eurobitume

The Eurobitume Life Cycle Assessment 4.0 for bitumen

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ALMA PETROLI

eni

ExxonMobil

moeve

NYNAS

OMV

Shell Bitumen

TotalEnergies

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List of Acronyms and Abbreviations

ADP	Abiotic Depletion Potential
AP	Acidification Potential
API	American Petroleum Institute
CAS	Chemical Abstracts Service
CH_4	Methane
CML	Centre of Environmental Science at Leiden
CO	Carbon Monoxide
CO_2	Carbon Dioxide
EF	Environmental Footprint
EINECS	European Inventory of Existing Commercial Chemical Substances
ELCD	European Life Cycle Database
EoL	End-of-Life
EP	Eutrophication Potential
EPD	Environmental Product Declarations
EU	European Union
GaBi	Ganzheitliche Bilanzierung (German for holistic balancing)
GHG	Greenhouse Gas
GWP	Global Warming Potential
H+	Hydrogen Ion
H_2S	Hydrogen Sulfide
HFO	Heavy Fuel Oil
ILCD	International Life Cycle Data System
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
LFO	Light Fuel Oil
LPG	Liquefied Petroleum Gases
MLC	Managed LCA Content
N	Nitrogen
NCV	Net Calorific Value
NMVOC	Non-Methane Volatile Organic Compound
NO_x	Nitrogen Oxides
ODP	Ozone Depletion Potential
P	Phosphorous
PCR	Product Category Rules
POCP	Photochemical Ozone Creation Potential
SFP	Smog Formation Potential
SO_2	Sulfur Dioxide
t	Tonne
UK	United Kingdom
VOC	Volatile Organic Compound
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

Bitumen is manufactured from the distillation of crude oil during petroleum refining. It is produced to meet various specifications based on physical properties for specific end uses. Bitumen's main characteristics, e.g., adhesivity, waterproofing, thermoplasticity, durability, ease of modification, reusability and recyclability, make it ideal as a construction and engineering material [5]. As bitumen's applications have evolved from ancient construction material to today's vital role in modern construction and other industrial sectors, the sustainability of bitumen has taken a more central role. The adoption of sustainability practices by the construction industry means that the relevance of quantifying the environmental impacts of bitumen production is greater than ever.

Eurobitume, the European industry association for the producers of refined bituminous products in Europe, is a non-profit organisation that works to promote the efficient, effective and safe use of bituminous binders in road, industrial and building applications. Eurobitume is committed to foster the sustainability of bitumen as construction material by providing reliable assessments of bitumen's environmental performance. Life Cycle Assessment (LCA) is the preferred tool for sustainability promotion as it provides a systematic framework to quantify the environmental impacts of a product throughout its entire life cycle.

Eurobitume has commissioned Sphera Solutions, Inc. (Sphera) to perform an LCA of refined bitumen products that are representative of those produced by Eurobitume's members within the European Union (EU) and the United Kingdom (UK). The present study updates Eurobitume's 2021 LCI report version 3.1 [6] with reviewed data and methodology, aiming to enhance accuracy and reliability of environmental impact results. It updates Eurobitume's previous report by incorporating more refinery primary data and more representative environmental impact of the crude oil supply stage. The major changes in scope and methodology are summarised in section 2.12.

The goal of the present LCA study is to provide life cycle inventory data and life cycle environmental impact results on the production of bitumen meeting the requirements of paving grade bitumen under EN 12591:2009 [7] and oxidised bitumen under EN 13304:2009 [8] representative of production by Eurobitume's members within the EU and the UK. Its intended application is to serve as a building block in broader life cycle studies taking bitumen into account. Its boundary is cradle-to-gate[1], i.e., it accounts for the environmental impacts of crude oil extraction, its transportation to a refinery, and bitumen production and storage inside the refinery. The environmental impacts are referenced to one metric tonne of bitumen produced by Eurobitume member refineries at refinery gate.

Baseline environmental impacts of refined bitumen products were assessed using primary data collected from Eurobitume member refineries (~76 % coverage of bitumen produced by Eurobitume members in the EU and UK) on 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 refined bitumen based on energy content.

Results for environmental impact indicators climate change, acidification, eutrophication, photochemical ozone formation and resource use (fossil fuels) are presented and discussed. In addition, the complete set of environmental impact indicators required by the EN 15804+A2:2019 standard of construction products [9] for the development of Environmental Product Declarations (EPD) is also included.

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[1] It should be considered that a comparison of the results with alternative products containing bio-based or secondary feedstocks usually requires the inclusion of the full life cycle, including especially the end-of-life stage.

Sensitivity analyses were carried out to assess the impact of variations in the feedstock supply mix and of multifunctionality approaches on the environmental impacts of refined bitumen products. Uncertainty analysis was also performed to better understand the impact on results of possible uncertainties in background and foreground data, as well as in the applied methodology. Background life cycle inventory data from Sphera's Managed LCA Content (MLC) 2024.1 databases[2] (formerly known as GaBi databases) were used throughout the assessment to complement primary data.

The intended audience of the present study is bitumen users and organisations studying environmental issues, such as the European Commission, national official bodies, asphalt producers, road authorities, and other industry associations as well as consultants and universities.

The report is structured and aligned in accordance with the ISO 14040:2006 [1] and ISO 14044:2006 [4] standards. The results of the present study are not intended to support comparative assertions (no environmental claims regarding the superiority of bitumen versus a competing product are made), but they are intended to be used for external communication to stakeholders using bitumen and to the general public. Therefore, a critical review has been carried out in accordance with ISO 14071:2024 [10] by an independent LCA expert.

The climate change indicator Global Warming Potential referring to a 100 year timeframe (GWP_{100}, calculated according to IPCC's AR6 methodology [11]) for bitumen is 530 kg CO_2 eq./t bitumen, as presented in Figure E-1. The major contributor to GWP_{100} impact is the supply of crude oil (70 % contribution), dominated by methane emissions (61 % of GWP_{100} from feedstock supply). Full-blown oxidation adds 86 kg CO_2 eq./t of bitumen; therefore, GWP_{100} of oxidised bitumen (EN 13304) is 616 kg CO_2 eq. /t of bitumen. The main driver of GWP_{100} behind both processes is the generation of the energy consumed to oxidise the bitumen. The sensitivity checks revealed that the environmental impacts of refined bitumen products are sensitive mostly to the feedstock supply basket that is processed in Eurobitume member refineries and, consequently, to the geopolitical events that determine the crude oil mix supply to the EU and UK.

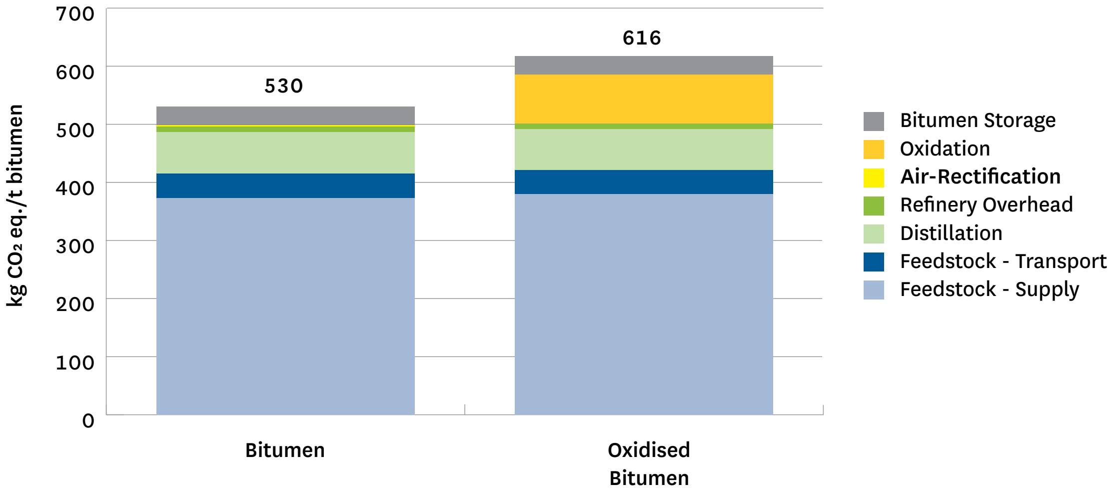

Figure E-1. GWP_{100} (AR6) for refined bitumen products

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[2] Sphera's MLC database includes all available and purchasable LCI data set. A search engine to explore the content of the database and also the documentation of the LCI data sets is accessible via the website: https://lcadatabase.sphera.com.

There is a significant increase (145 %) in GWP_{100} for bitumen with respect to Eurobitume's previous LCI study 'The 2021 Update to the Eurobitume Life-cycle Inventory for Bitumen 3.1' [6]. Such increase is mainly related to the change in the background data used to assess the environmental impact of the crude oil supply. By sourcing the environmental impact calculations of the crude oil supply on Sphera's life cycle inventory databases and the assessment of the refinery's impact on an updated set of primary data, the present study has overcome the key limitations identified in the critical review of the previous Eurobitume LCI.

1. Goal of the Study

Eurobitume, the European industry association for the producers of refined bituminous products in Europe, is a non-profit organisation and works to promote the efficient, effective and safe use of bituminous binders in road, industrial and building applications. An important part of its mission is to promote the sustainability of bitumen as construction material. Bitumen is a long-lasting material that can help achieve resilient infrastructure; it promotes sustainable industrialization given its reusability in road applications and fosters innovation as bitumen technology evolves.

As the applications and demand for bitumen increase, so does the need for more accurate and up-to-date quantification of its environmental impacts by relevant stakeholders. Life Cycle Assessment (LCA) generates comprehensive sustainability metrics that allow stakeholders to report on a product's environmental impacts with greater transparency throughout its life cycle, allowing at the same time more informed purchasing decisions from the customer side.

Eurobitume's efforts of providing reliable assessments of bitumen's environmental performance began in 1999 with the publication of its first eco-profile or partial Life Cycle Inventory (LCI) analysis of bitumen production [12]. Since then, some regular revision and updates have been performed in 2012 [13], 2019 [14], and 2021 [6]. As newer inventory data has become available, Eurobitume commissioned Sphera Solutions, Inc. (Sphera) to develop the latest revision on its LCI analysis of bitumen. The present study updates Eurobitume's 2021 LCI report version 3.1 with reviewed data and methodology, aiming to enhance accuracy and reliability of environmental impact results. It improves upon feedback from the critical review process of Eurobitume's previous report by incorporating more refinery primary data (see section 3.3.3) and more representative environmental impact of the crude oil supply stage (see section 3.3.1).

The goal of the present LCA study is to provide life cycle inventory data and life cycle environmental impact results on the production of bitumen and oxidised bitumen 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 taking bitumen into account. Its boundary is cradle-to-gate including infrastructure, i.e., it accounts for the environmental impacts of crude oil extraction, its transportation to a refinery, and bitumen production and storage inside the refinery. The environmental impacts are referenced to one metric tonne of bitumen compliant with EN 12591:2009 [7] or oxidised bitumen compliant with EN 13304:2009 [8] produced by an Eurobitume member refinery at refinery gate.

Baseline environmental impacts of refined bitumen products are assessed using primary data collected from Eurobitume member refineries (~76 % coverage of bitumen produced by Eurobitume members in the EU and UK) on crude oil 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 refined bitumen based on energy content.

Sensitivity analyses are carried out to assess the impact of variations in the feedstock supply mix and of multifunctionality approaches on the environmental impacts of refined bitumen products. Uncertainty analysis is also performed to better understand the impact on results of possible uncertainties in background and foreground data, as well as in the applied methodology. Background life cycle inventory data from Sphera's Managed LCA Content (MLC) 2024.1 databases (formerly known as GaBi databases) is used in all scenarios to completement primary data.

The intended audience of the present study is bitumen users and organisations studying environmental issues, such as the European Commission, national official bodies, asphalt producers, road authorities, and other industry associations as well as consultants, universities.

This report is structured and aligned in accordance with the ISO 14040:2006 [1] and ISO 14044:2006 [4] standards. The report does not contain any comparative assertions, but the results are intended to be used for external communication to the general public. Therefore, a critical review has been carried out in accordance with ISO 14071:2024 by an independent LCA expert [10].

This study is a generic LCA for bitumen in Europe (EU27 + UK) with a declared unit, system boundaries and the selected LCIA methodology following EN 15804+A2:2019 [9]. It could be used as baseline for developing a complementary Product Category Rules standard and specific Product Category Rules that may include bitumen 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), functional unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.1 Product System(s)

Bitumen is manufactured from the distillation of crude oil during petroleum refining. It is produced to meet various specifications based on physical properties for specific end uses. Bitumen's main characteristics, e.g., adhesivity, waterproofing, thermoplasticity, durability, ease of modification, reusability and recyclability, make it ideal as a construction and engineering material. [5] Bitumen can also naturally occur in petroleum deposits, which is not considered in this study due to the low relevance. Bitumen is primarily composed of hydrocarbons, but also contains elements like sulphur, nitrogen, oxygen, and metals. It is mainly produced by removing lighter components from crude oil during fractional distillation.

Its properties and characteristics depend on the source and type of crude oil from which it is derived, as well as the refining conditions applied during manufacturing. Its performance characteristics are mainly dependent on temperature and time. There are more than 250 known applications of refined bitumen, although the majority of the bitumen production in the world is used as binder in the manufacture of asphalt and in roofing products [5].

The bitumen produced is assumed to be compliant with EN 12591:2009 [7] with a penetration index (PI) ≤ 2.0, the most commonly used paving grade bitumen in Europe, as well as oxidised bitumen compliant with EN 13304:2009 [8] with a penetration index (PI) > 2.0. The EN 12591-compliant bitumen in this study covers the refinery streams 'asphalt' (CAS # 8052-42-4/EINECS # 232-490-9), Residues (petroleum), thermal cracked vacuum (CAS # 92062-05-0/EINECS # 295-518-9 and 'Residues (petroleum), vacuum' (CAS # 64741-56-6/EINECS # 265-057-8), the oxidised bitumen refers to 'Asphalt, oxidized' (CAS # 64742-93-4/EINECS # 265-196-4) [5].

The bitumen production assessed by the present study is representative of refineries within the EU and the UK operated by Eurobitume members producing a range of petroleum products other than bitumen in different shares.

Bitumen is produced through the refining of carefully selected crude oils. Feedstock is typically a mix of mainly crude oil and to a lower extent HFO. The most common refining processes involved in the production of bitumen are atmospheric and vacuum distillation. The lighter petrochemical and fuel fractions of the feedstock are separated from the heavy bottoms or atmospheric residue through atmospheric distillation. The lighter fractions are further processed in other refinery units into fuels and petrochemical feedstock, while the atmospheric residue is introduced into the vacuum distillation unit, where the heavier fraction, the vacuum residue, falls to the bottom of the column. See also Figure 3-2 for an illustration of the processes.

The bitumen, or a part of it, may be further processed through an air-rectified blowing process in order to do small corrections to the properties of the bitumen to meet the requirements under. The vacuum residue can also be severely oxidised to meet the specification of oxidised bitumen under

EN 13304:2009. The air-blowing process involves blowing air at elevated temperatures through the vacuum residue, changing its physical properties for specific applications. For the oxidation process a catalyst and flux may be needed. More details on bitumen and the production processes can be found in the publication 'The Bitumen Industry – A Global perspective' jointly published by the Asphalt Institute and Eurobitume [5].

