography for US sites, but incorrect geography for EU sites. US used as proxy for EU sites due to unavailability of region-specific datasets.	Transportation of raw materials from supplier to manufacturing facility in EU and North America.
Electricity from biomass (solid)	Sphera	2018	Within 10-year period	ES	Appropriate technology	Very good.	Production of electricity at facility in ES.
Electricity from hydro power	Sphera	2018	Within 10-year period	ES	Appropriate technology	Very good.	Production of electricity at facility in ES.
Electricity from natural gas	Sphera	2018	Within 10-year period	DE	Appropriate technology	Very good	Production of electricity at facility in DE.
Electricity from natural gas	Sphera	2018	Within 10-year period	US	Appropriate technology	Very good	Production of electricity at facility in US.
Electricity from photovoltaic	Sphera	2018	Within 10-year period	ES	Appropriate technology	Very good.	Production of electricity at facility in ES.
Electricity from wind power	Sphera	2018	Within 10-year period	ES	Appropriate technology	Very good.	Production of electricity at facility in ES.
Electricity grid mix	Sphera	2018	Within 10-year period	FR	Appropriate technology	Very good.	Production of electricity at facility in FR.
Electricity grid mix – ERCT	Sphera	2019	Within 10-year period	US	Appropriate technology	Very good.	Production of electricity at facility in US.
Electricity grid mix (eGRID)	Sphera	2019	Within 10-year period	US	Appropriate technology	Very good.	Production of electricity at facility in US.
Electricity mix (energy carriers, generic)	Sphera	2018	Within 10-year period	ES	Appropriate technology	Very good.	Production of electricity at facility in ES.
Heavy fuel oil at refinery (2.5wt.% S)	Sphera	2018	Within 10-year period	US	Appropriate technology	Very good.	Production of thermal energy for facilities in North America.

Dataset	Source	Year of Last Update	Time Coverage	Geographical Coverage	Technological Coverage	Overall Representatives	Description
Isobutene (from Isobutane)	Sphera	2021	Within 10-year period	DE	Proxy technology.	Poor. Proxy technology and incorrect geography. DE used as proxy for EU sites due to unavailability of region-specific datasets.	Ancillary materials used in production of SBS in EU and North America.
Kraft paper (EN15804 A1-A3)	Sphera	2021	Within 10-year period	EU-28	Appropriate technology	Good. Appropriate technology. Not specific geography for EU facilities. EU used as proxy for North America due to unavailability of region-specific datasets.	Packaging for final product made in EU and North America.
Lithium hydroxide	ts	2019	Within 10-year period	US	Proxy.	Poor. Proxy technology and incorrect geography. US used as proxy for EU sites due to unavailability of region-specific datasets.	Ancillary materials used in production of SBS in EU and North America.
Lubricants at refinery	Sphera	2018	Within 10-year period	US	Appropriate technology	Very good.	Manufacturing inputs at facilities in US.
Natural gas mix	Sphera	2018	Within 10-year period	US	Appropriate technology	Very good.	Energy for manufacturing SBS in North America.
Polyethylene film (LDPE/PE-LD)	Sphera	2021	Within 10-year period	US	Appropriate technology	Very good.	Packaging for final product made in North America.
Polyethylene Low Density Granulate (LDPE/PE-LD)	Sphera	2021	Within 10-year period	DE	Appropriate technology	Good. Appropriate technology. Incorrect geography. DE region used as proxy for EU sites due to unavailability of region-specific datasets.	Packaging for final product made in EU.
Polypropylene Film (PP) without additives	Sphera	2021	Within 10-year period	DE	Appropriate technology	Good. Appropriate technology. Incorrect geography. DE region used as proxy for EU sites.	Packaging for final product made in EU.
Polypropylene granulate (PP)	Sphera	2021	Within 10-year period	US	Appropriate technology	Very good.	Packaging for final product made in North America.
Process steam from heavy fuel oil (HFO) 85%	Sphera	2018	Within 10-year period	DE	Appropriate technology	Very good.	Production of thermal energy for facility in DE.
Process steam from natural gas 85%	Sphera	2018	Within 10-year period	DE	Appropriate technology	Very good.	Production of thermal energy for facility in DE.
Process steam from natural gas 85%	Sphera	2018	Within 10-year period	ES	Appropriate technology	Very good.	Production of thermal energy for facility in ES.

