

The Eurobitume Life Cycle Assessment for Polymer Modified Bitumen



Foreword

Polymer modified bitumen (PMB) has been used for over 40 years to improve the performance of bituminous materials in a wide range of applications. Multiple studies have demonstrated the benefits of modification by increasing the service life or optimising the thickness of pavement layers.

To quantify the environmental impact of using PMB, Eurobitume hereby provides a Life Cycle Assessment (LCA) for PMB. This LCA for PMB on the scope cradle-to-gate aims to provide environmental information for subsequent products, in order to make fair and complete environmental comparison based on functional unit.

Polymer modification increases the environmental impacts of bituminous binders on the scope cradle-to-gate, compared with a paving grade bitumen. Manufacture of polymers is the main contributor to the higher impact for PMB, while transport and modification process are minor contributors.

However, life cycle assessments of road infrastructures have to be considered over their full life cycle, taking into account the construction, maintenance and end-of-life stages.

Considering the functional unit of infrastructures over the full life cycle is essential for a credible comparison of their environmental footprint. It enables fair comparison between design and material options by accounting for durability, maintenance needs, performance over time, and prevents misleading conclusions based only on upfront impacts.

In road applications, pavement durability - where polymer modified binders play a decisive role - largely determines the service life of the infrastructure. Incorporating polymers into bitumen to produce polymer modified bitumen significantly improves mechanical properties, extending pavement service life and reducing maintenance needs and material consumption.

A complete “cradle-to-grave” life cycle analysis can demonstrate that SBS-based PMBs achieve a significant reduction in carbon footprint by imparting superior durability to the pavement or by enabling reductions in pavement layer thickness.

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List of Acronyms

AR	Assessment Report
CH ₄	Methane
CHP	Combined Heat and Power
CO	Carbon Monoxide
CO ₂	Carbon Dioxide
CO ₂ eq.	Carbon Dioxide Equivalent
EF	Environmental Footprint
EPD	Environmental Product Declarations
EU	European Union
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GLO	Region Global
GWP	Global Warming Potential
H+	Hydrogen Ion
HFO	Heavy Fuel Oil
ILCD	International Life Cycle Data System
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
kg	Kilogram
LCA	Life Cycle Assessment
LCA FE	Life Cycle Assessment for Experts
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
MLC	Managed LCA Content
NMVOG	Non-Methane Volatile Organic Compound
NO _x	Nitrogen Oxides
PMB	Polymer Modified Bitumen
RER	Region Europe
RNA	Region North America
SBS	Styrene-Butadiene-Styrene Block Copolymer
SO ₂	Sulfur Dioxide
t	Metric Tonne
UK	United Kingdom
% wt/wt	Weight Percentage

Glossary

Life Cycle

A view of a product system as “consecutive and interlinked stages, from raw material acquisition or generation from natural resources to final disposal” (ISO 14040:2006/Amd.1:2020, section 3.1) [1]. This includes all material and energy inputs as well as emissions to air, land and water.

Life Cycle Assessment (LCA)

“Compilation and evaluation of the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 14040:2006, section 3.2) [1].

Life Cycle Inventory (LCI)

“Phase of life cycle assessment involving the compilation and quantification of inputs and outputs for a product throughout its life cycle” (ISO 14040:2006, section 3.3) [1].

Life Cycle Impact Assessment (LCIA)

“Phase of life cycle assessment aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of the product” (ISO 14040:2006, section 3.4) [1].

Life Cycle Interpretation

“Phase of life cycle assessment in which the findings of either the inventory analysis or the impact assessment, or both, are evaluated in relation to the defined goal and scope in order to reach conclusions and recommendations” (ISO 14040:2006, section 3.5) [1].

Functional Unit

“Quantified performance of a product system for use as a reference unit” (ISO 14040:2006, section 3.20) [1].

Declared Unit

“Quantity of a product for use as a reference unit in the quantification of a partial carbon footprint of a product” (ISO 14067:2018) [2].

Allocation

“Partitioning the input or output flows of a process or a product system between the product system under study and one or more other product systems” (ISO 14040:2006, section 3.17) [1].

Foreground System

“Those processes of the system that are specific to it ... and/or directly affected by decisions analysed in the study” [3, p. 97]. This typically includes first-tier suppliers, the manufacturer itself and any downstream life cycle stages where the manufacturer can exert significant influence. As a general rule, specific (primary) data should be used for the foreground system.

Background System

“Those processes, where due to the averaging effect across the suppliers, a homogenous market with average (or equivalent, generic data) can be assumed to appropriately represent the respective process” and/or “Background system comprises those processes that are operated as part of the system but that are not under direct control or decisive influence of the producer of the good” [3, pp. 97-98]. As a general rule, secondary data are appropriate for the background system, particularly where primary data are difficult to collect.

Critical Review

“Process intended to ensure consistency between a life cycle assessment and the principles and requirements of the International Standards on life cycle assessment” (ISO 14044:2006, section 3.45) [4].

Executive Summary

Polymer Modified Bitumen (PMB) is bitumen modified with polymers to enhance performance properties. This report focuses on the most widely used polymer: SBS Styrenic Block Copolymers and possibly other additives to facilitate its use in paving applications. The investment in polymer modification seeks to extend the service life of the pavement to reduce lifecycle cost and environmental impact. SBS modified bitumen is widely used to enhance the performance of asphalt pavements subjected to heavy traffic or exposure to a wide range of temperatures. This report addresses two average products representative of current practices in paving application: a standard PMB (based on 3,5 % SBS) and a high-performance PMB (based on 6,0 % SBS).

Eurobitume, the European industry association for the producers of refined bituminous products in Europe, has commissioned Sphera Solutions, Inc. (Sphera) to perform a life cycle assessment (LCA) of PMB products that are representative of those produced by Eurobitume's members within the European Union (EU) and the United Kingdom (UK). The present study supplements Eurobitume's 2025 Life Cycle Assessment 4.0 for Bitumen study [5], expanding the breadth of bituminous products assessed under the lens of LCA to produce life cycle inventory (LCI) data and life cycle environmental impact results that can be used in the development of broader LCA studies which take into account the effect of polymer modification on the service life.

The goal of the present LCA study is to provide LCI data and life cycle environmental impact results on the production of PMB with SBS concentration of 3,5 % wt/wt (i.e., standard SBS concentration) and PMB with SBS concentration of 6,0 % wt/wt (i.e., high-performance PMB) within a refinery representative of Eurobitume members in the EU/UK region. The PMB products should be compliant with EN14023:2010 [6]. Its intended application is to serve as a building block in broader life cycle studies taking PMB into account. Its boundary is cradle-to-gate, i.e., it accounts for the environmental impacts of crude oil extraction, transportation of crude oil to the refinery, the production of paving grade bitumen (EN 12591), the production of the raw materials for SBS polymer, as well as the SBS polymer production and the polymer modification process. The environmental impacts are referenced to one metric tonne of PMB produced by Eurobitume member refineries at refinery gate.

The baseline environmental impacts of the PMB products were assessed using primary data collected from Eurobitume member refineries (4 member refineries in the EU and UK) during the data collection stage of the previous Life Cycle Assessment 4.0 for Bitumen study [5]. Collected data used in the present study includes feedstock supply mix (3-year average of feedstock supply, 2021-2023, comprising crude oil and heavy fuel oil, HFO), relevant refining processes, and the entire refinery utilities and emissions profile, and allocated to PMB products based on energy content.

Results for the environmental impact indicator Global Warming Potential over 100 years (GWP_{100} , IPCC's Six Assessment Report (AR6) [7]) are presented and discussed. In addition, the complete set of environmental impact indicators required by the EN 15804+A2:2019 standard of construction products [8] for the development of Environmental Product Declarations (EPD) is incorporated into the analysis.

Sensitivity analyses were carried out to assess [1] the impact that variations in the concentration of SBS and [2] the impact that transportation of bitumen to an offsite PMB production plant have on the GWP_{100} of PMB products. The sensitivity analysis shows that the standard PMB result applies to PMBs with 2,5-4,5 % SBS content, and the high-performance PMB result applies to PMBs with 4,6-7,0 % SBS content, both with less than 5 % deviation. Background life cycle inventory data from Sphera's Managed

LCA Content (MLC) 2024.1 databases (formerly known as GaBi databases) were used throughout the assessment to complement primary data. The intended audience of the present study is bitumen and PMB users and organisations studying environmental aspects, such as the European Commission, national official bodies, asphalt producers, road authorities, and other industry associations as well as consultants and universities.

The present non-ISO conform report does not contain any comparison of products that could be interpreted as a comparative assertions or superiority claim. Paving-grade bitumen according to EN 12591 and PMB have different properties and are used for different applications, hence a direct comparison of impacts is not meaningful. The results are intended to be used for external communication to the public, a critical review by an independent LCA expert is not foreseen.

GWP₁₀₀ impact calculated according to IPCC's AR6 methodology for PMB produced within the refinery boundaries and with a SBS concentration of 3,5 % wt/wt is 625 kg CO₂ eq./t PMB. Similarly, the GWP₁₀₀ for PMB with SBS concentration of 6,0 % wt/wt and produced within the refinery is 684 kg CO₂ eq./t PMB (Figure E- 1). The polymer modification process undergone by PMB-3,5 % wt/wt SBS (PMB-6,0 % wt/wt SBS) adds 95 (154) kg CO₂ eq./t of product in relation to bitumen (EN 12591)'s GWP₁₀₀, or ~18 % (~29 %). The major contributors to GWP₁₀₀ are the supply of crude oil (57 % contribution in PMB-3,5 % wt/wt SBS; 51 % in PMB-6,0 % wt/wt SBS) and the supply of SBS (16 % contribution in PMB-3,5 % wt/wt SBS; 25 % in PMB-6,0 % wt/wt SBS).