2.2 Product Function(s) and Declared Unit

Bitumen is mostly used in the construction industry serving the function of binder in asphalt for roads, runways, parking lots, sidewalks, etc. Construction materials like mineral aggregates are mixed with bitumen, which holds them together as the asphalt is then applied to roadways. In the roofing industry, bitumen's waterproofing function is of great value. In other building materials (e.g. carpet tile backing), bitumen is used for its sealing and insulating purposes.

Since the bitumen products evaluated in this study are assumed to be bitumen (EN 12591:2009) or oxidised bitumen (EN 13304:2009), the declared unit is:

1 tonne (1000 kilograms) of bitumen according to EN 12591:2009 or oxidised bitumen according to EN13304:2009 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 bitumen or oxidised bitumen products, as it allows the documentation of LCI data and related environmental impacts in reference to a physical quantity of product (1 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 [9].

2.3 System Boundary

This study considers the cradle-to-gate production of bitumen and oxidised bitumen, 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 oxidised bitumen products and 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 (and other feedstock production, e.g., HFO);
- A2: Feedstock transportation from the country or region of extraction to the refinery;
- A3: Production of bitumen and oxidised bitumen through refining processes;
- A3: Bitumen storage within the refinery.

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

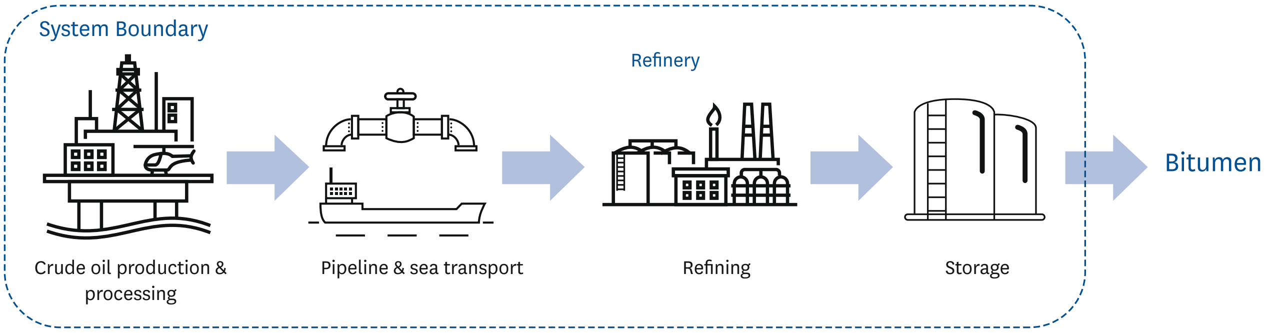


Figure 2-1. System boundary of the LCA study

The bitumen and oxidised bitumen 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 (mainly crude oil and some HFOs).

The bitumen and oxidised bitumen products are produced by distillation of the crude oil mix, using atmospheric and vacuum distillation columns. A share of the vacuum residue is further processed by an air-blowing process (air-rectification) to meet the requirements of bitumen under EN 12591:2009. Another share can be further processed in an air-blowing process to obtain oxidised bitumen products. The boundary excludes other refinery processes, such as thermal cracking (visbreaking) or deasphalting. Infrastructure for feedstock supply and refinery operation is excluded but analysed in a sensitivity analysis. Table 2-1 provides a list of activities included and excluded from the study's system boundary.

Table 2-1. Elements in the system boundary and excluded

Included	Excluded
Crude oil extraction	Employee commute
Production of other feedstocks (e.g. HFO)	Infrastructure manufacturing, use, and end of life
Feedstock transportation by pipeline and sea vessel	Other refinery processes associated with the production of refined fuels and petrochemicals
Atmospheric and vacuum distillation	
Air-blowing (air-rectification and oxidation) of vacuum-residue to meet requirements of bitumen and oxidised products	
Bitumen storage within refinery	

2.3.1 Time Coverage

The intended time coverage for the LCA study is the period 2019 to 2023. More specifically, feedstock supply data was collected for the 2019-2023 time period, and process data from refining units was collected for the year 2023.

A three-year average of 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. With the 6th package of sanctions by the EU against Russia in the context of the Russian war on Ukraine starting in June 2022 [15], an import ban has been imposed on Russian seaborn crude oil. The exception of crude oil imports by pipeline is not applied or relevant for the included refineries in this study. As a consequence, the share of Russian crude oil in the feedstock mix for the bitumen productions decreases considerably in 2022 compared to previous years and is zero in 2023. To understand the consequences of the change in feedstock supply for the bitumen producers in the EU or UK, a sensitivity analysis (Section 4.2) is provided in this study in which 2023 has also been chosen as reference year for the feedstock supply (as first year without Russian crude oil in the supply mix) and a 5-year average feedstock supply (2019-2023). More details about the feedstock supply mix are given in Section 3.2.1.

Results are expected to stay representative of paving grade bitumen production until there is a significant change in, e.g., production technologies, crude oil basket, use of recycled/secondary feedstock, bitumen specifications, among others. In the past, Eurobitume has updated its LCI studies every 5 years. Although the next content update is expected to happen in a similar timeframe, Eurobitume will follow changes in feedstock supply and bitumen production closely to determine any timeline adjustments for the next bitumen LCA update.

2.3.2 Technology Coverage

Conventional and unconventional onshore and offshore crude oil extraction and processing technologies are assumed to be used in the production and processing of the crude oil feedstock. A broader discussion about the used background data for the crude oil production is included in the sensitivity analysis of the feedstock supply (Section 4.2).

Individual transportation of the crude oil mix to the considered European refineries occurs through a combination of pipeline and sea vessel transport.

The considered refineries usually use atmospheric distillation to separate lighter petrochemical and fuel fractions from the heavy, non-boiling bottom fraction, known as atmospheric residue. This bottom fraction is further processed in a vacuum distillation tower which removes the last traces of the lighter fractions, leaving behind the heavier vacuum residue, also known as short residue.

The vacuum residue from the vacuum distillation can be further processed through an air-blowing process to meet the required physical properties of bitumen and oxidised bitumen. By blowing air through the bitumen at elevated temperatures, the vacuum residue may be modified to meet the requirements for bitumen under EN 12591:2009 or can be oxidised to obtain oxidised bitumen that meet the requirements under EN 13304:2009. It is assumed that the bitumen and oxidised bitumen products are stored in heated tanks inside the refinery. The study covers the average bitumen and oxidised bitumen production of Eurobitume's members.

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

2.4.1 Multi-output Allocation

In processes where more than one product is produced, it is necessary to divide the environmental impacts associated with the process among the multiple products. Multi-output allocation is a methodology that partitions the environmental burdens of a process in a way that reflects an underlying physical relationship (e.g., mass, energy content) or other relevant relationships among the co-products (e.g. economic value). Multi-output allocation generally follows the requirements of ISO 14044:2006, section 4.3.4.2.

In this study, allocation is applied to background and foreground data.

Allocation of background data (crude oil extraction data, production of energy and materials supplied to the foreground system) taken from the MLC 2024.1 database is documented online [16].

In the foreground system multifunctionality occurs especially in the atmospheric and vacuum distillation processes as a multitude of coproducts leave these processes (see Figure 3-2). The partitioning of impacts related to, e.g., the supply of feedstock, fuel, and electricity or direct emissions from the distillation processes is usually done by allocation. Allocation by energy (net calorific value) is applied to all inputs and outputs (other than products) as baseline case. This also follows EN15804+A2:2019 as the energy content of the distillation and refinery products is an inherent property of them. On the other hand, allocation by economic value for the distillation units is not possible as the products are mostly intermediate products for which economic values are usually not available. Allocation by energy is used as well in the background LCI data for the combined production of crude oil and gas. In the refinery model used for the LCI background datasets (e.g. HFO), allocation by energy (feedstock input) and allocation by mass (energy consumption) are applied.

As previously mentioned, allocation by energy (net calorific value) is applied in the refinery for the baseline scenario, and allocation by mass is analysed in a sensitivity analysis to better understand the influence of allocation on the results. In addition, the impact of the so-called 'Sensible Heat Method' on the results is analysed as well in the sensitivity analysis. The sensible heat method, a thermodynamic approach that calculates the energy consumption in the distillation units specifically for the bitumen, is applied in version 3.1 of 'The Eurobitume LCI for Bitumen' [6], which avoids allocation in the refinery by using this alternative approach. The approach has been also used by the Asphalt Institute for their 'LCA of Asphalt Binder' study [17]. More information on the sensible heat method is given in section 4.2.2.

For the refinery combined heat and power (CHP) production, allocation by exergetic content is applied. The use of allocation by energy for electricity and heat is in theory possible but would completely disregard the different useful work potential of steam and electricity; for more details see the BREF document for large combustion plants [18].

The energy overhead of the refinery (e.g., lighting, storage of crude, dewatering, desalting) has been allocated by energy (net calorific value). In the sensitivity analysis, allocation by mass has also been included for the products of the entire averaged refinery. The same holds true for the allocation of waste, water consumption and water discharge. More information is available in section 3.3.5.

2.4.2 End-of-Life Allocation

End-of-Life allocation generally follows the requirements of ISO 14044:2006, section 4.3.4.3. Such allocation approaches address the question of how to assign impacts from virgin production processes to material that is recycled and used in future product systems. It has been used for the treatment of waste from the refinery and for the end-of-life of the included infrastructure.

A main end-of-life allocation approach commonly used in LCA studies to account for end-of-life recycling and recycled content is the cut-off approach. In the cut-off approach (also known as 100:0 or recycled content approach), burdens or credits associated with material from previous or subsequent life cycles are not considered, i.e. are 'cut-off'. Therefore, scrap input to the production process is considered to be free of upstream virgin material burdens but, equally, no credit is received for scrap available for recycling at end of life. As stated above, in the foreground system this is only relevant for the generated waste in the refinery, and for the sensitivity analysis about the impact of the infrastructure. Information about the type of generated waste and the applied treatments was limited and the waste data refers to the entire refinery and is not bitumen specific, see Section 3.3.5 for more details. As there is a relevant uncertainty about the recovered energy from the incineration processes by using generic waste treatment data sets, the recovered amounts of energy have also been excluded from the published ILCD data sets.

2.5 Cut-off Criteria

No cut-off criteria are defined for this study.

As summarised in section 2.3, the system boundary was defined based on relevance to the goal of the study. For the processes within the system boundary, all available energy and material flow data have been included in the model. In cases where no matching life cycle inventories are available to represent a flow, proxy data have been applied based on conservative assumptions regarding environmental impacts.

The choice of proxy data is documented in Section 3. The influence of these proxy data on the results of the assessment has been carefully analysed and is discussed in Section 5.

2.6 Selection of Impact Categories and LCIA Methodology

Several impact assessment categories have been chosen for the Life Cycle Impact Assessment (LCIA) to discuss and present the environmental impacts of the bitumen production. Global Warming Potential (GWP) and non-renewable primary energy demand were chosen because of their relevance to climate change and energy efficiency, both of which are strongly interlinked, of high public and institutional interest, and deemed to be the most pressing environmental issues of our time. In addition, eutrophication, acidification, and photochemical ozone creation potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burdens associated with commonly regulated emissions such as nitrogen oxides (NO_x), sulphur dioxide (SO_2), volatile organic compounds (VOC), and others.

Various impact assessment methodologies are applicable for use in the European context including, e.g., Environmental Footprint v3.1 (EF 3.1), CML, etc. As this study might be used as background information in Environmental Product Declarations (EPD) of bitumen containing products, the impact assessment methods required for EPDs under EN 15804+A2:2019 [9] have been applied. EN 15804+A2:2019 refers to the latest available version of the Environmental Footprint (EF) impact assessment method, which is currently EF 3.1. EF 3.1 characterisation factors are considered to be robust and up-to-date available for the European context, are widely used and respected within the LCA community.

The global warming potential (GWP) impact category is assessed based on the current IPCC characterisation factors taken from the 6th Assessment Report (AR6) [11] for a 100-year timeframe (GWP_{100}), as this is currently the most commonly used metric. Since some readers might be interested in results using the IPCC's 5th Assessment Report (AR5) [19] for GWP_{100} indicators and for comparison reasons with the previous LCI for Bitumen study [6] , both AR6 and AR5 methodologies have been included in this assessment's results. It should be noted that there is no scientific justification for selecting the 100-year time horizon over other timeframes.

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-2. For potential use of the data in EPDs, a table of all indicator results required under EN15804+A2:2019 are presented in the results. Indicators like toxicity, ozone depletion or water consumption are not discussed due to their limitations and higher uncertainties regarding the impact assessment, background data and collected primary data.

Table 2-2. Impact category descriptions

Impact Category	Description	Unit	Reference
Global Warming Potential (GWP_{100})	A measure of greenhouse gas emissions, such as carbon dioxide (CO_2) and methane (CH_4). These emissions are causing an increase in the absorption of radiation emitted by the earth, increasing the natural greenhouse effect. This may in turn have adverse impacts on ecosystem health, human health and material welfare.	kg CO_2 equivalent	AR6: [11] AR5: [19]
Acidification Potential	A measure of emissions that cause acidifying effects to the environment. The acidification potential is a measure of a molecule's capacity to increase the hydrogen ion (H+) concentration in the presence of water, thus decreasing the pH value. Potential effects include fish mortality, forest decline and the deterioration of building materials.	moles H+ equivalent	[20, 21]
Eutrophication (freshwater)	Eutrophication covers all potential impacts of excessively high levels of macronutrients, the most important of which nitrogen (N) and phosphorus (P). Nutrient enrichment may cause an undesirable shift in species composition and elevated biomass production in both aquatic and terrestrial ecosystems. In aquatic ecosystems increased biomass production may lead to depressed oxygen levels, because of the additional consumption of oxygen in biomass decomposition.	Terrestrial: moles N equivalent Freshwater: kg P equivalent Marine: kg N equivalent	[20, 21, 22]
Photochemical Ozone Formation	A measure of emissions of precursors that contribute to ground level smog formation (mainly ozone (O_3)), produced by the reaction of VOC and carbon monoxide (CO) in the presence of nitrogen oxides under the influence of UV light. Ground level ozone may be injurious to human health and ecosystems and may also damage crops.	kg NMVOC equivalent	[23]

Impact Category	Description	Unit	Reference
Resource use, energy carriers	A measure of the total amount of non-renewable primary energy extracted from the earth. Resource use is expressed in energy demand from non-renewable resources including both fossil sources (e.g. petroleum, natural gas, etc.) and uranium for nuclear fuel. Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.	MJ	[24, 25]

It shall be noted that the above impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) actually follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the functional unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

No grouping or further quantitative cross-category weighting has been applied. Instead, each impact is discussed in isolation, without reference to other impact categories, before final conclusions and recommendations are made.

2.7 Interpretation to be Used

The results of the LCI and LCIA were interpreted according to the Goal and Scope. The interpretation addresses the following topics:

- Identification of significant findings, such as the main process step(s), material(s), and/or Iemission(s) contributing to the overall results.
- Evaluation of completeness, sensitivity, and consistency to justify the exclusion of data from the system boundaries as well as the use of proxy data.
- Conclusions, limitations and recommendations.

2.8 Data Quality Requirements

The data used to create the inventory model shall be as precise, complete, consistent, and representative as possible with regards to the goal and scope of the study under given time and budget constraints.