Dataset	Source	Year of Last Update	Time Coverage	Geographical Coverage	Technological Coverage	Overall Representatives	Description
Process steam from natural gas 85%	Sphera	2018	Within 10-year period	FR	Appropriate technology	Very good.	Production of thermal energy for facility in FR.
Process steam from natural gas 85%	Sphera	2018	Within 10-year period	US	Appropriate technology	Very good.	Production of thermal energy for facility in North America.
Rail transport cargo - Diesel, average train, gross tonne weight 1,000t / 726t payload capacity	Sphera	2021	Within 10-year period	GLO	Appropriate technology	Good. Appropriate technology. Not specific geography, GLO is only dataset available.	Transportation of raw materials from supplier to manufacturing facility in EU and North America.
Silicon mix (99%, using fossil reduction agents)	Sphera	2021	Within 10-year period	GLO	Proxy technology.	Good. Appropriate technology. Not specific geography, GLO is only dataset available.	Ancillary materials used in production of SBS in EU and North America.
Styrene (ESBM dehydrogenation)	Sphera	2021	Within 10-year period	NL	Appropriate technology	Good. Appropriate technology. Incorrect geography. NL used as proxy for EU sites due to unavailability of region-specific datasets.	Production of raw materials for SBS made in EU.
Styrene (ESBM dehydrogenation)	Sphera	2021	Within 10-year period	US	Appropriate technology	Very good.	Production of raw materials for SBS made in North America.
Talcum powder (filler)	Sphera	2021	Within 10-year period	EU-28	Appropriate technology	Good. Appropriate technology. Not specific geography, EU is only dataset available for EU sites. EU is used as proxy for US due to unavailability of region-specific datasets.	Ancillary materials used in production of SBS in EU and North America.
Thermal energy from diesel	Sphera	2018	Within 10-year period	US	Appropriate technology	Good. Appropriate technology. Correct geography for US sites, but incorrect geography for EU sites. US used as proxy for EU sites due to unavailability of region-specific datasets.	Energy for manufacturing SBS in EU and North America.
Thermal energy from gasoline	Sphera	2018	Within 10-year period	US	Appropriate technology	Very good.	Energy for manufacturing SBS in North America.
Thermal energy from LPG	Sphera	2018	Within 10-year period	EU-28	Appropriate technology	Good. Appropriate technology. Not specific geography, EU is only dataset available for EU sites.	Energy for manufacturing SBS in EU.
Thermal energy from LPG	Sphera	2018	Within 10-year period	US	Appropriate technology	Very good.	Energy for manufacturing SBS in North America.
Thermal energy from natural gas	Sphera	2018	Within 10-year period	ES	Appropriate technology	Very good.	Energy for manufacturing SBS in EU.

Dataset	Source	Year of Last Update	Time Coverage	Geographical Coverage	Technological Coverage	Overall Representatives	Description
Thermal energy from natural gas	Sphera	2018	Within 10-year period	DE	Appropriate technology	Very good.	Energy for manufacturing SBS in EU.
Thermal energy from natural gas	Sphera	2018	Within 10-year period	US	Appropriate technology	Very good.	Energy for manufacturing SBS in North America.
Thermal energy from propane	Sphera	2018	Within 10-year period	US	Appropriate technology	Good. Appropriate technology. Correct geography for US sites, but incorrect geography for EU sites. US used as proxy for EU sites due to unavailability of region-specific datasets.	Energy for manufacturing SBS in EU and North America.
Truck - Heavy Heavy-duty Diesel Truck / 53,333 lb payload - 8b	Sphera	2021	Within 10-year period	US	Appropriate technology	Good. Appropriate technology. Correct geography for US sites, but incorrect geography for EU sites. US used as proxy for EU sites due to unavailability of region-specific datasets.	Transportation of raw materials from supplier to manufacturing facility in EU and North America.
Truck-trailer, Euro 1, 34 - 40t gross weight / 27t payload capacity	Sphera	2021	Within 10-year period	GLO	Appropriate technology	Good. Appropriate technology. Not specific geography, GLO is only dataset available.	Transportation of raw materials from supplier to manufacturing facility in EU and North America.
White Oak lumber, 4 inch (769 kg/m3), kiln-dried (7% moisture content, 6.5% H2O content)	Sphera/ AHEC	2021	Within 10-year period	US	Appropriate technology	Good. Appropriate technology. Correct region for US sites, but incorrect geography for European sites.	Packaging for final product made in EU and North America.