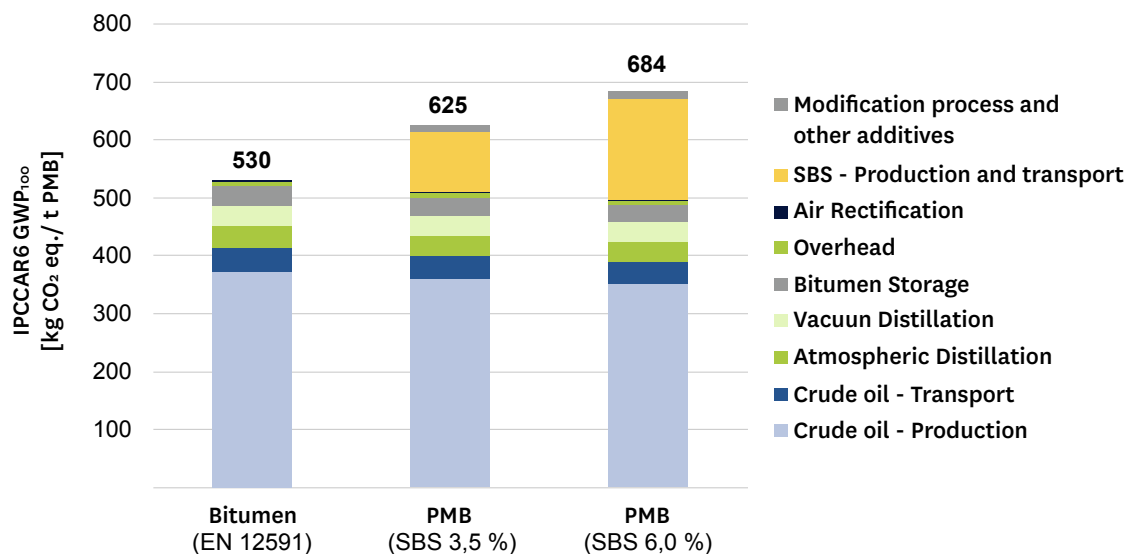


Figure E-1. GWP₁₀₀ (AR6) for paving grade bitumen and PMB products

1. Goal of the Study

Eurobitume, the European industry association for the producers of refined bituminous products in Europe, commissioned Sphera Solutions, Inc. (Sphera) to develop an extension to its recently published Life Cycle Assessment 4.0 for Bitumen study [5] to evaluate the environmental performance of polymer modified bitumen (PMB) production in Europe.

The goal of the present study is to provide life cycle inventory (LCI) data and life cycle environmental impact results on the production of PMB from refineries representative of production within the European Union (EU) and the United Kingdom (UK) produced by Eurobitume's members. Its intended application is to serve as a building block in broader life cycle studies evaluating PMB. Its boundary is cradle-to-gate excluding infrastructure, i.e., it accounts for the environmental impacts of crude oil extraction, its transportation to a refinery, the production and transport of polymers, and the production and storage of PMB inside the refinery. The environmental impacts are referenced to one metric tonne of PMB product compliant with EN14023:2010 [6] produced by an Eurobitume member refinery at refinery gate.

The baseline environmental impacts of PMB are assessed using primary data on PMB production from 4 Eurobitume member refineries collected during the data collection stage of the previous Life Cycle Assessment 4.0 for Bitumen study [5]. In total, the 4 refineries assessed produce ~167.000 metric tonnes per year (t/a). The crude oil supply mix considered for the baseline environmental impact assessment is a three-year average of feedstock supply between 2021-2023, comprising mainly crude oil. Relevant refining processes for the production and storage of PMB and the entire refinery utilities and emissions profile are accounted for and allocated to PMB based on energy content.

Sensitivity analyses are carried out to assess (1) the impact of variations in the concentration of copolymer in PMB and (2) the impact of off-site transport of bitumen to PMB processing plants on global warming potential at a 100-year time horizon (GWP_{100}). Background life cycle inventory data from Sphera's Managed LCA Content (MLC) databases (formerly known as GaBi databases) are used to complement primary data.

The intended audience of this supplementary study are PMB users, road authorities and private road owners, industry associations, consultants and universities, and national official bodies as well as international bodies like the European Commission.

The present report supplements the Life Cycle Assessment 4.0 for Bitumen study [5], which aligns in accordance with the ISO 14040:2006 [1] and ISO 14044:2006 [4] standards. It does not contain comparative assertions and, although the results are intended to be used for external communication to the public, a critical review by an independent LCA expert is not foreseen.

In line with the Life Cycle Assessment 4.0 for Bitumen study [5], the present supplementary study is a generic life cycle assessment (LCA) for PMB in Europe (EU27 + UK) with a declared unit, system boundaries, and life cycle impact assessment (LCIA) methodology following EN 15804+A2:2019 [8]. It could be used as baseline for developing a complementary Product Category Rules standard and specific Product Category Rules that may include PMB in construction works.

2. Scope of the Study

The following sections describe the scope of the project to achieve the stated goals. This includes, but is not limited to, the identification of specific product systems to be assessed, the product function(s), declared unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.1 Product System(s)

Polymer modified bitumen (PMB) is bitumen blended with polymer modifiers (e.g., styrene-butadiene-styrene (SBS) or/and other additives to enhance its characteristics in terms of elasticity, durability and aging resistance, and performance under stress (e.g., extreme temperatures, heavy traffic). This engineered bituminous binder is widely used to enhance the performance of asphalt pavements subjected to heavy traffic or exposure to a wide range of temperatures. In Europe, it is produced to meet specifications and testing primarily directed by the EN 14023:2010 standard [6].

Its properties and characteristics depend on the base bitumen from which it is derived, the polymer's characteristics (e.g., type, chemical structure, concentration), their compatibility, and key conditions of the refinery processes involved in its manufacturing (e.g., mixing temperature, time, intensity) [9]. The crude oil supply mix impacts the chemical composition and properties of the initial base bitumen feedstock, as well as how well it blends with the polymer.

PMB is a composite material consisting of a blend of base bitumen (92 %-97 % wt/wt), polymers (typically 2,5 %-7 % wt/wt), and other additives (0 %-1 % wt/wt) [10]. Bitumen is the primary component and is derived from crude oil refining. Within the bitumen matrix, polymer modifiers (e.g., SBS) form a three-dimensional network that enhances bitumen properties such as elasticity, flexibility, and toughness. Additionally, additives can act as cross-linking agents (e.g., sulphur), anti-aging agents, and adhesion promoters [9].

The PMB production assessed by the present study is representative of that occurring in refineries within the EU and the UK operated by Eurobitume members producing a range of petroleum products other than PMB and bitumen in different shares. A detailed description of the bitumen feedstock and PMB production process is provided in Section 3.2.1.

2.2 Product Function(s) and Declared Unit

Due to its enhanced performance characteristics, PMB is mostly used in high-performance applications across the EU and UK's construction industry. The most relevant applications are in road construction, airport infrastructure, bridge and waterproofing systems. Throughout these applications, PMB enhances durability and resistance to deformation, improves temperature and weather resilience, as well as adhesion [9]. This report addresses two average products representative of current practices in paving application: a standard PMB (based on 3,5 % SBS) and a high-performance PMB (based on 6,0 % SBS)

As the PMB product evaluated in this study is assumed to be compliant with EN 14023:2010 [6], the declared unit is:

1 metric tonne (1000 kilograms) of polymer modified bitumen (PMB) according to EN14023:2010 at the gate of Eurobitume member refineries.

The declared unit is consistent with the study’s goals of providing LCI and LCIA data on the production of PMB products, as it allows the documentation of LCI data and related environmental impacts in reference to a physical quantity of product (1 metric tonne) that is of common use in further life cycle studies of construction materials, e.g., for an Environmental Product Declaration (EPD) under EN 15804+A2:2019 [8].”

2.3 System Boundary

This study considers the cradle-to-gate production of PMB, i.e., it considers the environmental impacts associated with the supply of a representative feedstock mix (comprising crude oil blends and HFOs), including the extraction of a representative crude oil mix, its transportation to a refinery within the EU or UK, the production of bitumen and PMB products and its storage inside the refinery.

The system boundary is consistent with the modules A1, A2 and A3 of EN 15804+A2:2019 covering the life cycle stage production, as defined below:

- A1: Crude oil extraction
- A1: Production of SBS
- A2: Feedstock transportation from the country or region of extraction to the refinery
- A2: Transportation of SBS to the refinery
- A3: Production of bitumen through refining processes
- A3: Production of PMB through the polymer modification process
- A3: PMB storage within the refinery

Figure 2- 1 presents a schematic diagram of the system boundary considered in this study.