- Measured primary data are considered to be of the highest precision, followed by calculated data, literature data, and estimated data. The goal is to model all relevant foreground processes using measured or calculated primary data.
- Completeness is judged based on the completeness of the inputs and outputs per unit process and the completeness of the unit processes themselves. The goal is to capture all relevant data in this regard.
- Consistency refers to modelling choices and data sources. The goal is to ensure that differences in results reflect actual differences between product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artefacts.
- Reproducibility expresses the degree to which third parties would be able to reproduce the results of the study based on the information contained in this report. The goal is to provide enough transparency with this report so that third parties are able to approximate the reported results.

This ability may be limited by the exclusion of confidential primary data and access to the same background data sources.

- Representativeness expresses the degree to which the data matches the geographical, temporal, and technological requirements defined in the study's goal and scope. The goal is to use the most representative primary data for all foreground processes and the most representative industry-average data for all background processes. Whenever such data were not available (e.g., no industry-average data available for a certain country), best-available proxy data were employed.

An evaluation of the data quality with regard to these requirements is provided in Section 5 of this report.

2.9 Type and Format of the Report

In accordance with the ISO requirements [4] this document aims to report the results and conclusions of the LCA completely, accurately and without bias to the intended audience. The results, data, methods, assumptions and limitations are presented in a transparent manner and in sufficient detail to convey the complexities, limitations, and trade-offs inherent in the LCA to the reader. This allows the results to be interpreted and used in a manner consistent with the goals of the study.

2.10 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.

2.11 Critical Review

A critical review of this study in accordance with the ISO 14040:2006 and the ISO 14044:2006 standards has been carried out by Philippe Osset from Solinnen, an independent LCA expert.

Philippe Osset is fully independent from the commissioner and practitioner of the LCA study and 'not involved in defining the scope or conducting the LCA study' [10]. He is a dedicated LCA expert and has extended knowledge in the field of ISO standards for LCA, LCA methodology, critical reviews and the relevant scientific disciplines involved (e.g. bitumen, oil & gas production etc.).

The Critical Review Statement can be found in Annex A. The Critical Review Report containing the comments and recommendations by the independent expert as well as the practitioner's responses is available upon request from the study commissioner in accordance with ISO 14071:2024 [10].

2.12 Differences compared to Eurobitume LCI for bitumen 3.1

This version (4.0) of the Eurobitume LCA for Bitumen updates version 3.1 [6] with the latest update in 2021 [6]. Several relevant changes with regard to the scope have been applied in this update, which are summarised below:

- In version 3.1, IOGP inventory data was used for energy supply, venting, flaring and fugitive emissions of crude production in various regions, in combination with LCI background data to calculate the impacts of the feedstock supply. The observation has been made that, in general, the methane emissions of oil and gas production have been often underestimated in carbon footprint and LCA studies as methane leakages and venting are difficult to measure and require a comprehensive equipment count, suitable methane emission factors and data about the venting of associated gas to generate a GHG emission inventory (bottom-up approach). As the science continues to improve and new technologies such as satellite pictures are used to estimate the methane emissions of oil and gas production (top-down approach), so do the results of LCA. The present study updates upon its predecessor by using Sphera's MLC country-specific databases for crude oil extraction technologies.

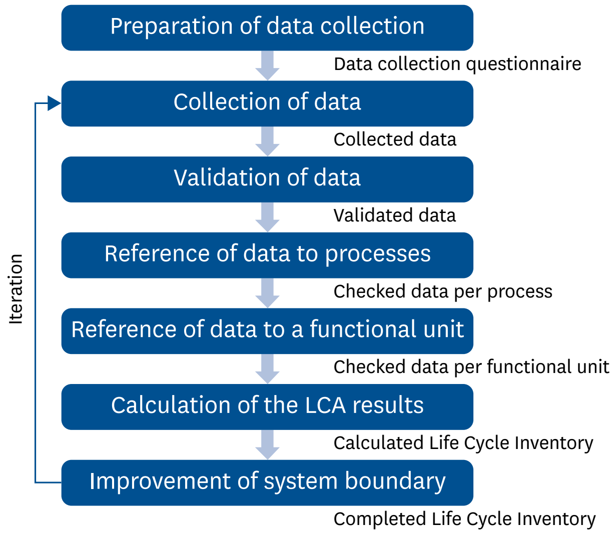
- Primary data has been collected from 17 refineries for the feedstock supply mix and the refinery units to especially replace the thermodynamic model for the energy consumption of the distillation units and the energy consumption of the storage based on literature, as this was one of the major identified limitations of the previous study.
- For the distillation units allocation by energy has been used to partition the impacts between the different products. The allocation has been further analysed in a sensitivity analysis and compared with the thermodynamic approach, the sensible heat method, which has been used in the previous study. As the sensible heat method calculates the energy consumption specific for bitumen, no allocation was needed in version 3.1.
- In contrast to the previous version, infrastructure has been mostly excluded from the system boundaries to be in line with existing PCRs for bitumen applying construction materials products, but analysed in a sensitivity analysis, e.g. EAPA's Guidance document for preparing product category rules (PCR) and environmental product declarations (EPD) for asphalt mixtures [26].
- Oxidised bitumen has been added to the study.

3. Life Cycle Inventory Analysis

3.1 Data Collection Procedure

Based on the findings and limitations from the previous study 'The Eurobitume LCI for bitumen, Version 3.1' [6], the collection of primary data from refineries operated by Eurobitume members has been conducted. The voluntarily data collection request has been send out by Eurobitume to all member companies with refinery operations in the European Union (EU) and the UK. No specific selection of refineries has been conducted, only in case of uncomplete data for relevant parts of the study (e.g. country of origin for feedstock supply) refineries have been excluded from the study. Primary data has been collected on the feedstock supply mix, the relevant refinery units, i.e., atmospheric and vacuum distillation, air-blowing, as well as bitumen storage. Primary data were collected using customised data collection templates. A total of 17 refineries operated by 8 different companies in the EU and the UK were able to provide a full set of primary data and have been included in the study. The collection of data was carried out using customised data collection templates sent out by email. Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking. If gaps, outliers, or other inconsistencies occurred, Sphera engaged with the data provider to resolve any open issues. The general data collection procedure is displayed in Figure 3-1.

Figure 3-1. Data collection and validation procedure applied by Sphera [27]



Included Refineries

The collected and included data represent operations in 8 countries in the EU and the UK, and an annual bitumen production of 6,1 million tonnes in 2023. The covered bitumen production represents ~76 % of the bitumen production by Eurobitume members or 45 % [28] of the total production in the EU and UK. Around 70 000 tonnes of the covered 6,1 million tonnes of bitumen products is oxidised bitumen. Refinery primary data from the following companies operating refineries in the EU and UK have been included in the study:

- Alma Petroli
- ENI
- ExxonMobil
- Moeve (former CEPSA)
- Nynas
- OMV
- Shell
- TotalEnergies

3.2 Product System

3.2.1 Overview of Product System

The focus of this LCA study is to provide LCI data and life cycle impact assessment (LCIA) results on the production of bitumen and oxidised bitumen representing the production of Eurobitume members in the EU and the UK.

The included refineries produce the two bitumen families, among a variety of other petroleum products, from a feedstock basket that is representative of the average feedstock for bitumen production in Eurobitume members' refineries (rather than specific to any individual refinery). The amount of crude oil in the average feedstock mix is modelled from refinery primary data. The extraction of crude oil is modelled as a technology mix of conventional and unconventional production methods for the basket of crude oils (per country of production) supplied to the Eurobitume member refineries that participated in the data collection process. The crude oil extraction models per country that are assessed are part of Sphera's MLC, version 2024.1.

In addition to crude oil, some refineries also use HFO as feedstock. The amount of HFO in the average feedstock mix is modelled from refinery primary data. The production of the HFO is modelled using LCI datasets from the MLC Database. A consideration of the specific crude oil mix used by the refineries from which the HFO is sourced was not possible; therefore, if available, country specific HFO LCI data sets have been used. For EU countries always the European-wide dataset (RER dataset) has been used. For more information with regard of the selected LCI data sets see section 3.4.2 and Table B-4 in the Annex. The contribution of the environmental impact of a given feedstock mix (per country of production) to the averaged crude oil extraction stage and HFO supply is weighted in accordance to the contribution of that refinery to total vacuum residue/bitumen production reported by member companies, taking into account the broad variations of refinery set-up between the 17 included refineries, ranging from smaller bitumen dedicated refineries to large refineries with or without important cracking capacity with a focus on gasoline and middle distillates.

Individual transportation of the feedstock mixes to the considered European refineries occurs through a combination of pipeline and sea vessel transport.

Bitumen is mostly produced by distillation of crude oil. In a first fractionation step at atmospheric pressure, the crude oil is separated into different fractions that are further processed in downstream separation and conversion units. In a second fractionation step the bottom fraction from the atmospheric distillation tower, known as atmospheric residue or long residue, is further processed under vacuum conditions to produce a series of vacuum gas oils and bitumen, known also as vacuum residue or short residue, at the bottom of the column.

Bitumen can be further processed by air-blowing processes in order to alter its physical properties and meet specific product requirements for bitumen under EN 12591:2009 and oxidised bitumen under EN 13304:2009. The feed to air-blowing processes is vacuum residue from the vacuum distillation column, most often arriving already at elevated temperature to the blowing unit. After initiation of the air-blowing, the reaction is exothermic and need to be cooled down with cooling water. Vacuum residue/bitumen that needs to be air-blown to meet the requirements under EN 12591:2009 is subjected to a mild oxidation process (230–260°C) using compressed air, also known as air-rectification. Oxidised bitumen (of full-blown bitumen) is obtained by blowing air through it at higher temperatures (280°C on average), a catalyst and flux may be used, resulting in a material that is harder and more viscous.

The oxidation process increases bitumen's viscosity and consistency at high temperature and enhances better temperature susceptibility. Based on the collected primary data the bitumen products are stored at the refinery, in average, at 170°C. The storage temperature for oxidised bitumen is around 30°C higher.

Figure 3-2 presents a simplified flow chart of the production of bitumen and oxidised bitumen products.

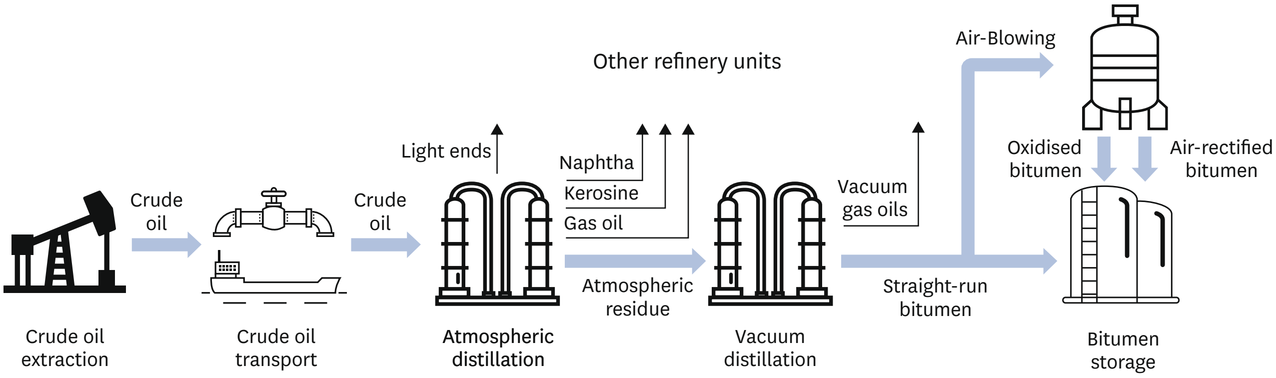


Figure 3-2. Simplified flow chart of the production of bitumen products

3.2.2 Product Composition

Refined bitumen produced from the distillation of crude oil during petroleum refining is a liquid mixture of dense, viscous, and sticky complex hydrocarbons. The properties of bitumen which make it ideal as construction and engineering material are its adhesivity, waterproofing, thermoplasticity, durability, ease of modification, reusability, and recyclability. These properties and the overall quality of bitumen depend primarily on the crude oil mix used and the refining operating conditions. The grade specification of bitumen products is achieved either directly by refining or by blending [5]. It is important to consider that this LCA is a cradle-to-gate study; possible direct use phase emissions from the bitumen itself (volatile emissions to air or rain water) are to be included in LCA studies covering the application or use stage of the bitumen. Further information can be found in the following document from Eurobitume & Asphalt Institute [5].

3.3 Manufacturing

Bitumen is produced from the distillation of crude oil in petroleum refineries. Depending on the specific applications, the refined bitumen is manufactured to meet different specifications. The following sections provide an overview of the manufacturing processes involved in the production of bitumen, and oxidised bitumen products.

3.3.1 Feedstock Supply

The manufacture of bitumen starts with the extraction of crude oil. Not every crude oil commercially available is suitable for bitumen production, but those with a bitumen content of 20 – 50 wt.%, which in general are classified as heavy crudes (API<26°). Bitumen properties are also a function of the properties of the crude oil mix; therefore, refiners carefully select the crude oil(s) to meet bitumen's specifications [5].

As mentioned above, some refineries included in the data collection are specialised in bitumen production or in the processing of heavier crudes. Other refineries produce bitumen mostly during dedicated bitumen campaigns over the year. In the latter case, the collected primary data on the crude slate refers usually to the specific bitumen campaign. In addition to crude oil, some refineries also use other feedstocks, especially HFO, which is considered in the weighted feedstock mix in Table 3-1 under 'Other feedstock'.

Crude oil production is modelled in Sphera's LCA FE using MLC datasets that assume a technology mix of conventional and unconventional production methods for the crude oils (per country of production) that supply Eurobitume member refineries. The datasets consider the country-specific technology mix situation regarding onshore vs. offshore drilling. A weighted average of the environmental impacts associated with the production of each crude oil (per country of production) and HFO was carried out to estimate the averaged environmental burden of the crude oil extraction stage and HFO supply for the representative refining operations. The estimation of the weight defining the contribution of the environmental burden of each country-specific crude oil dataset to the averaged burden of the feedstock supply is carried out as defined by equation (1). Primary data collected from refineries on country-specific crude oil supply and bitumen production are used to calculate the weights that define the contribution of each country-specific MLC dataset to the total environmental burden of feedstock production.

$$W = \sum_{i=1}^{n} w_i X_i \tag{1}$$

Where:

W [%] = *weight from crude oil extraction's (or HFO) environmental burden coming from a particular country z*

$i \rightarrow n$ = *number of refineries participating in the study, n=17*

w [%] = weights applied to each averaged value, equal to the share of bitumen production by refinery i with respect to the total bitumen production of all refineries evaluated in the study, based on refinery primary data.

X [%] = share of crude oil/HFO input coming from a particular country z with respect to the total crude oil basket input to refinery, based on refinery primary data

The share of countries from which crude oil is imported can vary over time for different reasons. The average feedstock supply mix weighted by bitumen output of the included refineries is therefore a 3-year average (2021-2023) to flatten possible fluctuations overtime. With the 6th package of sanctions by the EU against Russia in the context of the Russian war on Ukraine starting in June 2022 [15], an import ban has been imposed on Russian seaborn crude oil. The exception of crude oil imports by pipeline is not applied or relevant for the included refineries in this study. As a consequence, the feedstock supply mix of refineries in Europe has undergone significant change.