APPENDIX B VERIFICATION DOCUMENTS

Industrial Ecology Consultants

August 5, 2022

Maggie Wildnauer
Director of Life Cycle Services | WAP Sustainability Consulting

Critical Review Report: LCA of Styrene-Butadiene-Styrene Block Copolymer

The Life Cycle Assessment (LCA) practitioner, WAP Sustainability Consulting, contracted Industrial Ecology Consultants to perform an external independent critical review of the **LCA of Styrene-Butadiene-Styrene Block Copolymer** on behalf of the commissioning organization, **Asphalt Institute.**

The review of the study was performed to demonstrate conformance with the following standards:

- International Organization for Standardization (ISO). (2020). *Environmental management -- Life cycle assessment – Principles and framework* (ISO 14040:2006/Amd 1:2020).
- International Organization for Standardization. (2020). *Environmental management -- Life cycle assessment -- Requirements and guidelines* (ISO 14044:2006/Amd 1:2017/Amd 2 2020).
- International Organization for Standardization. (2014). *Environmental management -- Life cycle assessment -- Critical review processes and reviewer competencies: Additional requirements and guidelines to ISO 14044:2006*. (ISO/TS 14071:2014).
- International Organization for Standardization. (2017). *Sustainability in buildings and civil engineering works — Core rules for environmental product declarations of construction products and services.* (ISO 21930:2017).

The independent third-party critical review was conducted by an external expert per ISO 14044:2006 Section 6.2: Critical review by internal or external expert:

Thomas P. Gloria, Ph.D.
Founder, Chief Sustainability Engineer
Industrial Ecology Consultants

REVIEW SCOPE

The intent of this review was to provide an independent third-party external verification of a LCA study report in conformance with the aforementioned ISO standards. This review did not include an assessment of the Life Cycle Inventory (LCI) model, however, it did include a detailed analysis of the individual datasets used to complete the study.

REVIEW PROCESS

The review process involved the verification of all requirements set forth by the applicable ISO standards cataloged in comprehensive review table along with editorial comments. There was 1 round of comments by the reviewer submitted to the LCA practitioner. Responses by the LCA practitioner to each issue raised were resolved and acknowledged by the reviewer to have been satisfactorily addressed.

CRITICAL REVIEW STATEMENT

Based on the independent review objectives, the **LCA of Styrene-Butadiene-Styrene Block Copolymer, June 2022,** was determined to be ***in conformance*** with the applicable ISO standards. The plausibility, quality, and accuracy of the LCA-based data and supporting information are confirmed.

As the External Independent Third-Party Reviewer, I confirm that I have sufficient scientific knowledge and experience in chemical processes, base material production systems, and the applicable ISO standards to carry out this verification.

Sincerely,

Thomas P. Gloria, Ph.D.
Founder, Chief Sustainability Engineer
Industrial Ecology Consultants

Independent Review of LCA study of Construction products with no sub-category PCR

ISO 14044:2006/Amd 1:2017/Amd 2:2020, ISO 21930:2017

Date: 8/5/22	Doc.:LCA of Styrene-Butadiene-Styrene Block Copolymer, June 2022 by WAP Sustainability Consulting on behalf of Asphalt Institute
Reviewer:	Thomas Gloria, Ph.D., Industrial Ecology Consultants LCACP ID: 2008-03

(1)	(2)	(3)	(4)	(5)	(6)	(7)
Com-ment Type & No.	**Page No.**	**Para/ Fig/ Tbl/ Note**	**ISO/PCR Requirement**	**Comment (justification for change)/Proposed change**	**Decisions on each comment submitted**	**Status OPEN/ Closed**
			Are the methods used to carry out the study scientifically and technically valid?			
GE 1			The methods used to carry out the study are scientifically and technically valid.			Closed
			Are the data used appropriate and reasonable in relation of the goal of the study?			
GE 2			Yes, the data used are appropriate and reasonable.			Closed
			Do the interpretations reflect the limitations identified and the goal of the study			
GE 3			The study in general reflects the limitations identified.			Closed
			Is the report transparent and consistent?			
GE 4			The report is transparent and consistent.			Closed
			Editorial Comments			
ED1			No additional editorial comments.			
ED2						
ED3						
ED4						
ED5						
ED6						
ED7						

Type of comment: **GE** = general **TE** = technical **ED** = editorial