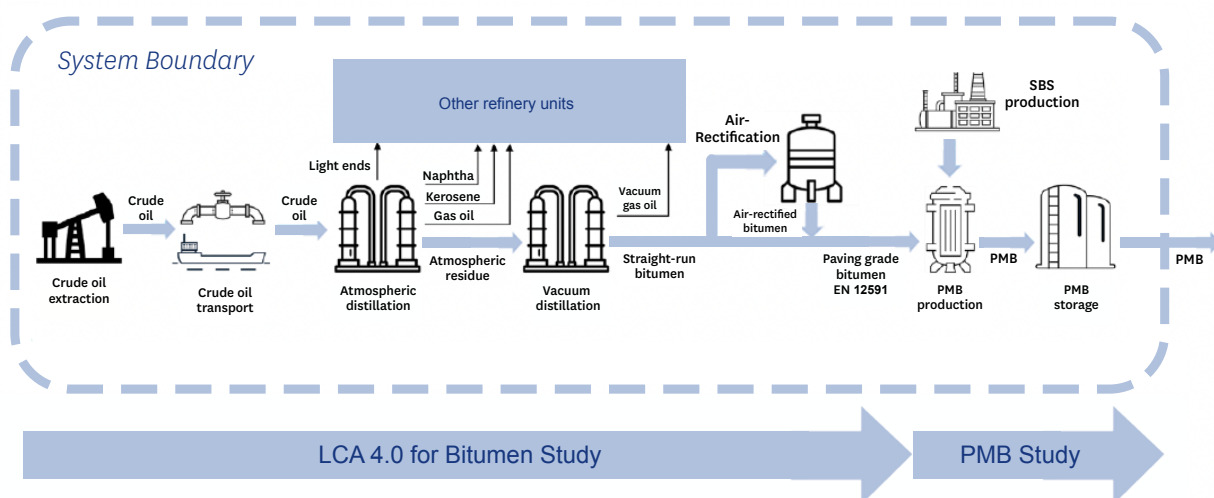


Figure 2-1. System boundary of the present LCA study

The bitumen and PMB are assumed to be produced in an average European refinery operated by Eurobitume members. The refinery is supplied by pipeline and/or sea vessel with a representative feedstock.

Bitume is produced by distillation of the crude oil, using atmospheric and vacuum distillation columns. Bitumen may also be further processed to meet the requirements of bitumen under EN 12591:2009. The EN 12591:2009-compliant bitumen flow is known as paving-grade bitumen and is the main feedstock in the production of PMB through polymer modification. Styrene-butadiene-styrene (SBS) is added as copolymer for PMB production, and its manufacturing and supply is included within the system boundary. The production of other additives (e.g., sulphur) and energy inputs (e.g., electricity, steam) to the polymer modification process is also accounted for within the system boundary, as is the storage of the bitumen and PMB products. The boundary excludes other refinery processes, such as thermal cracking (visbreaking) or deasphalting. Infrastructure for feedstock supply and refinery operation is excluded from the analysis. Table 2- 1 provides a list of activities included and excluded from the study’s system boundary.

Table 2-1. Elements included and excluded from the system boundary.

Included	Excluded
Crude oil extraction	Employee commute
Production of other feedstocks (e.g., HFO)	Infrastructure manufacturing, use, and end of life
Transportation of crude oil and other feedstock by pipeline and sea vessel	Other refinery processes associated with the production of refined fuels and petrochemicals
Atmospheric and vacuum distillation	
Air blowing (i.e., air-rectification) of straight-run bitumen to meet requirements of paving grade bitumen.	
Manufacturing of additives for polymer modification and transportation to refinery	
Polymer modification of paving grade bitumen	
Bitumen and PMB storage within refinery	

2.3.1 Time Coverage

The intended time coverage for the LCA study is the period between 2021 to 2023. More specifically, crude oil feedstock supply data was collected for the 2021-2023 time period, and process data from refining units was collected for the year 2023. A three-year average of crude oil feedstock supply mix data (2021-2023) was developed during the analysis to flatten the fluctuations in the crude oil supply between single years and to avoid selecting a specific year with a rather unusual feedstock supply compared to a longer time period. More information on the selection of the time period can be also found in the Life Cycle Assessment 4.0 for Bitumen study [5].

Results are expected to stay representative of PMB production until there is a significant change in, e.g., production technologies, crude oil basket, use of recycled/secondary feedstock, PMB specifications, among others.

2.3.2 Technology Coverage

The study covers the average PMB production of Eurobitume's members. A description of the technology coverage for the production of the paving grade bitumen feedstock is provided in Section 2.3.2 of the Life Cycle Assessment 4.0 for Bitumen study [5]. In terms of the polymer modification process, the refineries considered in this study use a typical process for the production of PMB. More details on the production process are given in section 3.2.1.

2.3.3 Geographical Coverage

The geographical coverage of this study considers the manufacture of paving grade bitumen products within the EU and the UK. The representative refinery modelled in this study is based on primary data collection of 17 refineries located in different countries of this region as listed in Table 3-1. The average feedstock is based on primary data of the individual refineries and covers a country specific origin and transport to the individual refineries, using country specific background data sets for the feedstock production from Sphera's Managed LCA Content (MLC) database.

2.4 Allocation and Other Methodological Approaches

Multi-output allocation by energy (net calorific value) is applied as baseline case in the foreground and background systems. This follows EN15804+A2:2019 as the energy content of the distillation and refinery products is an inherent property of them. Section 2.4 of the Life Cycle Assessment 4.0 for Bitumen study [5] provides a detailed overview of the multi-output allocation approaches applied in the modelling of the production of paving grade bitumen, and of the end-of-life allocation methodology assumed (i.e., cut-off approach).

Other important methodological choices applied in the Life Cycle Assessment 4.0 for Bitumen study [5], e.g., cut-off criteria, selection of impact categories and LCIA methodology, still apply for the present supplementary study. For a more in-depth description of the impact assessment categories and other metrics considered in both studies, refer to Section 2.4 of the Life Cycle Assessment 4.0 for Bitumen study [5].

2.5 Software and Database

The LCA model was created using the Life Cycle Assessment for Experts (LCA FE) software system for life cycle engineering, developed by Sphera Solutions Inc. The MLC 2024.1 database provides the life cycle inventory data for transportation and the supply of energy and materials, especially crude oil supply. The MLC database version 2024.1 used in the current study was kept consistent with that of the Life Cycle Assessment 4.0 for Bitumen study [5] in the interest of keeping the same environmental impacts associated with paving grade bitumen.

3. Life Cycle Inventory Analysis

3.1 Data Collection Procedure

The collection of primary data on the PMB process from refineries operated by Eurobitume members was conducted as part of the Life Cycle Assessment 4.0 for Bitumen study [5]. A description of the data collection process is provided under Section 3.1 of the aforementioned study. Primary data was collected for 4 refineries operated by 4 different companies in the EU and the UK, accounting for an annual PMB production of 167.200 tonnes in 2023.

3.2 Product System

3.2.1 Overview of Product System

The refineries included in this study produce PMB from straight-run bitumen (also known as vacuum residue or short residue) and bitumen that has undergone air-rectification, among a variety of other petroleum products. A crude oil basket that is representative of the average feedstock for bitumen production in Eurobitume members' refineries (rather than specific to any individual refinery) is modelled from refinery primary data. The crude oil basket is the same as that used in the Life Cycle Assessment 4.0 for Bitumen study [5] and therefore a discussion about its modelling and assumptions is provided under Section 3.2.1 of the aforementioned study.

Bitumen produced at the bottom of the vacuum distillation column is the primary feedstock for paving grade bitumen, which may be further processed through air-blowing to meet EN 12591:2009 requirements. During PMB production, EN 12591-compliant paving grade bitumen is heated, if needed, to 160–180 °C to reduce viscosity and allow efficient mixing. Polymers such as SBS, typically added in proportions of 2,5–7 % wt/wt, are mechanically dispersed into the hot bitumen using high-shear mills, which break down polymer particles and distribute them uniformly to form a homogeneous binder. After high-shear mixing, the blend is transferred to a lower-shear agitation tank and held at elevated temperatures for several hours, enabling polymer swelling and the development of a three-dimensional network that improves compatibility, elasticity, stiffness, and performance, particularly resistance to rutting and cracking [11]. Additives may be incorporated during or after high-shear mixing to enhance long-term stability and prevent phase separation. Once the polymer network has fully developed, the finished PMB is tested to ensure that required properties are met and is then stored in heated, agitated tanks to maintain homogeneity and avoid settling prior to dispatch [12] [9]. A simplified flow chart of the production of the PMB product evaluated in this study can be seen in Figure 2- 1.

3.2.2 Product Composition

PMB is mainly composed of paving grade bitumen, elastomeric polymers (e.g., SBS), and additives (e.g., crosslinkers, oils, waxes) that improve the compatibility and workability of the base bitumen, creating a homogeneous binder for better performance in its different applications. Paving grade bitumen is the base and it provides PMB's fundamental properties. The polymers added enhance elasticity, rutting resistance, and fatigue life [13]. Crosslinking agents, oils, waxes, or compatibilizers are used to improve polymer-bitumen interaction, reduce its viscosity, or lower production temperatures [14].

EN 14023 does not define or require a specific product composition for PMB; however, typical ranges of polymer content fall within the range of 2,5-7 % wt/wt, other additives fall within the range of 0-1 % wt/wt, while the rest is base bitumen (92-97 % wt/wt) [12].