To better understand the impact of the substitution of Russian crude oil by other origins on the environmental impacts of the bitumen production, a sensitivity analysis uses the 2023 feedstock supply mix (see Section 4.2). In addition, a 5-year average (2019-2023) feedstock supply mix was applied in the sensitivity analysis to analyse and discuss the influence on the environmental impacts of the bitumen. The sensitivity analysis on the feedstock supply mix also includes a discussion about the parameters influencing the carbon intensities of crude oil from different country of origins.

As the information about the country of origins for the crude slates are very sensitive information for the refineries, the weighted averaged feedstock supply has been aggregated to a continental/regional breakdown in Table 3-1.

Table 3-1. Weighted feedstock supply mixes by continent/region

Origin of crude oil	3-year average [%]	5-year average [%]	2023 [%]
Africa	5	5	6
Europe	28	27	29
Former Soviet Union (FSU)	18	22	5
Middle East	27	26	33
North America	6	4	11
South America	2	3	3
Other feedstock (HFO)	14	13	14
Total	**100**	**100**	**100**

3.2.2 Feedstock Transport

The transport of the extracted crude oil from the oil field to the refinery is modelled using a combination of pipeline(s) and maritime vessel transportation. For each of the crude oil blends from the various crude oil exporting countries from which the individual refineries are supplied a specific combination of modes of transportation (e.g., pipeline-sea vessel-pipeline, pipeline-sea vessel) and distances have been set up. For any crude oil, however, the immediate mode of transportation once extracted at the oil field is via pipeline, subsequently delivering the crude to a connecting sea vessel or directly to the refinery. For each country of origin (if possible, for the specific oil field) and each refinery, the logistic chain and distances have been determined individually, using maps and a website to calculate the distances between ports (https://sea-distances.org/). The same has been done for the HFO between country of origin and the bitumen producing refineries. Finally for each country of origin, average weighted distances by bitumen output of the refineries have been calculated based on the feedstock supply mix. Similar to the feedstock supply mixes presented in Table 3-3, the distances per country have been aggregated for the report to average distances per continent/region as displayed in Table 3-4 for the 3-year average feedstock supply. The different distances for the pipeline between import terminal in the EU and UK and the refinery are related to the fact that some refineries are located at the coast and have their own import terminal (or are located beside it) for other, a further pipeline transport is needed.

Table 3-2. Average transport distances per region/continent (2021-2023)

Origin of crude oil	Pipeline (oil field to terminal/refinery) [km]	Oil tanker (export terminal to import terminalrefinery) [km]	Pipeline (import terminal to refinery) [km]
Africa	210	5 580	100
Europe	120	440	60
Former Soviet Union (FSU)	3 340	2 980	50
Middle East	540	8 960	70
North America	110	9 120	100
South America	100	7 940	30
Other feedstock (mainly HFO)	0	3 570	0
Average total	**780**	**4 550**	**50**

Transport distances for the 5-year and 2023 feedstock supply used in the sensitivity analysis on the feedstock supply (see section 3.3.1 and 4.2.1) are given in Annex B. The overall transport distances for the different feedstock supplies are given in Table 3-3, in which the distances for the 3-year average are used for the baseline scenario and the 5-year average and 2023 distances have been only used for the sensitivity analysis on the feedstock supply. The stop of Russian crude oil imports (seaborne and by pipeline) has also an important influence on the transport distances. Whereas the average pipeline distance has dropped for 2023 compared to the 3-year and 5-year average, the average ship distance increases, as most of the substituted Russian oil is transported via ship from North America or the Middle East to the EU and UK.

Table 3-3. Aggregated transport distances per feedstock supply scenario

Origin of crude oil	Pipeline (oil field to terminal/refinery) [km]	Oil tanker (export terminal to import terminal/refinery) [km]	Pipeline (import terminal to refinery) [km]
Baseline Scenario			
3-year average (2021-2023)	780	4 550	50
Sensitivity analysis			
5-year average (2019-2023)	970	4 330	50
2023	320	5 830	50

The electricity consumed during the operation of the pipeline in the crude oil producing country is assumed to be generated from diesel fuel (for all countries). The sea transport vessel is powered by heavy fuel oil (which production is modelled with one European-wide (RER) averaged HFO dataset used for all seaborn transports regardless of the feedstock country of origin). The pipelines in Europe are assumed to be operated with electricity from the European grid.

3.3.3 Refinery Operations

Distillation Units

In the baseline scenario the energy consumption of the distillation process is calculated for the vacuum residue/bitumen by using the collected primary data from the considered refineries and applying an allocation by energy (net calorific value) to partition the impacts of the distillation units between the coproducts. In addition, allocation by mass and a thermodynamic calculation of the energy consumption for the bitumen based on the sensible heat to avoid the allocation has been calculated and compared in a sensitivity analysis (see section 4.2.2).

Atmospheric Distillation

The first refining process in the production of refined bitumen is the atmospheric distillation of crude oil. Atmospheric distillation separates the lighter, low boiling point fractions within the crude oil mix (vaporizing them) from the heavier ones, which due to their high boiling points and high molecular weights, have very low volatility. The non-boiling, heaviest fraction is retrieved at the bottom of the column as atmospheric residue. This residue is the fraction that is further distilled in a vacuum distillation tower to produce vacuum residue/bitumen.

Table 3-4. Atmospheric distillation input-output table per tonne of crude oil input

Type	Flow	Value	Unit
Inputs	Crude oil mix	1 000,000	kg/tonne of crude oil mix
	Additives*	0,121	kg/tonne of crude oil mix
	Electricity from onsite plant**	38,602	MJ/tonne of crude oil mix
	Electricity from grid	51,443	MJ/tonne of crude oil mix
	Steam	62,777	MJ/tonne of crude oil mix
	Natural gas	29,281	MJ/tonne of crude oil mix
	Refinery gas	290,522	MJ/tonne of crude oil mix
Outputs	Refinery gas	4,109	kg/tonne of crude oil mix
	LPG	24,552	kg/tonne of crude oil mix
	Naphtha	119,944	kg/tonne of crude oil mix
	Kerosene	93,675	kg/tonne of crude oil mix
	Gas oil	124,865	kg/tonne of crude oil mix
	Light gas oil	35,737	kg/tonne of crude oil mix
	Heavy gas oil	28,589	kg/tonne of crude oil mix
	Fuel oil	22,976	kg/tonne of crude oil mix
	Atmospheric residue	542,139	kg/tonne of crude oil mix
	Product losses	3,415	kg/tonne of crude oil mix
	Steam	0,800	MJ/tonne of crude oil mix

* Additives include caustic solution, H_2S scavenger, demulsifiers, and filmers.
**See section 3.3.4. for more information

The atmospheric distillation tower is modelled in the LCA FE software using the input-output data provided in Table 3-4. The input-output data is based on primary refinery data that was averaged using bitumen 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 bitumen production by a specific refinery with respect to the total bitumen production of all refineries evaluated in the study. All average input-output values are also normalised to one tonne of feedstock mix. A yield of 99,6 % is obtained for the atmospheric distillation, around 0,4 % of the feedstock input is accounted as loss (impurities in the crude).

Vacuum Distillation

Atmospheric residue is the main feed to the vacuum distillation tower, which uses reduced pressure to separate the remaining lighter fractions in the residue and avoid unwanted thermal cracking of such fractions. The products of this process are heavy distillates (i.e. several types of gas oils that are heavier than the middle distillates produced by atmospheric distillation) and vacuum residue. In case the vacuum residue is not further processed to get shorter products, e.g. in a cracker.

The input-output data provided in Table 3-5 was used to model the vacuum distillation unit in Sphera's LCA FE software. The input-output values are based on primary refinery data averaged using bitumen production by refinery as weighting and normalised to one tonne of atmospheric residue product.

Table 3-5. Vacuum distillation input-output table per tonne of atmospheric residue input

Type	Flow	Value	Unit
Inputs	Atmospheric residue	1 000,000	kg/tonne of atm. residue
	Electricity from onsite plant*	25,442	MJ/tonne of atm. residue
	Electricity from grid	33,904	MJ/tonne of atm. residue
	Steam	76,544	MJ/tonne of atm. residue
	Natural gas	84,250	MJ/tonne of atm. residue
	Refinery gas	216,156	MJ/tonne of atm. residue
	Fuel oil	26,308	MJ/tonne of atm. residue
Outputs	Refinery gas	0,137	kg/ tonne of atm. residue
	Cracked distillates	88,469	kg/ tonne of atm. residue
	Vacuum gas oil (VGO)	373,553	kg/ tonne of atm. residue
	Vacuum residue (bitumen)	483,228	kg/ tonne of atm. residue
	Wax	51,439	kg/ tonne of atm. residue
	Product losses	3,174	kg/ tonne of atm. residue
	Steam	6,574	MJ/tonne of atm. residue

*See section 3.3.4. for more information

It should be noted that the yield of an individual product in the atmospheric distillation and vacuum distillation, is highly dependent on the composition of the crude. Therefore, the output of both distillation units for an individual refinery can be significantly different compared to the averaged and weighted inventory of the included refineries presented above.

The included refineries produce in total 6,15 million ton of vacuum residues/bitumen, around 520 000 t are further treated by air-blowing (air-rectification) to meet the properties of bitumen under EN 12591:2009 another 80 000 t are fully blown to oxidised bitumen.

Air-Rectification

Air-rectification or semi-blowing is a mild grade of bitumen oxidation in which the hot compressed air (230–260 °C) passing through the bitumen slightly modifies its physical properties (e.g., decreases the penetration, increases stiffness and softening point). This process produces a bitumen that meets the required specifications under EN 12591:2009.

Table 3-6 presents the input-output data used in the LCA FE model to assess the environmental impact of the air-rectification process. Similar to the modelling of the previous process units, the input -output data is based on primary refinery data that was averaged using bitumen production by refinery as weighting and normalised to one tonne of air-rectified bitumen product.

Table 3-6. Air-rectification input-output table per tonne of air-rectified bitumen product

Type	Flow	Value	Unit
Inputs	Vacuum residue/Bitumen	1 005,911	kg/tonne air-rectified bitumen
	Electricity from onsite plant*	36,047	MJ/tonne air-rectified bitumen
	Electricity from grid	47,979	MJ/tonne air-rectified bitumen
	Steam	129,048	MJ/tonne air-rectified bitumen
	Natural gas	160,879	MJ/tonne air-rectified bitumen
	Refinery gas	61,762	MJ/tonne air-rectified bitumen
	Thermal energy from fuel oil	18,606	MJ/tonne air-rectified bitumen
Outputs	Air-rectified bitumen	1 000,000	kg/tonne air-rectified bitumen
	Losses	5,911	kg/tonne air-rectified bitumen

*See section 3.3.4. for more information

In total, around 460 000 tonnes of semi-blown bitumen are produced. Together with the 5,55 million tonnes of vacuum residue/bitumen leaving the refineries without further treatment a total amount of 6,01 million tonnes of bitumen meeting EN 12591:2009 requirements are covered by the study.

Oxidation

Full blowing or oxidation of bitumen is a more severe process than air-rectification that significantly changes the physical properties of vacuum residue/bitumen. Fully oxidised bitumen (or fully blown bitumen) has an increased softening point, decreased penetration, and increased viscosity. It is mainly used in roofing applications. Flux oil and phosphoric acid as catalyst are added for the oxidation.

The input-output data (based on primary refinery data that was averaged using bitumen production by refinery as weighting and normalised to one tonne of oxidised bitumen product) for the full oxidation model in LCA FE is presented in Table 3-7.

Table 3-7. Bitumen oxidation input-output table per tonne of oxidised bitumen product

Type	Flow	Value	Unit
Inputs	Vacuum residue/Bitumen	978,205	kg/tonne oxidised bitumen
	Flux oil	21,795	kg/tonne oxidised bitumen
	Phosphoric acid	0,758	kg/tonne oxidised bitumen
	Electricity from onsite plant*	64,606	MJ/tonne oxidised bitumen
	Electricity from grid	86,095	MJ/tonne oxidised bitumen
	Steam	656,931	MJ/tonne oxidised bitumen
	Natural gas	368,674	MJ/tonne oxidised bitumen
Outputs	Oxidised bitumen	1 000,000	kg/tonne oxidised bitumen
	Losses	0,758	kg/tonne oxidised bitumen

*See section 3.3.4. for more information

Bitumen Storage within Refinery

The refined bitumen products are stored in heated and insulated storage tanks at refineries. Storage conditions, e.g., temperature, safety, maintenance, and cleaning are carefully monitored.

Table 3-8 presents an overview of the averaged input-outputs flows gathered in the data collection and included in the LCA FE storage model. Similarly to other process units, the input-outputs flows are modelled using primary refinery data that was averaged using bitumen production by refinery as weighting and subsequently normalised to one tonne of stored bitumen. The inventory has been used for both products, bitumen and oxidised bitumen, although oxidised bitumen might be stored at higher temperatures. Based on the primary data collected for the storage and the calculation of the energy consumption based on design data in version 3.1, the conclusion can be done that refinery-specific management has an important influence on the energy consumption. A theoretical adjustment of the energy consumption for the storage of oxidised bitumen has therefore not been done. It should be also noted that residual heat from the distillation units is recovered and used within the storage without any consideration in the collected data due to missing data or complexity. It is therefore important to consider that the inventory for storage is specific to this study and will not necessarily be representative for bitumen storage outside the considered refineries, also because of the possibly different tank sizes and bitumen throughputs.

Table 3-8. Bitumen storage input-output table per tonne of stored bitumen product

Type	Flow	Value	Unit
Inputs	Bitumen	999,656	kg/tonne stored bitumen
	Additives*	0,344	kg/tonne stored bitumen
	Electricity from onsite plant**	18,835	MJ/tonne stored bitumen
	Electricity from grid	25,101	MJ/tonne stored bitumen
	Steam	335,086	MJ/tonne stored bitumen
	Natural gas	47,344	MJ/tonne stored bitumen
	Refinery gas	23,826	MJ/tonne stored bitumen
Outputs	Stored bitumen	1 000,000	kg/tonne stored bitumen

* Additives include H_2S scavenger, wax, and adhesion promoters.

** See section 3.3.4. for more information

3.3.4 Electricity, Steam and Heat Supply

The representative refinery modelled in the foreground system sources electricity from an onsite power plant and the grid. A fraction of the electricity consumption (42,9 %) is generated by an onsite combined heat and power (CHP) plant, which also supplies the consumed steam of the refinery. The rest (57,1 %) is assumed to be sourced from the grid, applying a country mix which represents the included refineries weighted by bitumen output. For all countries, the medium voltage 1 kV - 60 kV data sets with reference year 2020 from Sphera's MLC database 2024 have been used. Further documentation on this background dataset is provided in Section 3.4.1.

This electricity mix for the grid supply is assumed to power all refining operations within the boundaries of this study. The fractions of electricity sourced from the onsite CHP plant vs. the grid are calculated using weighted averages (weighted by refinery bitumen output) of the total electricity purchased from the grid, sold to the grid, and electricity produced onsite for the entire refinery operation, as reported by participating Eurobitume member companies.

The refinery's CHP plant (producing both electricity and steam) is modelled using primary data from Eurobitume member refineries. Ten refineries provided data for a central CHP plant, the other refineries do not produce electricity onsite or were not able to provide data). The overall efficiency of the CHP plant is 78 % and 25 % of the produced energy is electricity. The environmental impact of the plant's operations is partitioned between electricity and steam outputs via exergy allocation. Exergy values for electricity and steam are 1 MJ and 0,33 MJ, respectively (similar assumption to that of standard MLC background datasets, for more details see the BREF document for large combustion plants [18]). Fuels consumed are natural gas, refinery gas, and light fuel oil (LFO) and heavy fuel oil (HFO). The averaged fuel mix is 63 % natural gas, 36 % refinery gas and 1 % fuel oil. The upstream environmental burden from the production of all fuels is accounted for in the CHP model, which holds true also for internally supplied fuels, such as refinery gas.

Other emissions to air and water from the operation of the power plant are calculated using an average emission profile per MJ of total fuel combusted. As direct emissions like, methane (CH_4) or NMVOC were mostly not available on a refinery unit level, emissions to air and water (by specific species) reported by the participating refineries for their entire operation have been divided by their total amount of combusted fuels to calculate an emission profile for the fuel combustion per unit of average combusted fuel.

This approach has been used for all emissions beside carbon dioxide (CO_2). Carbon CO_2 emissions from the fuel combustion are calculated using the quantity of fuel combusted and its corresponding emission factor as published by IPCC under 'Default Emission Factor' in Table 2-2 of the IPCC document [29]. This results in a comprehensive inventory of emissions to air and water per MJ of combusted fuel that is used to round off the calculation of the environmental impact of fuel combustion in the CHP but also for the fuel combustion within the refinery units. The emission profile per average combusted fuel is given in Annex B.

As stated above, CO_2 emissions from the direct combustion of fuels to provide heat or steam have been calculated based on CO_2 emission factors provided by the IPCC [29] and the amount of combusted fuel. For the other emissions, the average calculated emission profile has been used. As the focus within this study was on the bitumen production, the entire steam and heat production supplied to the network could not be included in the modelling. Therefore, the assumption has been done that all steam supplied to the representative refinery is produced by the CHP plant. Primary data on steam consumption provided by the different refineries included information on temperature and pressure properties. Therefore, steam consumption provided in mass units has been converted into MJ using steam tables.

3.3.5 Entire Refinery's Water Supply, Waste Management and Overhead

A few utilities (i.e., water consumption, wastewater, waste disposal) and the overhead operations could not be related to specific refining processes as this kind of data is mostly not separately collected by the refineries. Therefore, primary data on entire refinery have been allocated to the different products of the averaged refinery alongside overhead's energy use assumptions. Table 3-9 presents the entire refinery's product slate that was utilised in the allocation of water supply, waste flows, and overhead operations. The product slate is based on the weighted average (by bitumen output) of all refinery products reported by the refineries.

Table 3-9. Entire refinery product slate

Refinery's Product Slate	Amount produced [metric tone/year]	Net Calorific Value [MJ/kg]	Source*
Refinery gas	190 121	45,6	Primary data
LPG	102 616	45,8	Primary data
Naphtha	104 873	44,4	Primary data
Gasoline	1 012 507	43,2	[30]
Kerosene	509 635	43,4	Primary data
Diesel	2 431 680	43,1	[30]
Light Fuel oil	242 902	42,6	[31]
Heavy Fuel oil	261 262	40,2	[31]
Base oils	51 373	40,0	[32]
Coke	10 700	31,4	[32]
Bitumen	410 921	39,6	Primary Data
Sulphur	41 409	9,3	[32]
Wax	38 476	41,0	[32]
Methanol	28 888	19,9	[30]
Benzene	8 329	40,6	[32]
Other Refinery products/ not specified	1 257 052	40,2	Estimated*

* For products for which the net calorific value could not be taken from the primary data, values from literature or Sphera's proprietary refinery LCI model have been used. NCV of heavy fuel oil assumed as relatively low and conservative assumption (less impact allocated to other refinery products by energy allocation).

In the baseline scenario this allocation has been done by energy, as it has also been done for the distillation units. Mass allocation for the overhead was applied in the sensitivity analysis (see sections 4.2.2 for more information). The following tables display the water balance, waste flows and the refinery's overhead energy consumption for the baseline scenario (allocation by energy) and for the sensitivity analysis (allocation by mass). For allocation by energy, the input and output flows in the overhead are around 8 % lower due to the lower calorific value of the bitumen compared to other refinery products.

The supply of water for process and cooling purposes in the production of refined bitumen is modelled in Sphera's LCA FE using the entire refinery's water consumption data from groundwater, surface water, and from public utility sources.
Discharged wastewater (to wastewater treatment plants and water bodies) has been calculated by subtracting the evaporated water from the water input, as the measured water discharge includes collected rainwater as well. The water balance, presented in Table 3-10, excludes the calculated rainwater in the discharge.
The LCA FE model applies an energy-based allocation methodology (based on net calorific value (NCV) of products) over the entire refinery's product slate to partition the refinery's water balance among its different products and assign a fraction of it to refined bitumen. As the sensitivity analysis in section 4.2.2 investigates the impacts of the selected approach to solve multifunctionality in the refinery on the results, also the water flows per tonne of bitumen using mass allocation are given in the table.

Table 3-10. Water balance for representative refinery model

Type	Flow	Value [t/year]	Allocation by Energy [kg/t bitumen]	Mass [kg/t bitumen]
Inputs	Groundwater	2 420 016	333	361
	Surface water	7 215 990	993	1 077
	Public utilities	1 834 243	252	274
Outputs	Wastewater to WWTP	654 243	90	98
	Discharge to water body	7 585 412	1 044	1 132
	Evaporation	3 230 594	445	482

Refinery wastes are mainly hazardous (e.g., oil and cleaning sludges, solvents) and non-hazardous wastes (e.g., some metal and organic materials). Both types of waste are accounted for in the LCA FE model and different disposal options are modelled, e.g., recovery/treatment, incineration, landfilling, and reuse/recycling activities. The modelling of refinery wastes is carried out using the entire refinery's waste data, as process specific waste data is usually not collected within the refineries. The same energy and mass-based allocation approach used for the water flows is then applied by the LCA FE model to assign a portion of the waste management flows to refined bitumen products. Table 3-11 presents an overview of the representative refinery waste flows included in the model.

Table 3-11. Waste flows from representative refinery

Type	Flow	Value [t/year]	Allocation by Energy [kg/t bitumen]	Mass [kg/t bitumen]
Outputs	Hazardous waste to recovery/treatment	6 152	0,847	0,918
	Hazardous waste to incineration	4 166	0,573	0,622
	Hazardous waste to landfill	656	0,090	0,098
	Hazardous waste to recycling	2 178	0,300	0,325
	Non-hazardous waste to recovery/treatment	55	0,008	0,008
	Non-hazardous waste to incineration	1 408	0,194	0,210
	Non-hazardous waste to landfill	2 546	0,350	0,380
	Non-hazardous waste to recycling	8 111	1,116	1,210

Finally, overhead operations (e.g., lighting, storage of crude, dewatering, desalting) are assumed to account for 3 % of the overall energy consumption of the refinery. The value of 3 % is a qualified estimation by Eurobitume members operating refineries that has been collected in a survey in the previous study [14] and has been considered as still valid by the companies included in the data collection. The same energy-based allocation approach was applied to the overhead energy as the one applied to apportion total water supply and waste management impacts to refined bitumen. The allocated energy consumption of the overhead is summarised in Table 3-12.

Table 3-12. Allocated energy overhead per tonne of bitumen

Flow	Allocation by Energy [MJ/t bitumen]	Mass [MJ/t bitumen]
Refinery gas	49,6	53,7
Natural gas	6,98	7,56
Heavy fuel oil	3,20	3,47
Light fuel oil	1,66	1,80
LPG	1,62	1,76
Coke	4,17	4,52
Electricity	4,18	4,53
Steam	2,20	2,38

3.4 Background Data

The production of paving grade bitumen products was modelled in Sphera’s LCA FE software using primary data supplied by Eurobitume member refineries wherever available. Background data from Sphera’s LCA FE’s MLC database were mainly used to model the upstream environmental burden of the production (extraction) of feedstock supply, transport of feedstock, energy supply from external (fuels and grid electricity) as well as auxiliary processes. The following sections document which LCI background data has been used. The documentation for all LCA FE datasets can be found online under https://lcadatabase.sphera.com/ [16].

3.4.1 Fuels and Energy

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

Electricity

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 is provided in the section ‘Fuel Inputs’ below. The environmental burdens for the fraction of electricity sourced from the grid are calculated using country-specific electricity grid mix datasets (medium voltage 1 kV - 60 kV) from Sphera’s MLC database v. 2024.1. The country mix represents the included refineries weighted by bitumen output (see Table 3-11 above). Table 3-13 presents the list of national electricity grid mixes from the LCA FE 2024.1 database.

Table 3-13. Key energy datasets used in inventory analysis

Energy	Country	Dataset	Data Provider	Reference Year	Proxy?
Electricity	UK	GB: Electricity grid mix 1 kV - 60 kV	Sphera	2020	No
	Italy	IT: Electricity grid mix 1 kV - 60 kV	Sphera	2020	No
	Spain	ES: Electricity grid mix 1 kV - 60 kV	Sphera	2020	No
	France	FR: Electricity grid mix 1 kV - 60 kV	Sphera	2020	No
	Sweden	SE: Electricity grid mix 1 kV - 60 kV	Sphera	2020	No
	Austria	AT: Electricity grid mix 1 kV - 60 kV	Sphera	2020	No
	Germany	DE: Electricity grid mix 1 kV - 60 kV	Sphera	2020	No
	The Netherlands	NL: Electricity grid mix 1 kV - 60 kV	Sphera	2020	No

Fuels for Electricity, Steam, and Heat Generation

Fuels associated with the production of refined bitumen products are natural gas, refinery gas, light fuel oil (LFO) and heavy fuel oil (HFO). The upstream environmental burden from the supply of all fuels is accounted for in the LCA model through the use of the background datasets listed in Table 3-14.

Table 3-14. Key fuels datasets used in inventory analysis

Energy	Region	Dataset	Data Provider	Reference Year	Proxy?
Fuels	Europe	RER: Natural gas mix	Sphera	2020	No
	Europe	RER: Refinery gas at refinery	Sphera	2020	No
	Europe	RER: Light fuel oil at refinery	Sphera	2020	No
	Europe	RER: Heavy fuel oil at refinery (1,0wt.% S)	Sphera	2020	No

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. MLC datasets that represent the production of crude oil through conventional (onshore and offshore drilling) and unconventional production (oil sands, in-situ) are considered for the respective production country.

A total of 36 country-specific crude oil production datasets (‘Oil Production all technologies’) are considered for the feedstock supply of the representative refinery. Six geographical proxy datasets were used in cases where no matching life cycle inventory was available to represent a country crude oil production mix. The choice of proxy dataset was guided by geographical proximity to the missing country-specific dataset. The share of crude oil supply for which no country-specific dataset was available is approximately 1 %.

Each dataset represents the national crude oil production mix using annual averaged data. The reference year for all datasets is the year 2019. The models apply allocation by net calorific value to partition the environmental footprint of the extraction process among crude oil, natural gas, and natural gas liquids (NGL). In the background system of the MLC datasets, individual country-specific situations are modelled for electricity consumption, thermal energy and process steam supply, transport processes, and other energy carriers. The impacts are calculated per kilogram of crude oil extracted and ready for further processing.

Background datasets from Sphera's MLC were also used for the supply of HFO (2,5 wt.% sulphur) as refinery feedstock. The country-specific datasets cover the entire supply chain of the production of HFO, from well drilling and crude oil production (conventional and unconventional) to transportation of crude oil and processing in the refinery. The MLC datasets also consider country-specific downstream refining technologies, crude oil and refinery products properties (e.g. sulphur contents), as well as output spectrum of the refineries. The inventories are mainly based on industry data and are completed, where necessary, with secondary data. A total of 9 country-specific HFO datasets have been used. In cases where no matching life cycle inventories are available to represent the country-specific HFO flows, geographical proxy datasets have been applied. The European region (RER) dataset has been used for all European countries from which HFO is sourced.

In addition, auxiliary raw materials (e.g. process water), additives, as well as the downstream environmental impact of wastewater treatment and waste treatment have been used. The list of used LCI background data sets is given in Annex B.

3.4.3 Transportation

Transportation datasets from Sphera's MLC database have been used for the transport of the refinery feedstock supply as described in section 3.3.2. Table 3-15 summarises the used data sets.

Table 3-15. Transportation and fuel datasets

Mode / fuels	Geographic Reference	Dataset	Data Provider	Reference Year	Proxy?
Pipeline	GLO	Pipeline average (electricity driven)	Sphera	2023	no
Oil Tanker	GLO	Oil tanker, 5 000 - 300 000 dwt payload capacity, deep sea	Sphera	2023	no
Electricity	RER	Electricity from diesel fuel (diesel generator)	Sphera	2020	no
	RER	Electricity grid mix 1 kV-60 kV	Sphera	2020	no
Heavy fuel oil	RER	Heavy fuel oil at refinery	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 3-16 summarises the LCI for the two different bitumen products, Bitumen according to EN 12591 and oxidised bitumen under EN 13304 using the 3-year average crude supply and energy allocation for the distillation units. The inventory for bitumen includes 92,4 % untreated bitumen and 7,6 % bitumen treated by air-rectification. A contribution analysis of the origin of impacts is presented in Section 4.1 of Chapter 4.

Table 3-16. Cradle-to-gate LCI results of bitumen (in kg/t of bitumen)

Type	Flow	Bitumen [kg/t]	Oxidised Bitumen [kg/t]
Resources	Water consumption	658	739
	Crude oil	994	1003
	Hard coal	2,21	2,77
	Lignite	2,19	3,05
	Natural gas	79,4	101,6
	Uranium	2,3E-04	3,5E-04
Emissions to air	CO_2	284	360
	CO_2 (biotic)	5,91	8,34
	CH_4	8,09	8,42
	CH_4 (biotic)	8,0E-02	8,7E-02
	N_2O	8,5E-03	1,0E-02
	NO_x	1,13	1,16
	SO_2	0,67	0,79
	NMVOC	1,65	1,74
	CO	0,34	0,38
	$PM_{2,5-10}$	8,2E-02	8,7E-02
	$PM_{2,5}$	1,1E-02	1,3E-02
	Heavy metals	2,7E-04	3,1E-04
Emissions to fresh water	Ammonia	9,9E-04	1,1E-03
	Nitrate	1,3E-02	1,5E-02
	Phosphate	7,4E-04	9,1E-04
	Heavy metals	1,5E-02	1,7E-02
Emissions to sea water	Ammonia	6,6E-07	1,4E-06
	Nitrate	4,6E-04	5,0E-04
	Phosphate	9,1E-05	1,6E-04
	Heavy metals	2,6E-03	2,7E-03

4. LCIA Results

This section contains the results for the Life Cycle Impact Assessment (LCIA) with the impact categories and additional metrics defined in section 2.6. It shall be reiterated at this point that the reported impact categories represent impact potentials, i.e., they are approximations of environmental impacts that could occur if the emissions would (a) follow the underlying impact pathway and (b) meet certain conditions in the receiving environment while doing so. In addition, the inventory only captures that fraction of the total environmental load that corresponds to the chosen functional unit (relative approach).

LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

4.1 Overall Results

The present study evaluates the cradle-to-gate environmental impacts associated with 1 (metric) tonne of bitumen (EN 12591) and oxidised bitumen (EN 13304) 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 17 refineries in 8 European countries and bitumen production of 6,15 million tonnes in 2023, ~76 % of the bitumen production by Eurobitume members or 45 % [28] of the total production in the EU and UK. 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). Further results using mass allocation or the thermodynamic approach to calculate the energy consumption for the bitumen as well as different reference years for the feedstock supply are presented and discussed in the sensitivity analysis in section 4.2.