3.3 Manufacturing

PMB is manufactured from paving grade bitumen, the primary base material and fundamental component. Section 3.3 of the study Life Cycle Assessment 4.0 for Bitumen [5] provides an overview of the manufacturing processes involved in the production of paving grade bitumen. The following section provides an overview of the polymer modification process subsequent to the atmospheric and vacuum distillation steps.

3.3.1 Polymer Modification Process

The production of PMB, as described in section 3.2.1, is modelled using standard SBS concentration (3,5 % wt/wt) and high-performance SBS concentration (6,0 % wt/wt) in Sphera’s LCA FE software, using both Managed LCA Content (MLC) background datasets and primary data collected from Eurobitume member refineries. The amounts of input and output flows are modelled using primary refinery data for the year 2023, averaged using PMB production by refinery as weighting, i.e., the weights applied to each input-output value reported by the Eurobitume refineries is equal to the share of PMB production by a specific refinery with respect to the total PMB production of all refineries evaluated in the study. Subsequently, the input-output data was normalized to one tonne of PMB product.

Table 3-1. Polymer modification input-output table per tonne of PMB output.

Type	Flow	Standard SBS Concentration (3,5 % wt/wt)	High-performance PMB (6,0 % wt/wt)	Unit
Inputs	Bitumen	963,21	938,21	kg/tonne of PMB
	Sytrene-Butadiene-Sytrene (SBS)	35,00	60,00	kg/tonne of PMB
	Other additives	1,79	1,79	kg/tonne of PMB
	Electricity	28,10	28,10	MJ/tonne of PMB
	Steam	95,10	95,10	MJ/tonne of PMB
	Thermal energy from natural gas	40,20	40,20	MJ/tonne of PMB
Outputs	PMB	1000,00	1000,00	kg/tonne of PMB

The input-output flows used to model the polymer modification process in Sphera’s LCA FE are presented in Table 3- 1. The environmental impacts associated with PMB product storage are accounted for in the present study by assuming similar energy requirements to those required by the storage of paving grade bitumen and disclosed in Section 3.3.3 of the Life Cycle Assessment 4.0 for Bitumen report [5].

3.3.2 Refinery Utilities

The representative refinery producing PMB sources electricity from an onsite power plant and the grid. The fraction of electricity consumption generated by the onsite combined heat and power (CHP) plant is consistent with the previous Life Cycle Assessment 4.0 for Bitumen study (42,87 %) [5]. The rest (57,13 %) is assumed to be sourced from the grid, applying a country mix consistent with the aforementioned study. All steam consumed by the representative refinery is supplied by the CHP plant. Further information on the electricity and steam consumption modelling data, assumptions, and methodology is available on Section 3.3.4. of the Life Cycle Assessment 4.0 for Bitumen report [5].

The modelling of water consumption, wastewater, waste disposal, and the overhead operations are also consistent with the Life Cycle Assessment 4.0 for Bitumen study [5]. This means that the same refinery data and modelling approach were applied and allocated to the production of PMB.

For further information, see Section 3.3.5. of the Life Cycle Assessment 4.0 for Bitumen report [5].

3.4 Background Data

The production of PMB was modelled in Sphera's LCA FE software using primary data supplied by Eurobitume member refineries wherever available and background data from Sphera's MLC 2024.1 database. Background datasets were mainly used to model the upstream environmental burden of the extraction of crude oil supply, crude oil transport, energy supply from sources external to the representative refinery (fuels and grid electricity) as well as auxiliary processes and production of additives of the polymer modification process.

Sections 3.4.1 to 3.4.3 of the Life Cycle Assessment 4.0 for Bitumen report [5] document the LCI background datasets used in the production of paving grade bitumen, the base feedstock in the production of PMB. The sections below document the background datasets used in the modelling of the polymer modification process specifically. Documentation for all LCA FE datasets can be found online under <https://lcadatabase.sphera.com/>[15].

3.4.1 Fuels and Energy

The main energy inputs into the PMB production process are electricity, steam, and natural gas as fuel. In line with the system boundary of this study, i.e., cradle-to-gate, the upstream environmental impacts associated with the production of electricity, steam, and natural gas are taken into account, as well as direct impacts from its use at the representative refinery.

The representative refinery sources electricity from an onsite power plant (42,87 % of the electricity consumed) and from the grid (57,13 %). The environmental impacts from the fraction of electricity generated onsite through CHP are modelled using primary data from Eurobitume member refineries and background datasets that account for the production of the fuels burned in the CHP plant. Documentation on such datasets and on the country-specific electricity grid mixes datasets used for the fraction of electricity sourced from the grid is provided in the Life Cycle Assessment 4.0 for Bitumen report [5].

On the other hand, all steam needed in the polymer modification process is assumed to be generated onsite at the CHP plant. Similar to before, the MLC datasets that account for the production of the fuels used in the CHP plant are reported in the Section 3.4.1 of the Life Cycle Assessment 4.0 for Bitumen report [5].

3.4.2 Raw Materials and Processes

LCI background data has been used for the production (extraction) of crude oil and HFO used as feedstock for the refining. Information on such background datasets is available in the Life Cycle Assessment 4.0 for Bitumen report [5].

A background dataset developed by WAP Sustainability Consulting and commissioned by the Asphalt Institute [17] was used in the modelling of the SBS supply, as a primary data collection on SBS was out of scope for this study. The dataset represents the cradle-to-gate production of SBS, i.e. the production of raw materials, their transportation to the manufacturing facility, and the manufacturing operations (anionic polymerisation) [16]. The inventory is based on primary data from four companies at six sites in Europe, Mexico and the United States. Although the selected dataset is not fully representative of SBS production in Europe, it was chosen for its availability and the quality of its data. Additionally, the dataset excludes the transportation of the product from the manufacturing facility to the customer. Therefore, a road transportation of 500 km was assumed between the manufacturing plant and the representative refinery.

Additives other than SBS were modelled using sulphur as proxy background dataset since sulphur derivatives are used as cross-linking agents in the polymer modification process. Table 3- 2 presents the background datasets used to model the supply of raw materials to the polymer modification process.

Table 3-2. Raw materials dataset.

Raw material	Geographical Reference	Dataset	Data Provider	Reference Year	Proxy?
SBS	RNA	Styrene-butadiene-styrene (SBS) block copolymer	Asphalt Institute	2021	No
Other additives	RER	Sulphur (elemental) at refinery	Sphera	2020	Yes

3.4.3 Transportation

Transportation datasets from Sphera's MLC database have been used for the transport of the refinery crude oil supply (see the Life Cycle Assessment 4.0 for Bitumen report [5]) and the inbound transportation of SBS from its manufacturing plant (in Europe) to the refinery.

Table 3- 3 presents the background datasets used to model the transportation and fuel in the LCA model.

Table 3-3. Transportation and fuel datasets

Mode / fuels	Geographical Reference	Dataset	Data Provider	Reference Year	Proxy?
Road Truck transport	GLO	Truck-trailer, Euro 6 D-E, 34 - 40t gross weight / 27t payload capacity	Sphera	2023	No
Diesel fuel	RER	Diesel mix at filling station	Sphera	2020	No

3.5 Life Cycle Inventory Analysis Results

ISO 14044:2006 defines the Life Cycle Inventory (LCI) analysis result as the “outcome of a life cycle inventory analysis that catalogues the flows crossing the system boundary and provides the starting point for life cycle impact assessment”. As the complete inventory comprises hundreds of flows, the below table only displays a selection of flows based on their relevance to the subsequent impact assessment in order to provide a transparent link between the inventory and impact assessment results. Table 3- 4 summarises the LCI for the two different PMB products, PMB-3,5 % wt/wt SBS and PMB-6,0 % wt/wt SBS.

Type	Flow	PMB-3,5% wt/wt SBS [kg/t]	PMB-6,0% wt/wt SBS [kg/t]	
Resources	Water consumption	1,05E+03	1,32E+03	
	Crude oil	9,93E+02	9,93E+02	
	Hard coal	3,97E+00	5,17E+00	
	Lignite	2,78E+00	3,09E+00	
	Natural gas	1,18E+02	1,43E+02	
	Uranium	3,11E-04	3,56E-04	
	Emissions to air	CO ₂	3,76E+02	4,34E+02
CO ₂ (biotic)		1,19E+01	1,58E+01	
CH ₄		8,24E+00	8,32E+00	
CH ₄ (biotic)		8,44E-02	8,70E-02	
N ₂ O		9,77E-03	1,05E-02	
NO _x		1,22E+00	1,29E+00	
SO ₂		7,04E-01	7,18E-01	
NM VOC		1,68E+00	1,69E+00	
CO		3,90E-01	4,23E-01	
PM _{2,5-10}		1,46E-02	1,71E-02	
PM _{2,5}		8,52E-02	8,70E-02	
Heavy metals		3,08E-04	3,23E-04	
Emissions to fresh water		Ammonia	8,21E-05	9,50E-05
		Nitrate	1,55E-02	1,72E-02
		Phosphate	9,49E-04	1,08E-03
		Heavy metals	2,04E-02	2,37E-02
Emissions to sea water	Ammonia	2,53E-09	4,04E-09	
	Nitrate	4,86E-04	4,98E-04	
	Phosphate	9,70E-05	9,47E-05	
	Heavy metals	2,61E-03	2,62E-03	

4 LCIA Results

4.1 Overall Results

The present study evaluates the cradle-to-gate environmental impacts associated with 1 (metric) tonne of polymer modified bitumen (PMB) (EN14023:2010) produced at an average refinery representative of Eurobitume member’s refineries within the EU and UK.