Global Warming Potential Results

Results are shown for the global warming potential over a 100-year period (GWP_{100}) calculated according to IPCC's Fifth Assessment Report (AR5) [19][3] excluding climate carbon feedback and IPCC's Six Assessment Report (AR6) [11] methodologies. The GWP_{100} AR6 indicator corresponds with the 'Climate Change, total' indicator under EN 15804+A2:2019 [9].

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[3] The chosen GWP factors from the AR5 are without 'climate carbon feedback' to allow a direct comparison with the results from Version 3.1 of Eurobitume's LCI for Bitumen report [8] and due to their still high uncertainty. 'Climate carbon feedbacks can amplify or suppress climate change by altering the rate at which CO_2 builds up in the atmosphere through changes in the land and ocean sources and sinks [18]'. An example are carbon releases due to thawing terrestrial permafrost.

Figure 4-1 presents the contribution analysis to GWP_{100} of the two bitumen products evaluated in this study (bitumen and oxidised bitumen) using the 3-year average feedstock supply and allocation by energy.

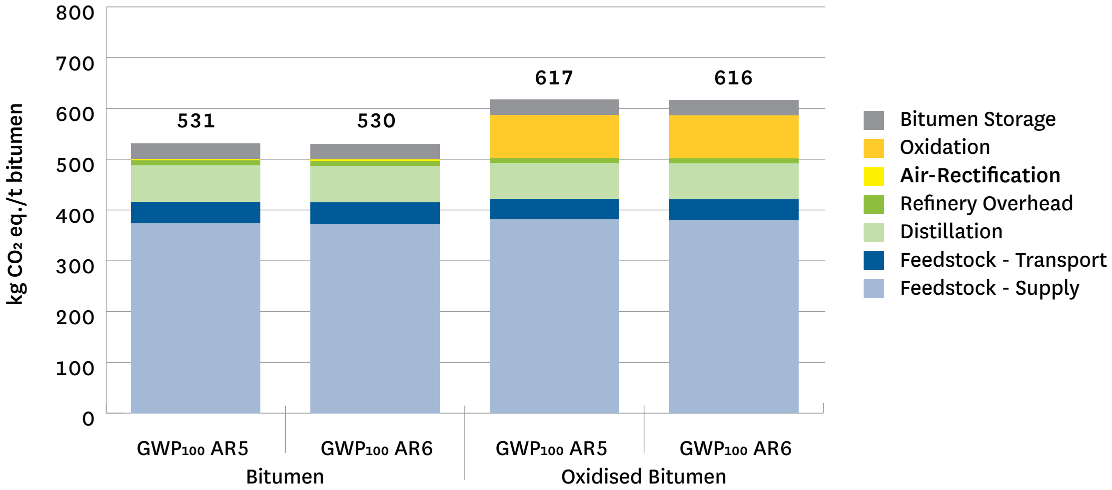

Figure 4-1. GWP_{100} (AR5 and AR6) for bitumen products

GWP_{100} for the bitumen (EN12591) product is 531 and 530 kg CO_2 eq./t of bitumen when evaluated under AR5 and AR6 methodologies, respectively. Full blowing or oxidation of bitumen consumes a relevant amount of energy, which adds about 85 kg CO_2 eq./t to the bitumen product. Therefore, additional processing to tune product properties and meet specifications increases the GWP_{100} to 617 or 616 kg CO_2 eq./t of bitumen for oxidised bitumen (EN 13304) (~16 % increase), respectively for AR5 and AR6 methodologies. There is no significant difference between the GWP_{100} results obtained applying AR5 (excluding climate carbon feedback) methodology and those from AR6.

The major contributor to GWP_{100} across all products evaluated is the extraction of the crude oil and HFO supplied to the refinery (70 % and 62 % for bitumen and oxidised bitumen, respectively). The transport of crude to the refinery contributes with an additional 8 % and 7 % respectively for the aforementioned products. Atmospheric and vacuum distillation of the crude oil contribute 14 % to GWP_{100} of bitumen and 11 % in the case of oxidised bitumen products. Whereas the impact for the storage has been calculated in version 3.1 of 'The Eurobitume LCI for bitumen' based on literature and assumptions for the design data of the storage, primary data has been collected in this study for the storage of the bitumen, which resulted in distinct higher energy consumption (~500 MJ of steam, fuels and electricity per tonne of bitumen compared to 100 MJ/t of bitumen in the previous study) and GWP_{100} impacts for the bitumen products.

Figure 4-2 provides further insight on the contribution of the main greenhouse gases (GHGs) to bitumen (EN 12591)'s GWP_{100} (AR6).

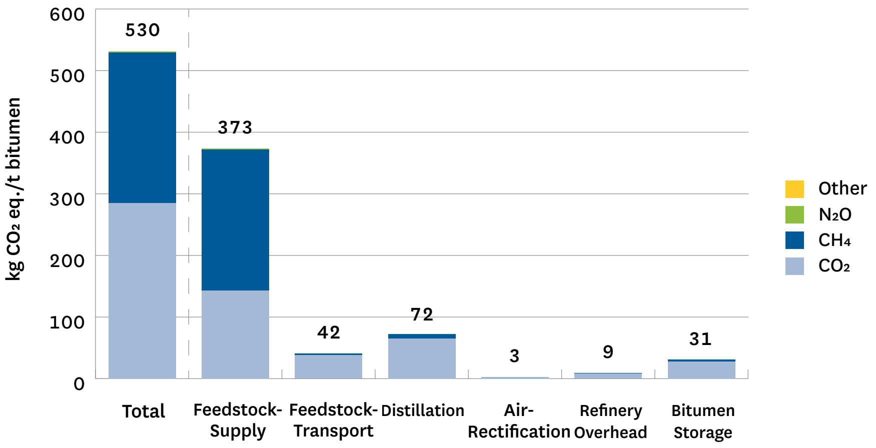

Figure 4-2. Individual GHGs for bitumen GWP_{100} (AR6)

Methane (CH_4) emissions contribute 46 % to bitumen (EN12591)'s total GWP_{100}, while CO_2 emissions make up another 54 %. The relevance of CH_4 for bitumen's GWP_{100} originates on its high share of GHG emissions (61 % of total feedstock supply's GWP_{100}) during crude oil extraction, mainly through venting, flaring and fugitives (VFF) emissions. The sensitivity analysis in section 4.2.1 contains a discussion about the broad range of especially methane emissions for crude oil production from different origins. Emissions from nitrous oxide (N_2O) and other GHGs are negligible. A similar trend is expected to be true for air-rectified and oxidised bitumen products. Further interpretation of the results is given in section 5.1.

Other Environmental Impact Categories

Other environmental impact categories are evaluated according to the characterisation factors of the EF 3.1 (Environmental Footprint 3.1) methodology, to which EN 15804+A2:2019 [9] refers to assess the environmental impact of construction materials. The following sections present the environmental impact results for key indicators like acidification, eutrophication-freshwater, photochemical ozone formation, and resource use-fossils.

Acidification Potential

Figure 4-3 presents the contribution analysis for the acidification potential of the bitumen products according to EF 3.1 methodology.

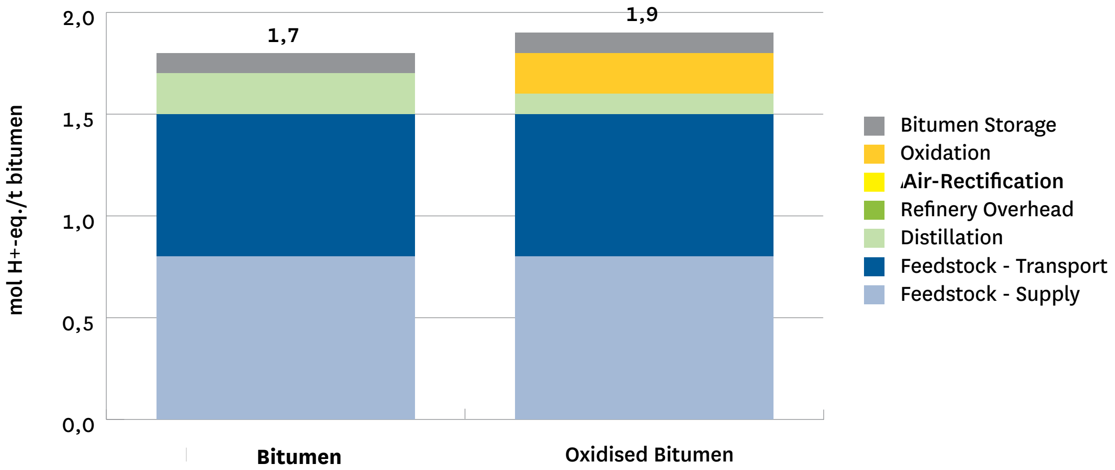

Figure 4-3. Acidification potential for bitumen products

Atmospheric emissions of sulphur dioxide (SO_2), nitrogen oxides (NO_x), and other acidifying substances can undergo chemical conversion in the atmosphere into (e.g., sulphuric and nitric) acids. Their deposition can change the chemical composition of soils and surface waters leading to the problem of acidification. The assessment of the acidification potential from the production chain behind the bitumen products revealed that this environmental metric is driven by extraction of crude oil (46 % for bitumen and 43 % for oxidised bitumen) and its subsequent transportation to the refinery (40 % and 36 %, respectively). Acidification emissions are mainly originated during the burning of fossil fuels; therefore, the oxidised bitumen product accounts for an increased acidification potential from the additional energy needed for the full-blown oxidation process.

Eutrophication Potential in Freshwater

Figure 4-4 presents the contribution analysis for the eutrophication potential in fresh water for the bitumen products.

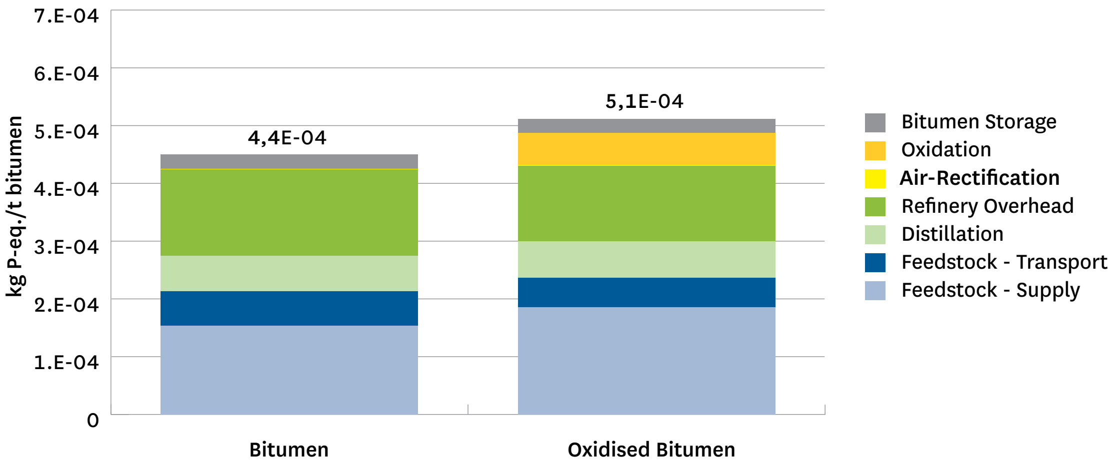

Figure 4-4. Eutrophication potential in freshwater for bitumen products

Freshwater eutrophication is a process where nutrients like nitrogen and phosphorus accumulate in water bodies, leading to negative impacts like algal blooms, oxygen depletion, and several other problems associated with water contamination. Emissions of phosphate and phosphorous compounds to water, from the extraction of crude oil are the main drivers (40 % for bitumen and 38 % for oxidised bitumen) behind the potential for eutrophication in freshwater. Refinery overhead operations is another significant driver (29 % for bitumen and 26 % for oxidised bitumen) to eutrophication in freshwater, due to water supply and wastewater treatment. Finally, the feedstock transport contributes ~10 %, on average, to the overall impact, caused by fuel and electricity supply, and the distillation units are another 12 % (on average) of the overall eutrophication impacts.

Photochemical Ozone Formation Potential

The assessment of the potential for photochemical ozone formation arising from the production of each bitumen product is presented in Figure 4-5.

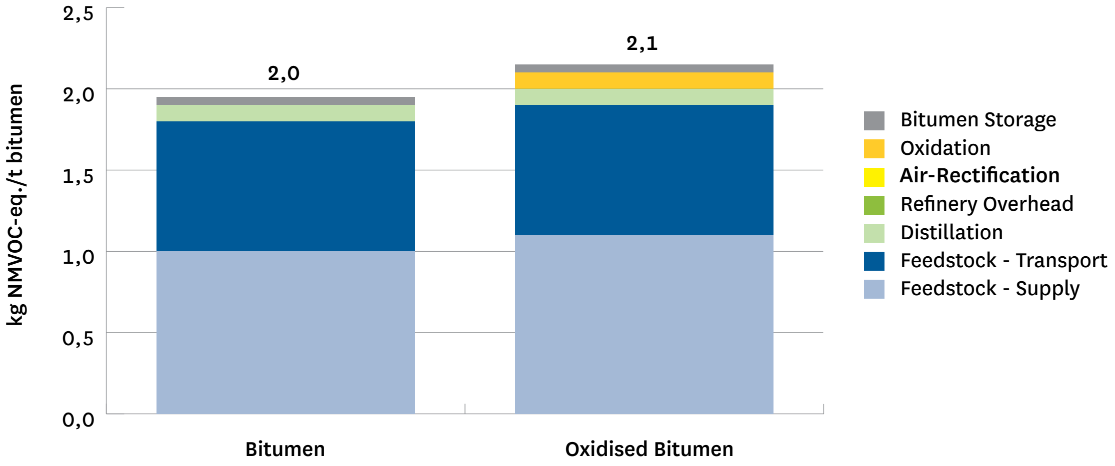

Figure 4-5. Photochemical ozone formation for bitumen products

Photochemical ozone formation occurs when sunlight reacts with a number of air pollutants to form reactive chemical species like ozone. NO_x, volatile organic compounds (VOCs), non-methane VOCs (NMVOCs), and carbon monoxide (CO) are some of the main emissions behind photochemical ozone creation. During bitumen production, NMVOC emissions from crude production (51 % for bitumen and 50 % for oxidised bitumen) and NO_x emissions from feedstock (crude oil and HFO) transportation's tankers (40 % and 37 %, respectively) are the main contributors to the potential formation of photochemical ozone.

Resource Use – Fossils

Another environmental performance indicator of interest is measuring the use of fossil fuel resources. Figure 4-6 presents the assessment of the environmental impact of resource use from fossil fuels for the two bitumen products.

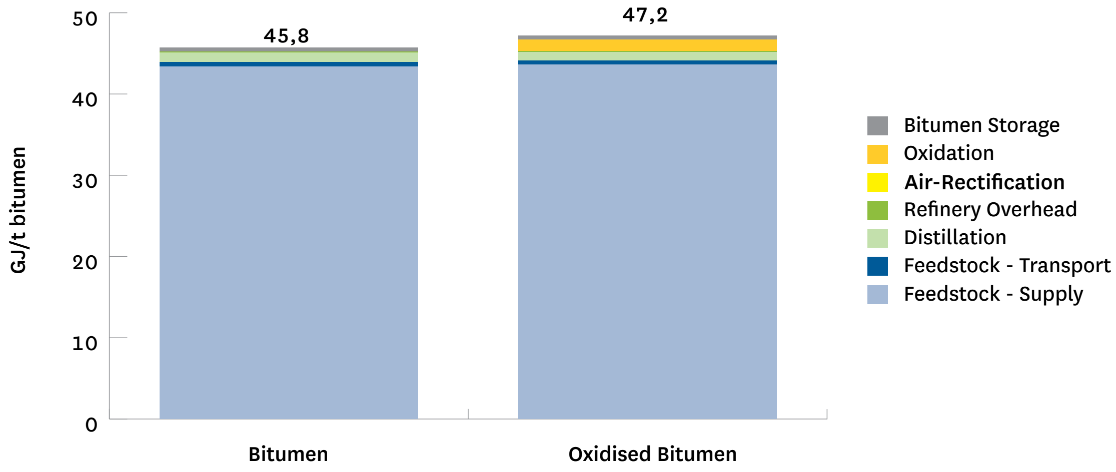

Figure 4-6. Resource use, fossils, for bitumen products

This indicator assesses the potential depletion of natural fossil fuel resources from the production of the bitumen products. As expected, the extraction of crude oil and the supply of other feedstocks is the dominant process contributing to this impact (95 % for bitumen and 92 % for oxidised bitumen). It should be considered that the majority (~38,7 GJ/t of bitumen) of the impact under feedstock supply is actually not burned or finally consumed but stays within the product.

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 bitumen, and Table 4-2 for the oxidised bitumen product. 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 bitumen

EN15804+A2 Impact Indicators (Based on EF 3.1)	**Units**	**Total**	**Feedstock-Supply**	**Feedstock-Transport**	**Distillation**	**Air-Rectification**	**Bitumen Storage**	**Overhead**
Environmental Impact Indicators								
Climate change, total	[kg CO_2 eq.]	5,30E+02	3,73E+02	4,17E+01	7,24E+01	2,67E+00	3,13E+01	9,10E+00
Climate change, fossil	[kg CO_2 eq.]	5,28E+02	3,71E+02	4,17E+01	7,23E+01	2,67E+00	3,14E+01	8,97E+00
Climate change, biogenic	[kg CO_2 eq.]	2,10E+00	2,12E+00	-1,26E-01	1,01E-01	6,00E-03	-1,29E-01	1,27E-01
Climate change, land use and land use change	[kg CO_2 eq.]	2,65E-01	1,02E-01	1,47E-01	1,09E-02	1,59E-04	2,46E-03	2,50E-03
Ozone depletion	[kg CFC-11 eq.]	3,32E-10	4,41E-11	8,09E-12	1,73E-10	7,42E-12	5,58E-11	4,39E-11
Acidification	[Mole of H+ eq.]	1,72E+00	7,87E-01	6,93E-01	1,51E-01	5,32E-03	6,75E-02	1,77E-02
Eutrophication, freshwater	[kg P eq.]	4,45E-04	1,77E-04	4,67E-05	5,83E-05	2,03E-06	2,76E-05	1,33E-04

EN15804+A2 Impact Indicators (Based on EF 3.1)	Units	Total	Feedstock-Supply	Feedstock-Transport	Distillation	Air-Recti-fication	Bitumen Storage	Overhead
Eutrophication, marine	[kg N eq.]	4,44E-01	1,24E-01	3,00E-01	1,08E-02	3,82E-04	5,71E-03	3,05E-03
Eutrophication, terrestrial	[Mole of N eq.]	4,86E+00	1,35E+00	3,29E+00	1,20E-01	4,19E-03	6,42E-02	2,93E-02
Photochemical ozone formation, human health	[kg NMVOC eq.]	2,03E+00	1,04E+00	8,23E-01	1,04E-01	3,60E-03	4,42E-02	1,32E-02
Resource use, mineral and metals	[kg Sb eq.]	1,02E-04	5,59E-05	1,49E-06	7,69E-06	1,16E-07	3,62E-05	4,92E-07
Resource use, fossils	[MJ]	4,58E+04	4,34E+04	5,02E+02	1,17E+03	4,34E+01	5,14E+02	1,24E+02
Water use	[m³ world equiv.]	7,21E+00	1,45E+00	2,45E-01	1,52E+00	6,32E-02	6,17E-01	3,32E+00
Resource use indicators								
Use of renewable primary energy (PERE)	[MJ]	2,34E+02	3,91E+01	1,47E+01	1,11E+02	4,74E+00	4,02E+01	2,41E+01
Renewable primary energy resources used as raw materials (PERM)	[MJ]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	2,00E+00	0,00E+00	1,00E+00
Total use of renewable primary energy resources (PERT)	[MJ]	2,34E+02	3,91E+01	1,47E+01	1,11E+02	4,74E+00	4,02E+01	2,41E+01
Use of non-renewable primary energy (PENRE)	[MJ]	7,06E+03	4,71E+03	5,02E+02	1,17E+03	4,34E+01	5,14E+02	1,24E+02
Non-renewable primary energy resources used as raw material (PENRM)	[MJ]	3,87E+04	3,87E+04	0,00E+00	0,00E+00	2,00E+00	0,00E+00	1,00E+00
Total use of non-renewable primary energy resources (PENRT)	[MJ]	4,58E+04	4,34E+04	5,02E+02	1,17E+03	4,34E+01	5,14E+02	1,24E+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
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
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
Use of net fresh water (FW)	[m3]	6,58E-01	5,72E-02	1,56E-02	7,73E-02	3,25E-03	2,91E-02	4,76E-01
Output flows and waste categories								
Hazardous waste disposed (HWD)	[kg]	2,62E-05	7,48E-07	2,19E-08	2,53E-05	9,56E-09	7,61E-08	5,32E-08
Non-hazardous waste disposed (NHWD)	[kg]	5,40E+00	2,66E+00	5,81E-02	2,41E-01	1,02E-02	1,68E-01	2,26E+00
Radioactive waste disposed (RWD)	[kg]	4,38E-02	7,63E-03	1,28E-03	2,30E-02	9,81E-04	7,37E-03	3,52E-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
Materials for recycling (MFR)	[kg]	1,42E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,42E+00
Materials for energy recovery (MER)	[kg]	7,67E-01	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	7,67E-01
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
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
Biogenic carbon content								

EN15804+A2 Impact Indicators (Based on EF 3.1)	Units	Total	Feedstock-Supply	Feedstock-Transport	Distillation	Air-Recti-fication	Bitumen Storage	Overhead
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
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
Optional indicators								
Particulate matter	[Disease incidences]	2,68E-05	6,82E-06	1,68E-05	2,02E-06	7,08E-08	8,81E-07	2,18E-07
Ionising radiation, human health	[kBq U235 eq.]	7,55E+00	8,17E-01	1,96E-01	4,41E+00	1,89E-01	1,39E+00	5,44E-01
Ecotoxicity, freshwater	[CTUe]	2,85E+04	2,73E+04	3,68E+02	5,96E+02	1,28E+01	1,60E+02	8,73E+01
Human toxicity, cancer	[CTUh]	4,96E-07	4,68E-07	7,12E-09	1,35E-08	3,72E-10	4,72E-09	2,29E-09
Human toxicity, non-cancer	[CTUh]	1,43E-05	1,33E-05	2,40E-07	4,60E-07	1,50E-08	2,35E-07	1,16E-07
Land Use	[Pt]	2,63E+02	5,52E+01	5,95E+01	6,64E+01	2,60E+00	6,38E+01	1,54E+01

Table 4-2. EN 15804+A2 impact indicators for oxidised bitumen

EN15804+A2 Impact Indicators (Based on EF 3.1)	Units	Total	Feedstock-Supply	Feedstock-Transport	Distillation	Bitumen Storage	Oxidation	Overhead
Environmental Impact Indicators								
Climate change, total	[kg CO_2 eq.]	6,16E+02	3,80E+02	4,08E+01	7,08E+01	3,13E+01	8,46E+01	9,10E+00
Climate change, fossil	[kg CO_2 eq.]	6,14E+02	3,77E+02	4,08E+01	7,07E+01	3,14E+01	8,44E+01	8,97E+00
Climate change, biogenic	[kg CO_2 eq.]	2,31E+00	2,16E+00	-1,23E-01	9,92E-02	-1,29E-01	1,74E-01	1,27E-01
Climate change, land use and land use change	[kg CO_2 eq.]	2,68E-01	1,03E-01	1,44E-01	1,06E-02	2,46E-03	5,35E-03	2,50E-03
Ozone depletion	[kg CFC-11 eq.]	5,06E-10	5,01E-11	7,91E-12	1,69E-10	5,58E-11	1,79E-10	4,39E-11
Acidification	[Mole of H+ eq.]	1,90E+00	8,11E-01	6,77E-01	1,48E-01	6,75E-02	1,82E-01	1,77E-02
Eutrophication, freshwater	[kg P eq.]	5,13E-04	1,93E-04	4,57E-05	5,70E-05	2,76E-05	5,62E-05	1,33E-04
Eutrophication, marine	[kg N eq.]	4,55E-01	1,30E-01	2,93E-01	1,06E-02	5,71E-03	1,23E-02	3,05E-03
Eutrophication, terrestrial	[Mole of N eq.]	4,98E+00	1,42E+00	3,21E+00	1,17E-01	6,42E-02	1,36E-01	2,93E-02
Photochemical ozone formation, human health	[kg NMVOC eq.]	2,15E+00	1,07E+00	8,04E-01	1,02E-01	4,42E-02	1,16E-01	1,32E-02
Resource use, mineral and metals	[kg Sb eq.]	1,08E-04	5,67E-05	1,46E-06	7,52E-06	3,62E-05	5,11E-06	4,92E-07
Resource use, fossils	[MJ]	4,72E+04	4,36E+04	4,90E+02	1,14E+03	5,14E+02	1,38E+03	1,24E+02
Water use	[m^3 world equiv.]	8,89E+00	1,58E+00	2,40E-01	1,49E+00	6,17E-01	1,65E+00	3,32E+00
Resource use indicators								
Use of renewable primary energy (PERE)	[MJ]	3,46E+02	4,35E+01	1,43E+01	1,09E+02	4,02E+01	1,15E+02	2,41E+01
Renewable primary energy resources used as raw materials (PERM)	[MJ]	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Total use of renewable primary energy resources (PERT)	[MJ]	3,46E+02	4,35E+01	1,43E+01	1,09E+02	4,02E+01	1,15E+02	2,41E+01

EN15804+A2 Impact Indicators (Based on EF 3.1)	Units	Total	Feedstock-Supply	Feedstock-Transport	Distillation	Bitumen Storage	Oxidation	Overhead
Use of non-renewable primary energy (PENRE)	[MJ]	8,51E+03	4,86E+03	4,90E+02	1,14E+03	5,14E+02	1,38E+03	1,24E+02
Non-renewable primary energy resources used as raw material (PENRM)	[MJ]	3,87E+04	3,87E+04	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00
Total use of non-renewable primary energy resources (PENRT)	[MJ]	4,72E+04	4,36E+04	4,90E+02	1,14E+03	5,14E+02	1,38E+03	1,24E+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
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
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
Use of net fresh water (FW)	[m3]	7,39E-01	6,24E-02	1,52E-02	7,56E-02	2,91E-02	8,16E-02	4,76E-01
Output flows and waste categories								
Hazardous waste disposed (HWD)	[kg]	2,59E-05	7,66E-07	2,14E-08	2,48E-05	7,61E-08	2,37E-07	5,32E-08
Non-hazardous waste disposed (NHWD)	[kg]	9,40E+00	2,71E+00	5,68E-02	2,36E-01	1,68E-01	3,97E+00	2,26E+00
Radioactive waste disposed (RWD)	[kg]	6,71E-02	8,70E-03	1,25E-03	2,25E-02	7,37E-03	2,38E-02	3,52E-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
Materials for recycling (MFR)	[kg]	1,42E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	1,42E+00
Materials for energy recovery (MER)	[kg]	7,67E-01	0,00E+00	0,00E+00	0,00E+00	0,00E+00	0,00E+00	7,67E-01
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
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
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
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
Optional indicators								
Particulate matter	[Disease incidences]	2,91E-05	7,18E-06	1,64E-05	1,98E-06	8,81E-07	2,36E-06	2,18E-07
Ionising radiation, human health	[kBq U235 eq.]	1,20E+01	9,69E-01	1,91E-01	4,31E+00	1,39E+00	4,54E+00	5,44E-01
Ecotoxicity, freshwater	[CTUe]	2,90E+04	2,75E+04	3,60E+02	5,82E+02	1,60E+02	3,21E+02	8,73E+01
Human toxicity, cancer	[CTUh]	5,10E-07	4,73E-07	6,97E-09	1,32E-08	4,72E-09	1,02E-08	2,29E-09
Human toxicity, non-cancer	[CTUh]	1,49E-05	1,34E-05	2,34E-07	4,50E-07	2,35E-07	4,68E-07	1,16E-07
Land Use	[Pt]	3,24E+02	5,78E+01	5,82E+01	6,49E+01	6,38E+01	6,34E+01	1,54E+01

4.2 Sensitivity Analysis

4.2.1 Feedstock supply

To better understand the impact that possible changes in the average feedstock supply mix might have on the environmental burdens associated with the production of bitumen products, a sensitivity analysis was performed in which the baseline 3-year average feedstock was compared with (a) a 5-year average 2019-2023, and (b) with the 2023 average feedstock supply basket. This especially reflects the changes undergone by the feedstock supply mix of European refineries due to the sanctions imposed on Russian crude oil imports starting in June 2022, as discussed in section 3.3.1. Table 3-1 in Section 3.3.1 provides an overview of the origins of the different crude oil supply mixes for the different time periods evaluated. Figure 4-7 presents the results of the sensitivity analysis for the different bitumen products.

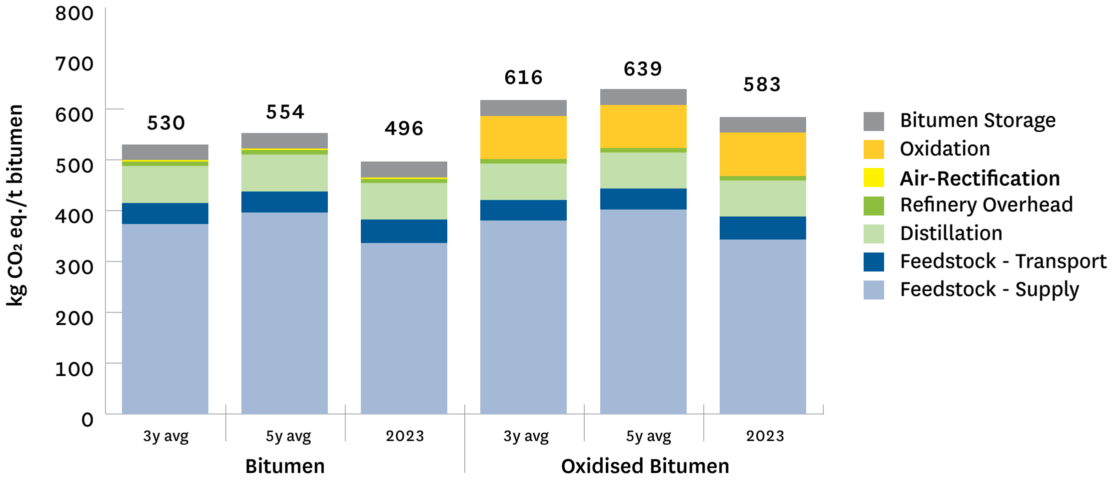

Figure 4-7. GWP$_{100}$ for bitumen products with different feedstock supplies

For the two bitumen products, GWP$_{100}$ increases, on average, 5 % with respect to the 3-year average baseline when the crude oil mix supply for the representative refinery is averaged over the 5-year period 2019-2023. However, when the crude oil supply mix is averaged only over the year 2023, GWP$_{100}$ decreases, on average, 6 % with respect to the baseline 3-year feedstock supply.