Primary data coverage for the study spans operations in 4 refineries in 4 European countries and bitumen production of 167.200 tonnes in 2023. The following results in this section apply all energy allocation for the distillation units and use the 3-year average (2021-2023) feedstock supply (mainly crude oil and some HFO).

Global Warming Potential Results

Results are shown for the global warming potential over a 100-year period (GWP_{100}) calculated according to IPCC’s Six Assessment Report (AR6) [7] methodology. The GWP_{100} AR6 indicator corresponds with the ‘Climate Change, total’ indicator under EN 15804+A2:2019 [8]. Figure 4- 1 presents the contribution analysis to GWP_{100} of PMB with SBS concentration of 3,5 % wt/wt (standard concentration) and 6,0 % wt/wt (high-performance PMB) and compares it to that of paving grade bitumen (EN 12591), using the 3-year average feedstock supply and allocation by energy.

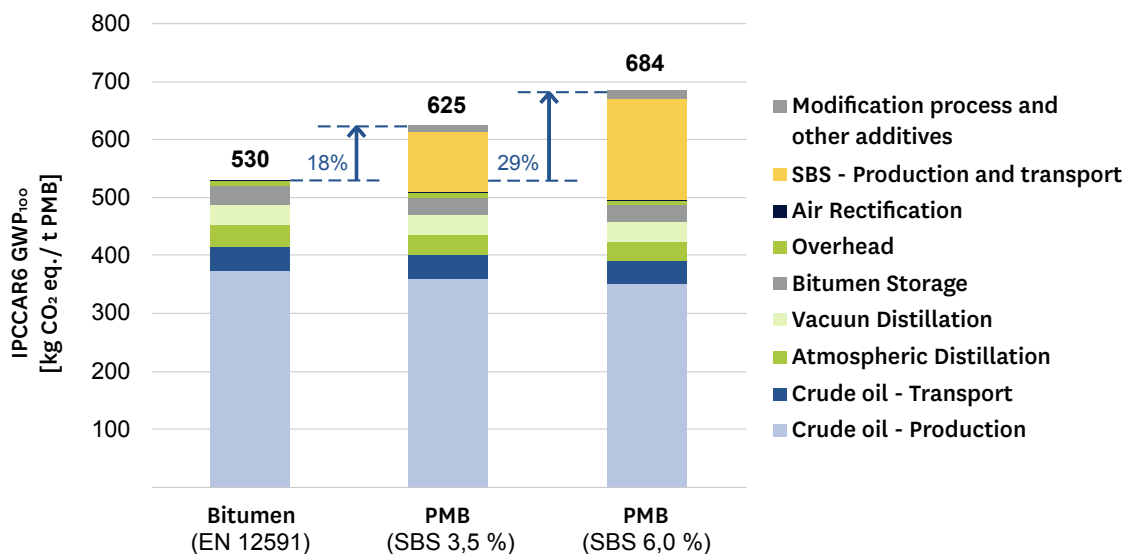


Figure 4-1. GWP_{100} (AR6) for paving grade bitumen and PMB

GWP_{100} for the PMB-3,5 % wt/wt SBS (standard concentration) product is 625 kg CO₂-eq./t of PMB, while that of PMB-6,0 % wt/wt SBS (high-performance PMB) product is 684 kg CO₂-eq./t of PMB. This means that the production of standard (high-performance) PMB adds 95 (154) kg CO₂ eq./t in relation to bitumen (EN 12591)’s GWP_{100} , or ~18 % (~29%) increase. Major drivers are crude oil production (57 % contribution in PMB-3,5 % wt/wt SBS; 51 % in PMB-6,0 % wt/wt SBS) and the SBS production and transport (16 % contribution in PMB-3,5 % wt/wt SBS; 25 % in PMB-6,0 % wt/wt SBS). The impacts associated with the rest of the material/energy inputs and outputs of the polymer modification process accounts for only 2 % of the GWP_{100} for both PMB products.

Atmospheric and vacuum distillation of the crude oil contribute 11 % (10 %) to GWP₁₀₀ of PMB-3,5 % wt/wt SBS (PMB-6,0 % wt/wt SBS). The transport of crude oil to the refinery represents 6 % to the GWP₁₀₀ of any of the PMB products. Product storage accounts for 5 % (4 %) of PMB-3,5 % wt/wt SBS (PMB-6,0 % wt/wt SBS)'s GWP₁₀₀.

Figure 4- 2 provides further insight on the contribution analysis to GWP₁₀₀ (AR6) of the polymer modification process.

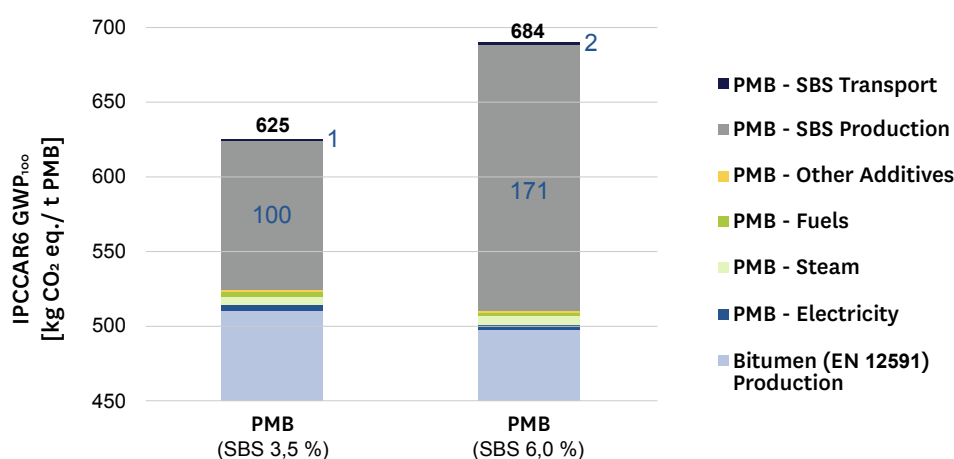


Figure 4-2. Contribution analysis to GWP₁₀₀ (AR6) for the polymer modification process

Figure 4-2 shows that most of the GWP₁₀₀ impact for PMB-3,5 % wt/wt SBS and PMB-6,0 % wt/wt SBS comes from the production of paving grade bitumen (EN12591) (82 % for PMB-3,5 % wt/wt SBS and 73 % for PMB-6,0 % wt/wt SBS). The detailed contribution breakdown to the PMB production reveals that the dominant driver is the production of copolymer SBS (16 % for PMB- 3,5 % wt/wt SBS and 25 % for PMB-6 % wt/wt SBS). Additives and energy inputs for PMB production contribute marginally (less than 1 % each).

Other Environmental Impact Categories

The complete set of environmental impact categories and indicators from the EF 3.1 assessment method, required by the EN 15804+A2:2019 standard of construction products, are presented in Table 4- 1 for PMB with SBS concentration of 3,5 % wt/wt and in Table 4- 2 for PMB with SBS concentration of 6,0 % wt/wt. Both tables present environmental impact results considering energy allocation of primary refinery data and a 3-year average of crude oil supply (2021-2023).

Table 4- 1: EN 15804+A2 impact indicators for PMB with 3,5% wt/wt SBS concentration.

EN15804+A2 Impact Indicators (Based on EF 3.1)	Units	Total	Crude Oil Production	Crude Oil Transport	Distillation	Air-Rectification	SBS Production and Transport	Polymer Modification	PMB Storage	Overhead
Environmental Impact Indicators										
Climate change, total	[kg CO ₂ eq.]	6,25E+02	3,59E+02	4,02E+01	6,97E+01	2,57E+00	1,01E+02	1,33E+01	3,02E+01	8,76E+00
Climate change, fossil	[kg CO ₂ eq.]	6,25E+02	3,57E+02	4,02E+01	6,96E+01	2,57E+00	1,03E+02	1,32E+01	3,03E+01	8,64E+00
Climate change, biogenic	[kg CO ₂ eq.]	-2,41E-03	2,05E+00	-1,21E-01	9,77E-02	5,78E-03	-2,06E+00	3,17E-02	-1,24E-01	1,22E-01
Climate change, land use and land use change	[kg CO ₂ eq.]	3,23E-01	9,82E-02	1,42E-01	1,05E-02	1,53E-04	6,60E-02	8,91E-04	2,37E-03	2,41E-03
Ozone depletion	[kg CFC-11 eq.]	1,93E-07	4,25E-11	7,79E-12	1,67E-10	7,15E-12	1,93E-07	3,39E-11	5,37E-11	4,23E-11
Acidification	[Mole of H ⁺ eq.]	1,84E+00	7,59E-01	6,67E-01	1,46E-01	5,12E-03	1,57E-01	2,72E-02	6,50E-02	1,71E-02
Eutrophication, freshwater	[kg P eq.]	5,97E-04	1,71E-04	4,50E-05	5,61E-05	1,95E-06	1,56E-04	1,27E-05	2,66E-05	1,28E-04
Eutrophication, marine	[kg N eq.]	4,83E-01	1,20E-01	2,89E-01	1,04E-02	3,68E-04	5,27E-02	2,33E-03	5,50E-03	3,05E-03
Eutrophication, terrestrial	[Mole of N eq.]	5,28E+00	1,30E+00	3,17E+00	1,15E-01	4,04E-03	5,78E-01	2,56E-02	6,18E-02	2,82E-02
Photochemical ozone formation, human health	[kg NMVOC eq.]	2,17E+00	1,01E+00	7,92E-01	1,01E-01	3,47E-03	1,93E-01	1,94E-02	4,26E-02	1,27E-02
Resource use, mineral and metals	[kg Sb eq.]	1,43E-04	5,39E-05	1,44E-06	7,41E-06	1,12E-07	4,43E-05	6,26E-07	3,49E-05	4,74E-07
Resource use, fossils	[MJ]	4,73E+04	4,18E+04	4,83E+02	1,12E+03	4,18E+01	2,96E+03	2,55E+02	4,95E+02	1,20E+02
Water use	[m ³ world equiv.]	1,84E+01	1,39E+00	2,36E-01	1,46E+00	6,09E-02	1,11E+01	3,02E-01	5,94E-01	3,20E+00
Resource use indicators										
Use of renewable primary energy (PERE)	[MJ]	3,20E+02	3,76E+01	1,41E+01	1,07E+02	4,56E+00	7,28E+01	2,17E+01	3,88E+01	2,32E+01
Renewable primary energy resources used as raw materials (PERM)	[MJ]	1,64E+01	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,64E+01	0,00E+00	0,00E+00	0,00E+00
Total use of renewable primary energy resources (PERT)	[MJ]	3,36E+02	3,76E+01	1,41E+01	1,07E+02	4,56E+00	8,92E+01	2,17E+01	3,88E+01	2,32E+01
Use of non-renewable primary energy (PENRE)	[MJ]	8,45E+03	4,54E+03	4,83E+02	1,12E+03	4,18E+01	1,41E+03	2,38E+02	4,95E+02	1,20E+02

EN15804+A2 Impact Indicators (Based on EF 3.1)	Units	Total	Crude Oil Production	Crude Oil Transport	Distillation	Air- Rectification	SBS Production and Transport	Polymer Modification	PMB Storage	Overhead
Non-renewable primary energy resources used as raw material (PENRM)	[MJ]	3,89E+04	3,73E+04	0,00E+00	0,00E+00	0,00E+00	1,59E+03	1,66E+01	0,00E+00	0,00E+00
Total use of non-renewable primary energy resources (PENRT)	[MJ]	4,73E+04	4,18E+04	4,83E+02	1,12E+03	4,18E+01	3,01E+03	2,55E+02	4,95E+02	1,20E+02
Input of secondary material (SM)	[kg]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Use of renewable secondary fuels (RSF)	[MJ]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Use of non-renewable secondary fuels (NRSF)	[MJ]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Use of net fresh water (FW)	[m3]	1,05E+00	5,50E-02	1,50E-02	7,44E-02	3,13E-03	4,01E-01	1,52E-02	2,80E-02	4,58E-01
Output flows and waste categories										
Hazardous waste disposed (HWD)	[kg]	2,23E-04	7,20E-07	2,11E-08	2,44E-05	9,21E-09	1,98E-04	4,51E-08	7,33E-08	5,12E-08
Non-hazardous waste disposed (NHWD)	[kg]	6,45E+00	2,56E+00	5,60E-02	2,32E-01	9,79E-03	1,19E+00	5,22E-02	1,62E-01	2,18E+00
Radioactive waste disposed (RWD)	[kg]	6,18E-02	7,35E-03	1,24E-03	2,21E-02	9,45E-04	1,51E-02	4,51E-03	7,10E-03	3,39E-03
Components for re-use (CRU)	[kg]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Materials for recycling (MFR)	[kg]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Materials for energy recovery (MER)	[kg]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Exported electrical energy (EEE)	[MJ]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Exported thermal energy (EET)	[MJ]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Biogenic carbon content										
Biogenic carbon content in product	[kg]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Biogenic carbon content in packaging	[kg]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Optional indicators										

EN15804+A2 Impact Indicators (Based on EF 3.1)	Units	Total	Crude Oil Production	Crude Oil Transport	Distillation	Air-Rectification	SBS Production and Transport	Polymer Modification	PMB Storage	Overhead
Particulate matter	[Disease incidences]	2,81E-05	6,57E-06	1,62E-05	1,95E-06	6,81E-08	1,87E-06	3,49E-07	8,48E-07	2,10E-07
Ionising radiation, human health	[kBq U235 eq.]	1,10E+01	7,87E-01	1,88E-01	4,25E+00	1,82E-01	2,83E+00	8,62E-01	1,34E+00	5,24E-01
Ecotoxicity, freshwater	[CTUe]	2,87E+04	2,63E+04	3,55E+02	5,74E+02	1,23E+01	1,20E+03	9,06E+01	1,54E+02	8,41E+01
Human toxicity, cancer	[CTUh]	5,09E-07	4,51E-07	6,86E-09	1,30E-08	3,58E-10	2,85E-08	2,33E-09	4,55E-09	2,21E-09
Human toxicity, non-cancer	[CTUh]	1,47E-05	1,28E-05	2,31E-07	4,43E-07	1,44E-08	7,86E-07	9,12E-08	2,27E-07	1,12E-07
Land Use	[Pt]	4,76E+02	5,32E+01	5,73E+01	6,40E+01	2,50E+00	2,11E+02	1,20E+01	6,15E+01	1,49E+01

Table 4-2: EN 15804+A2 impact indicators for PMB with 6 % wt/wt SBS concentration.

EN15804+A2 Impact Indicators (Based on EF 3.1)	Units	Total	Crude Oil -Supply	Crude Oil -Transport	Distillation	Air-Rectification	SBS Supply	Polymer Modification	Bitumen Storage	Overhead
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Environmental Impact Indicators

Climate change, total	[kg CO ₂ eq.]	6,84E+02	3,50E+02	3,91E+01	6,79E+01	2,51E+00	1,73E+02	1,33E+01	2,94E+01	8,54E+00
Climate change, fossil	[kg CO ₂ eq.]	6,85E+02	3,48E+02	3,91E+01	6,78E+01	2,50E+00	1,77E+02	1,32E+01	2,95E+01	8,41E+00
Climate change, biogenic	[kg CO ₂ eq.]	-1,53E+00	1,99E+00	-1,18E-01	9,52E-02	5,63E-03	-3,53E+00	3,17E-02	-1,21E-01	1,19E-01
Climate change, land use and land use change	[kg CO ₂ eq.]	3,63E-01	9,56E-02	1,38E-01	1,02E-02	1,49E-04	1,13E-01	8,91E-04	2,31E-03	2,34E-03
Ozone depletion	[kg CFC-11 eq.]	3,31E-07	4,14E-11	7,59E-12	1,62E-10	6,96E-12	3,31E-07	3,39E-11	5,23E-11	4,12E-11
Acidification	[Mole of H ⁺ eq.]	1,91E+00	7,39E-01	6,50E-01	1,42E-01	4,99E-03	2,69E-01	2,72E-02	6,33E-02	1,66E-02
Eutrophication, freshwater	[kg P eq.]	6,98E-04	1,66E-04	4,38E-05	5,47E-05	1,90E-06	2,67E-04	1,27E-05	2,59E-05	1,25E-04
Eutrophication, marine	[kg N eq.]	5,09E-01	1,16E-01	2,81E-01	1,01E-02	3,58E-04	9,03E-02	2,33E-03	5,36E-03	2,86E-03
Eutrophication, terrestrial	[Mole of N eq.]	5,57E+00	1,27E+00	3,08E+00	1,12E-01	3,94E-03	9,91E-01	2,56E-02	6,02E-02	2,75E-02
Photochemical ozone formation, human health	[kg NMVOC eq.]	2,26E+00	9,79E-01	7,72E-01	9,79E-02	3,38E-03	3,31E-01	1,94E-02	4,15E-02	1,23E-02
Resource use, mineral and metals	[kg Sb eq.]	1,72E-04	5,25E-05	1,40E-06	7,22E-06	1,09E-07	7,59E-05	6,26E-07	3,40E-05	4,62E-07
Resource use, fossils	[MJ]	4,83E+04	4,07E+04	4,71E+02	1,09E+03	4,07E+01	5,08E+03	2,55E+02	4,82E+02	1,17E+02
Water use	[m ³ world equiv.]	2,62E+01	1,36E+00	2,30E-01	1,43E+00	5,93E-02	1,91E+01	3,02E-01	5,78E-01	3,12E+00

Resource use indicators

EN15804+A2 Impact Indicators (Based on EF 3.1)	Units	Total	Crude Oil -Supply	Crude Oil -Transport	Distillation	Air- Rectification	SBS Supply	Polymer Modification	Bitumen Storage	Overhead
Use of renewable primary energy (PERE)	[MJ]	3,66E+02	3,66E+01	1,38E+01	1,04E+02	4,45E+00	1,25E+02	2,17E+01	3,78E+01	2,26E+01
Renewable primary energy resources used as raw materials (PERM)	[MJ]	2,81E+01	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,81E+01	0,00E+00	0,00E+00	0,00E+00
Total use of renewable primary energy resources (PERT)	[MJ]	3,94E+02	3,66E+01	1,38E+01	1,04E+02	4,45E+00	1,53E+02	2,17E+01	3,78E+01	2,26E+01
Use of non-renewable primary energy (PENRE)	[MJ]	9,29E+03	4,42E+03	4,71E+02	1,09E+03	4,07E+01	2,43E+03	2,38E+02	4,82E+02	1,17E+02
Non-renewable primary energy resources used as raw material (PENRM)	[MJ]	3,91E+04	3,63E+04	0,00E+00	0,00E+00	0,00E+00	2,73E+03	1,66E+01	0,00E+00	0,00E+00
Total use of non-renewable primary energy resources (PENRT)	[MJ]	4,83E+04	4,07E+04	4,71E+02	1,09E+03	4,07E+01	5,15E+03	2,55E+02	4,82E+02	1,17E+02
Input of secondary material (SM)	[kg]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Use of renewable secondary fuels (RSF)	[MJ]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Use of non-renewable secondary fuels (NRSF)	[MJ]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Use of net fresh water (FW)	[m3]	1,32E+00	5,36E-02	1,46E-02	7,25E-02	3,05E-03	6,87E-01	1,52E-02	2,73E-02	4,46E-01
Output flows and waste categories										
Hazardous waste disposed (HWD)	[kg]	3,64E-04	7,02E-07	2,06E-08	2,38E-05	8,97E-09	3,39E-04	4,51E-08	7,14E-08	4,99E-08
Non-hazardous waste disposed (NHWD)	[kg]	7,16E+00	2,50E+00	5,45E-02	2,26E-01	9,53E-03	2,04E+00	5,22E-02	1,58E-01	2,12E+00
Radioactive waste disposed (RWD)	[kg]	7,15E-02	7,16E-03	1,20E-03	2,16E-02	9,20E-04	2,59E-02	4,51E-03	6,91E-03	3,30E-03
Components for re-use (CRU)	[kg]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Materials for recycling (MFR)	[kg]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Materials for energy recovery (MER)	[kg]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

EN15804+A2 Impact Indicators (Based on EF 3.1)	Units	Total	Crude Oil -Supply	Crude Oil -Transport	Distillation	Air- Rectification	SBS Supply	Polymer Modification	Bitumen Storage	Overhead
Exported electrical energy (EEE)	[MJ]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Exported thermal energy (EET)	[MJ]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Biogenic carbon content

Biogenic carbon content in product	[kg]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Biogenic carbon content in packaging	[kg]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00

Optional indicators

Particulate matter	[Disease incidences]	2,87E-05	6,40E-06	1,58E-05	1,90E-06	6,64E-08	3,21E-06	3,49E-07	8,26E-07	2,04E-07
Ionising radiation, human health	[kBq U235 eq.]	1,28E+01	7,67E-01	1,84E-01	4,14E+00	1,77E-01	4,85E+00	8,62E-01	1,30E+00	5,11E-01
Ecotoxicity, freshwater	[CTUe]	2,89E+04	2,56E+04	3,46E+02	5,59E+02	1,20E+01	2,05E+03	9,06E+01	1,50E+02	8,19E+01
Human toxicity, cancer	[CTUh]	5,17E-07	4,39E-07	6,68E-09	1,26E-08	3,49E-10	4,89E-08	2,33E-09	4,43E-09	2,15E-09
Human toxicity, non-cancer	[CTUh]	1,49E-05	1,24E-05	2,25E-07	4,32E-07	1,40E-08	1,35E-06	9,12E-08	2,21E-07	1,09E-07
Land Use	[Pt]	6,20E+02	5,18E+01	5,58E+01	6,23E+01	2,44E+00	3,62E+02	1,20E+01	5,99E+01	1,45E+01

4.2 Sensitivity Analysis

4.2.1 SBS Concentration

SBS concentration is the dominant driver of environmental impacts associated with the polymer modification process that produces PMB. Therefore, a sensitivity analysis was performed to investigate the impact of the typical range of SBS concentrations (i.e., 2,5 % - 7 % wt/wt) on PMB's GWP₁₀₀. The average SBS concentration reported by the refineries included in this analysis is ~4,6 % wt/wt.

The sensitivity analysis was performed to test the robustness of the study results with respect to typical variations in SBS concentration and to support the definition of representative average PMB products, i.e., standard (PMB-3.5 % SBS) and high-performance PMB (PMB-6.0 % SBS). It is not intended to provide formulation-specific environmental impact values.

The sensitivity analysis shows that the standard PMB result applies to PMBs with 2,5-4,5 % SBS content, and the high-performance PMB result applies to PMBs with 4,6-7,0 % SBS content, both with less than 5 % deviation.

In the present study, a correlation between energy consumption and average SBS concentration reported by refineries could not be analysed. No data were available in a specific refinery for a deeper analysis to evaluate and understand the potential variations in energy consumption due to different SBS concentrations. Therefore, energy consumption remains independent of SBS concentration in the present study.

4.2.2 Transportation to Offsite PMB Production Plants

The baseline results of the study assume the production and storage of PMB within the boundaries of a representative refinery, i.e., they do not include additional environmental impact associated with the offsite production of PMB and the transport of bitumen. Since PMB is produced both within European refineries and at dedicated offsite plants, a sensitivity analysis was developed to assess the impact on PMB's GWP₁₀₀ of offsite transportation of bitumen to a PMB production plant outside of the refinery. Various bitumen transport distances from 50 km to 300 km away from the base refinery were evaluated. A 40-tonne truck with payload of 25 tonne and 100 % utilisation and an empty return trip was assumed for the modelling of road transport, and it was assumed that no heating was needed during transport. Figure 4-3 shows the additional GWP₁₀₀ impact per tonne of transported product for various distances.

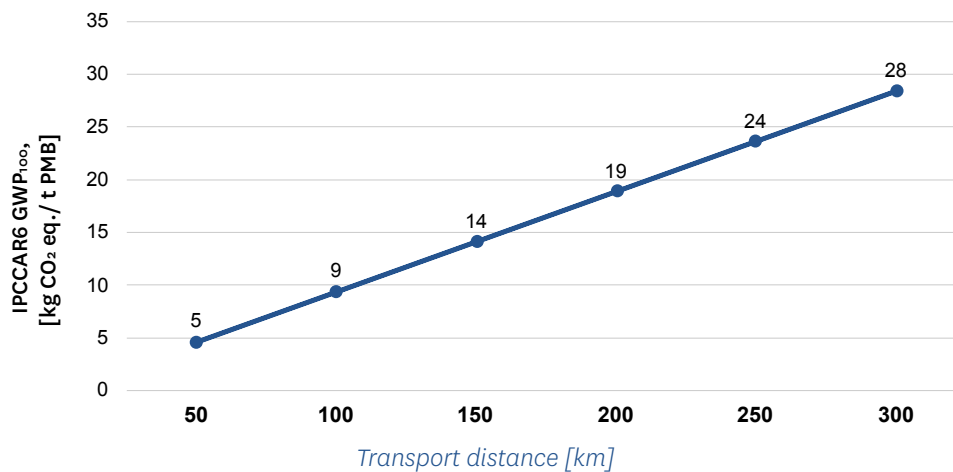


Figure 4-3: GWP₁₀₀ of transport of one tonne bitumen.

From a quantitative perspective, the GWP₁₀₀ of one tonne of bitumen is expected to increase by 0,09 kg CO₂ eq. for every kilometer the bitumen feedstock is transported away from the base refinery. However, there are a few additional considerations to account for when assessing the environmental impacts of offsite PMB production:

(1) Offsite PMB production plants may operate with technologies that differ from the production route evaluated in the current study.

(2) Offsite production plants may require additional product storage, which has not been taken into consideration in this study.

(3) Offsite production plants may also require additional bitumen feedstock heating, which has not been included in the present study.

For these reasons, it is likely that the GWP_{100} of one tonne of PMB produced at an offsite production plant may be greater than the baseline GWP_{100} assessed in the present study for one tonne of PMB produced within the refinery boundaries (i.e., at refinery gate). The present sensitivity analysis was solely conducted with the aim of understanding the impacts of a possible offsite bitumen transport.

5 Interpretation

5.1 Identification of Relevant Findings

The present LCA study has developed life cycle inventory (LCI) data and life cycle environmental impact results on the cradle-to-gate production of polymer modified bitumen (PMB) within a refinery that is representative of the operations of Eurobitume's members in the EU and UK. The study is based on primary data collected from 4 refineries located in 4 different countries within the region. The potential environmental impact results of PMB produced within the refinery were calculated with an LCA model developed using the collected primary data alongside background datasets in Sphera's LCA FE software system for life cycle engineering. The baseline environmental impact results of this study consider energy allocation of primary refinery data and a 3-year average of feedstock supply (2021-2023).

The GWP_{100} impact calculated according to the IPCC's AR6 methodology for PMB produced within the refinery boundaries with an SBS concentration of 3,5 wt% is 625 kg CO₂ eq/t PMB. For PMB containing 6,0 wt% SBS, produced within the refinery, the GWP_{100} is 684 kg CO₂ eq/t PMB. The polymer modification process undergone by PMB-3,5 % wt/wt SBS (PMB-6,0 % wt/wt SBS) adds 95 (154) kg CO₂ eq./t of product in relation to bitumen (EN 12591)'s GWP_{100} , or ~18 % (~29 %). The major contributors to GWP_{100} are the supply of crude oil (57 % contribution in PMB-3,5 % wt/wt SBS; 51 % in PMB-6,0 % wt/wt SBS) and the supply of SBS (16 % contribution in PMB-3,5 % wt/wt SBS; 25 % in PMB-6,0 % wt/wt SBS). The present study also provides the full list of EN 15804+A2:2019 environmental indicators (EF 3.1 methodology) which are required by the aforementioned standard for the development of EPDs.

5.2 Assumptions and Limitations

The present study has been carried out on behalf of Eurobitume with the goal of understanding the potential cradle-to-gate environmental impacts of PMB products (e.g., PMB-3,5 % wt/wt SBS, PMB-6,0 % wt/wt SBS) produced within a refinery that is representative of the production of Eurobitume's members in the EU and UK. Two sets of environmental impacts results were developed: (1) PMB with a standard SBS concentration (assumed to be 3,5 % wt/wt), and (2) PMB with high-performance SBS concentration representative of PMB binders with enhanced performance characteristics (assumed to be 6,0 % wt/wt). The study's baseline analysis assumed the production of paving grade bitumen (according to EN 12591) using a 3-year average (2021-2023) crude oil supply and the energy allocation (net calorific value) approach. The results from this analysis are specifically representative of the aforementioned products and are not intended to be applied to other bitumen-derived products, other product specifications, other geographical regions, and/or refineries outside the ones included in

this study. In addition, the intent of this study has not been to conduct any comparative assessment of the refined bitumen products with alternative products with similar functionalities.

The data collection process was conducted as part of the Life Cycle Assessment 4.0 for Bitumen study [5] and was focused on the input-output data of the polymer modification process from 4 refineries operated by 4 companies in the EU and the UK, producing a total of ~167.000 t/a of PMB products. Data collected for the polymer modification process is representative of the year 2023. Some of the data collected was not process-specific but rather corresponded to refinery-wide flows, e.g., water supply, waste management, and overhead operations. Assumptions and limitations on the primary data collected to develop the 3-year average crude oil feedstock supply mix and other refinery-wide flows used in the present study are listed under Section 5.2 of the Life Cycle Assessment 4.0 for Bitumen report [5].

The copolymer considered in the polymer modification processes modelled is styrene-butadiene-styrene (SBS). No primary data was collected to model the production of SBS. Instead, a background dataset developed by the Asphalt Institute in 2022 (reference year 2020) including primary data for SBS production in Europe and North America was used in the modelling of the SBS supply [16]. Proxy background datasets were used in the modelling of additives other than SBS (e.g., sulphur as proxy of sulphur derivatives used as cross-linking agents).

With regards to energy data, the same CHP and electricity mix data as in the Life Cycle Assessment 4.0 for Bitumen study [5] is used in the interest of consistency and inclusion of more refinery data. Therefore, for additional information on assumptions and limitations regarding refinery-wide energy data, please refer to Section 5.2 of the aforementioned study.

In terms of product storage, it was assumed that PMB's storage is similar to that of paving grade bitumen (EN 12591). On the other hand, environmental impacts from infrastructure have been excluded from the present study, keeping consistency with the Life Cycle Assessment 4.0 for Bitumen study [5]. Finally, since the baseline analysis considers the production of PMB products within the representative refinery boundaries, bitumen transport associated with offsite production of PMB is excluded from the baseline results and rather analysed in a sensitivity analysis.

5.3 Data Quality Assessment

Inventory data quality is judged by its precision (measured, calculated or estimated), completeness (e.g., unreported emissions), consistency (degree of uniformity of the methodology applied) and representativeness (geographical, temporal, and technological).

To cover these requirements and to ensure reliable results, first-hand refinery data in combination with consistent background LCA information from the Sphera's MLC v. 2024.1 were used. An extended discussion on data quality assessment and ratings is provided under Section 5.5 of the Life Cycle Assessment 4.0 for Bitumen report [5].

5.3.1 Precision and Completeness

- **Precision:** The data in the foreground system (refinery units) is almost entirely based on measured data or calculated data, using primary data from the considered refineries in this study; therefore, precision is considered to be high. Achieved data quality level (quality rating): very good (1).
- **Completeness:** Each foreground process was checked for mass balance and completeness of the emission inventory. No data were knowingly omitted. Completeness of foreground unit process data

is considered to be high. All background data are sourced from Sphera's MLC with the documented completeness. Achieved data quality level (quality rating): good (2).

5.3.2 Consistency and Reproducibility

- **Consistency:** All primary data were collected with the same level of detail, while all background data were sourced from Sphera's MLC. Achieved data quality level and quality rating: very good (1).
- **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modelling approaches in this report. Based on this information, any third-party should be able to approximate the results of this study using the same data and modelling approaches. Nonetheless, disclosure of all data used is not possible. Achieved data quality level (quality rating): good (2).

5.3.3 Representativeness

- **Temporal:** Primary data for the refinery units of interest refer to the latest available and complete calendar year, which was 2023, when the data collection started. Data used from Sphera's MLC are representative for the years 2019 to 2023 (please see section 3.4 of the Life Cycle Assessment 4.0 for Bitumen report for extended information about all background data). As the study is intended to be up to date to the best extend possible, temporal representativeness is considered to be very high. Achieved data quality level (quality rating): very good (1).
- **Geographical:** All primary and secondary data were collected specific to the countries under study. Where country-specific data were unavailable, proxy data were used. Geographical representativeness is considered to be very high with regard to the goal and scope of this study. Achieved data quality level (quality rating): very good (1).
- **Technological:** All primary and secondary data were modelled to be specific to the technologies or technology mixes under study. Especially for the refinery units, the technological representativeness is considered to be very high. Achieved data quality level (quality rating): very good (1).

5.3.4 Overall Data Quality

Based on the formula and definitions provided in Section 5.4.4. of the Life Cycle Assessment 4.0 for Bitumen report [5], the overall data quality rating (DQR) of the current study is presented in Table 5-1.

Table 5- 1: Overall data quality assessment according to (JRC, 2010 [3]).

Data quality criteria	Data quality level	Data quality rating
Precision (P)	Very good	1
Completeness (C)	Good	2
Consistency (M)	Very good	1
Temporal representativeness (TiR)	Very good	1
Geographical representativeness (GR)	Very good	1
Technological representativeness (TeR)	Very good	1
Overall data quality rating (DQR)	High Quality	1,5

5.4 Model Completeness and Consistency

5.4.1 Completeness

All relevant process steps for the production of PMB were considered and modelled. The production process chain is considered sufficiently complete and detailed with regards to the goal and scope of this study.

5.4.2 Consistency

System boundary, allocation rules, and the impact assessment methods have been applied consistently throughout the study.

All assumptions, methods and data are consistent with each other, with Eurobitume's Life Cycle Assessment 4.0 for Bitumen report [5] (which the present study supplements), and with the study's goal and scope. Differences in background data quality were minimized by using LCI data from Sphera's MLC, based on a consistent methodology and set of modelling principles.

5.5 Conclusions and Recommendations

5.5.1 Conclusions

An LCA study on the cradle-to-gate production of polymer modified bitumen (PMB) compliant with EN14023:2010 [6] by Eurobitume's member refineries within the EU and the UK was developed to provide LCI data and life cycle environmental impact results that can be used in the development of broader life cycle studies evaluating PMB including its impact on the pavement service life.

The present report supplements and should be used in conjunction with the Eurobitume's 2025 Life Cycle Assessment 4.0 for Bitumen study [5], providing environmental impact results for an additional bitumen product that is rapidly growing in the European market. The main results of this assessment are LCI data and life cycle environmental impact results for PMB with SBS concentration of 3,5 % wt/wt (i.e., standard SBS concentration) and PMB with SBS concentration of 6,0 % wt/wt (i.e., high-performance PMB). The sensitivity analysis shows that the standard PMB result applies to PMBs with 2.5-4.5 % SBS content, and the high-performance PMB result applies to PMBs with 4.6-7.0 % SBS content, both with less than 5 % deviation. Special emphasis is given on this report to GWP₁₀₀ (IPCC's Six Assessment Report (AR6) [7]) and other impact categories required by the standard EN 15804+A2:2019 for the development of EPDs. Contribution analysis and sensitivity analyses complement the assessment.

The collection of representative LCI data for the modelling of PMB production covered 4 Eurobitume member refineries within the EU and UK region. The study can be considered as a very good approximation for the entire SBS-based PMB production in a refinery landscape in the EU.

Among the most relevant findings is the relevance of the SBS supply to PMB's GWP_{100} , besides the findings already identified for the base bitumen in Eurobitume's 2025 Life Cycle Assessment 4.0 for Bitumen study [5]. The use of a 3-year average (2021-2023) crude oil feedstock supply as baseline scenario provides robust environmental impact results that avoid the market fluctuations in single-year feedstock supply scenarios.

5.5.2 Recommendations

Sphera points out the following list of suggestions to Eurobitume for the continuous improvement in life cycle inventory data and life cycle environmental impact results:

- Update the LCI for PMB products during the next cycle of updates for Eurobitume studies (next 3-5 years).
- Increase the study's coverage of European PMB production by including additional PMB producing refineries and dedicated PMB production plants in future updates.
- Given the relevance of SBS supply in the environmental performance of PMB products, expand data collection efforts in this area to improve accuracy of results.

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