The decrease in GWP$_{100}$ for the bitumen products when applying the 2023 feedstock mix compared to the 3-year average is related to the substitution of Russian oil with crude oil mainly from the Middle East and North America. The range of GWP$_{100}$ impacts from country-specific crude oil production is wide, mainly related to venting, flaring and fugitive (VFF) emissions. Particularly, the amounts of flared and vented associated gas, and fugitive methane emissions from the equipment used to produce and transport well fluids and crude oil, can be quite different across countries of crude oil origin. The data basis for the VFF emissions in the MLC database is the IEA Global Methane Tracker [33].

Changes in GWP$_{100}$ of the refined bitumen products when using different time periods for averaging the feedstock supply presented in Figure 4-7 are mostly related to the substitution of Russian crude oil. The GWP$_{100}$ of Russian crude oil (485 kg CO$_2$ eq./t of crude) in the MLC databases is above the calculated GWP$_{100}$ for the 3-year average feedstock supply (386 kg CO$_2$ eq./t of crude). The Russian crude oil is mostly substituted with crude oil from the Middle East and from North America with lower carbon intensity than the Russian crude oil (USA: 347 kg CO_2 eq./t crude, Saudi-Arabia: 196 kg CO_2 eq./t crude). As a consequence, the GWP_{100} for the bitumen products using the 2023 feedstock mix is ~6 % lower. The carbon intensities or GWP_{100} values of individual countries of crude oil origin have been cross-checked with data published in 'Global carbon intensity of crude oil production' by Masnadi et. Al [34] and are quite comparable. The use of the GWP_{100} values calculated in Masnadi et al. instead of the LCI data from Sphera's MLC database to recalculate the GWP_{100} of the average feedstock supply mix would reduce the impact for the 3-year average feedstock supply mix by 7 %. The 2023 feedstock supply mix would be 4 % lower and the 5-year average feedstock supply would be 9 % lower. Overall, the usage of the Masnadi GWP values for crude oil, published already in 2018, would only slightly change the GWP results of the bitumen products (~4,7 % for bitumen using the 3-year average feedstock supply and 2,9 % for the bitumen using the 2023 feedstock supply mix).

The calculation or measurement of VFF emissions is affected by uncertainty, regardless of if a bottom-up approach with emission factors and equipment count is used, a top-down approach with satellite-based measurement, or if a hybrid approach is taken where both approaches are used. Therefore, an update of this study with the updated cycle already adopted by Eurobitume is important to cover possible improvements, especially regarding the measurement of methane emissions during crude oil production as well as to take into account possible mitigation measures for VFF emissions. Therefore, it will be of interest to understand the potential implications of the 'EU Regulation to reduce methane emissions in the energy sector' [35] on data availability and methane emissions.

It should be also noted that refineries are usually adapted to very specific crude slates. A change in the crude supply for the European refineries in such a relatively short time frame as documented in Table 3-1 must be seen as a very special occasion. The theoretical use of single crude oil origins, e.g., with a very low or very high specific GWP_{100} impact, is technically and in regard to availability, not possible. Consequently, a feedstock supply scenario with a single crude oil origin is not further investigated.

4.4.2 Approach for Multifunctionality of Distillation Process

Within the system boundary, the refinery's atmospheric and vacuum distillation units are multioutput processes that produce a significant number of petroleum fractions, each of them with a different functionality.

The baseline scenario approaches the multifunctionality issue through the application of allocation by energy content. In this approach, the environmental burden of the distillation processes is partitioned according to the energy content of the coproducts. This approach is favoured by the idea that higher energy content products are valued more because they represent a greater proportion of the energy originally contained in the crude oil. However, allocation by energy is only one of the different lenses through which multifunctionality can be addressed.

As a second sensitivity analysis, the approach to address multifunctionality was varied to evaluate the magnitude of the associated variations in GWP_{100}. The alternative multifunctionality approaches are (a) allocation by mass and (b) a thermodynamic model based on the calculation of the sensible heat required to refine bitumen, which is further explained in the following section.

Sensible Heat Method

Throughout the atmospheric and vacuum fractionation processes, the fraction of crude oil corresponding to refined bitumen remains in the liquid phase and does not change state, allowing for its enthalpies of vaporisation and condensation to be disregarded. This assumption allows a simplified thermodynamic calculation approach to estimate the energy required in the production of vacuum residue/bitumen, i.e. the sensible heat required to raise the temperature of the bitumen fraction within the crude oil from the initial crude oil temperature to the final storage temperature of bitumen. Using the specific heat capacity of bitumen (2100 J/kg K) and the overall temperature change from crude oil (~30°C) to bitumen storage (~170°C), the calculation of the sensible heat is as follows:

$$Q = m \cdot C \cdot \Delta T$$

$$Q = [1000\ kg\ bitumen] \left[\frac{0{,}0021\ \mathrm{MJ}}{kg\ bitumen\ K}\right] [140\ K] \tag{2}$$

Primary data was used to estimate the overall temperature change following the data collection procedure described in Section 3.1, while the specific heat capacity of bitumen is consistent with Eurobitume's previous LCI study [6] and taken from 'The Shell Bitumen Handbook' [36]. The calculated energy consumption is 294 MJ/t of bitumen. Based on the calculated energy consumption, a fuel consumption of 342 MJ/t of bitumen has been calculated applying an average efficiency of the furnaces of 86 % across all included refineries. The fuel mix has been calculated based on the provided primary data for the distillation units, which is 78,37 % refinery gas, 17,56 % natural gas and 4,07 % fuel oil. As the calculated sensible heat covers only the energy to increase the temperature of crude oil to the storage temperature of bitumen, the electricity consumption of the distillation from the averaged collected primary data has been added applying a mass allocation, which is 150 MJ electricity per tonne of bitumen.

The feedstock input has been calculated based on an average distillation yield of 99,3 % obtained from the data collection of the included refineries. Applying a mass allocation for the feedstock supply results in 1 007 kg of feedstock demand per t of bitumen. Table 4-3 summarises the feedstock and energy inputs per ton of bitumen applying the different approaches.

Table 4-3. Feedstock and energy input per ton of bitumen

Inputs per t of bitumen	Allocation by		Sensible Heat Method
	Energy	Mass	
Feedstock input [kg]	966	1 007	1007
Electricity [MJ]	146	150	150
Steam [MJ]	128	133	0
Natural gas [MJ]	112	114	60
Refinery gas [MJ]	494	509	268
Light fuel oil [MJ]	27	26	14

MLC background datasets (fuel supply) and emission profile for the combustion of the used fuels is the same as for the baseline scenario described under 3.3.3. Figure 4-8 presents the results of the sensitivity analysis when the multifunctionality approach is varied.

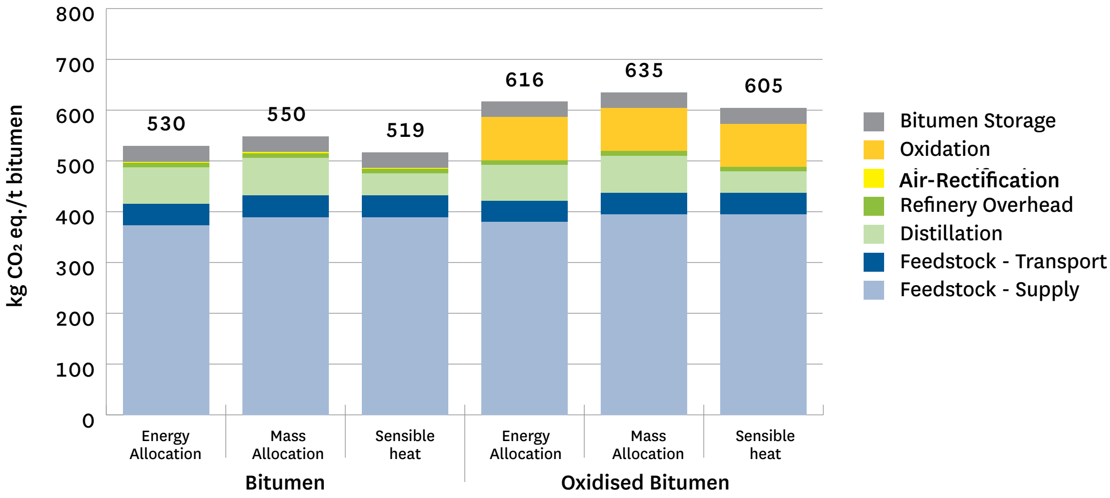

Figure 4-8. GWP$_{100}$ (AR6) of bitumen products varying multifunctionality approach

The GWP$_{100}$ of the evaluated refined bitumen products increases, on average, 3-4 % with respect to the baseline results when allocation by mass is applied. Considering the uncertainty inherently involved in LCA's allocation approaches, the marginal variation in GWP$_{100}$ is of low significance. On the other hand, the GWP$_{100}$ of the refined bitumen products decreases by 2 % (on average) with respect to baseline results when the sensible heat method is applied as a way of avoiding allocation.

4.2.3 Infrastructure

Infrastructure or capital goods are often excluded in LCAs due to their mostly low influence. In addition, existing product category rules (PCR) for bitumen applications usually exclude infrastructure from the system boundaries (compare e.g., the 'PCR for asphalt mixtures' of the National Asphalt Pavement Association [37] or the 'Guidance Document for preparing PCR and EPD for asphalt mixtures' of the European Asphalt Pavement Association [26]). Nonetheless, to get a better understanding of the possible influence of the infrastructure, a sensitivity analysis has been performed including as much as possible of the infrastructure for the bitumen production. The infrastructure for the crude oil production is included in the used MLC datasets for the crude oil supply. For the feedstock transport by pipeline and oil tanker as well as for the refinery dedicated infrastructure models have been set-up for this study.

Pipeline

The material composition for the pipeline as well as auxiliary materials and diesel consumption of the construction machines per km have been taken from [38]. An average pipeline infrastructure of 4,2E-6 m (32 inch) to transport one tonne-kilometre of crude oil has been calculated for Europe and used for all pipeline transports in the feedstock supply.

The following data and assumptions have been used:

- Length of European crude oil pipeline network 9 800 km [39]
- Crude oil pumped in 2023: 309 million t of crude [39]
- Average distance of transported crude: 250 km [40]

Oil Tanker

The empty ship weight has been calculated based on 106 000 deadweight tonnes of the assumed ship and a deadweight tonne coefficient of 0,83 which results in an empty ship weight of 21 700 t. The material composition of the oil tanker has been taken from [41], energy and auxiliary consumption from [42]. The following assumption have been used to calculate the amount of crude oil / heavy fuel oil the ship can transport over its lifetime:

- Lifetime: 30 a
- Speed: 12 knots
- Utilisation of the ship (idling): 85 %
- Time for loading and unloading: 24 h each

Average distances per trip have been taken from Table 3-5.

Refinery

The infrastructure for the refinery has been modelled based on the information given in [43] and [38], resulting in the following material mix per tonne of crude oil feedstock input:

- Unalloyed steel 0,15 kg/t of crude oil
- High alloyed steel 0,012 kg/t of crude oil
- Mineral wool 0,001 kg/t of crude oil
- Concrete 0,033 kg/t of crude oil
- Plastics (PVC) 0,0016 kg/t of crude oil

A list of used LCI data sets for the infrastructure models is given in Annex B.

The following diagram illustrates the relative influence of the added infrastructure (transport and refinery) on the bitumen production (bitumen production excl. infrastructure = 100 %). It should be considered that the relative changes do not include the infrastructure for the crude oil supply, as the infrastructure results for the crude oil supply cannot be separated from the used LCI background data for the feedstock production. For impact category climate change the additional infrastructure increases the GWP_{100} (AR6) result less than 1 %. Also for the other indicators that have been discussed above, is the relative increase by the additional refinery mostly below 1 %, only for eutrophication, freshwater the increase is 2 %. In addition, indicators from the set of core indicators under EN 15804+A2:2019 with higher relative increase have been added. Especially the resource use, mineral and metals indicator shows a significant increase (21 %). It should be noted that this indicator has not been discussed above as bitumen does not contain any feedstocks or additives which are relevant for this indicator, the influence of the additional infrastructure is therefore also more sensitive than for other indicators.

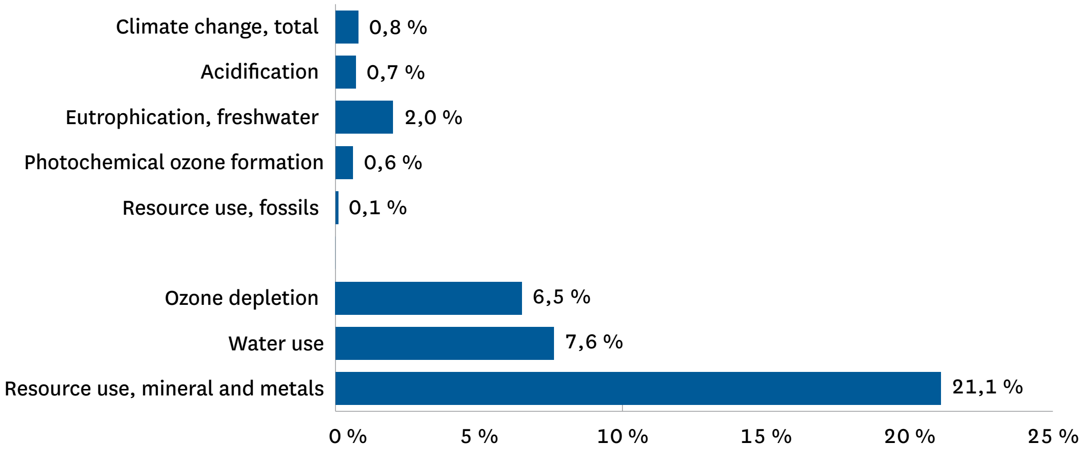

Figure 4-9. Relative influence of infrastructure on bitumen

4.3 Uncertainty Analysis

In general, several levels of uncertainty exist in an LCA study, e.g. uncertainty in the foreground data, in background data and in methodological choices (e.g. allocation, selection of the impact method).

Due to the high relevance of the feedstock supply on the overall LCA results of the bitumen products, possibly higher impacts for the average feedstock supply due to higher impacts in the used LCI background data would have a direct effect on the results. In Figure 4-10 the impacts of the 3-year average feedstock supply have been varied by ±20 % for the impact categories climate change, acidification, eutrophication (freshwater) and photochemical ozone formation to understand the impact on the overall results. Especially for GWP changes in the background data of the feedstock supply would have direct and important effect on the overall impacts of the bitumen. A ±20 % increase in GWP_{100} impacts for the feedstock supply would results in a 14 % increase or decrease in overall GWP_{100} for the bitumen. Relevance for oxidised bitumen is slightly lower due to the higher overall impacts of the bitumen. For the other included impact categories, the uncertainty in the background data would have a less important influence on the overall results (≤10 %).

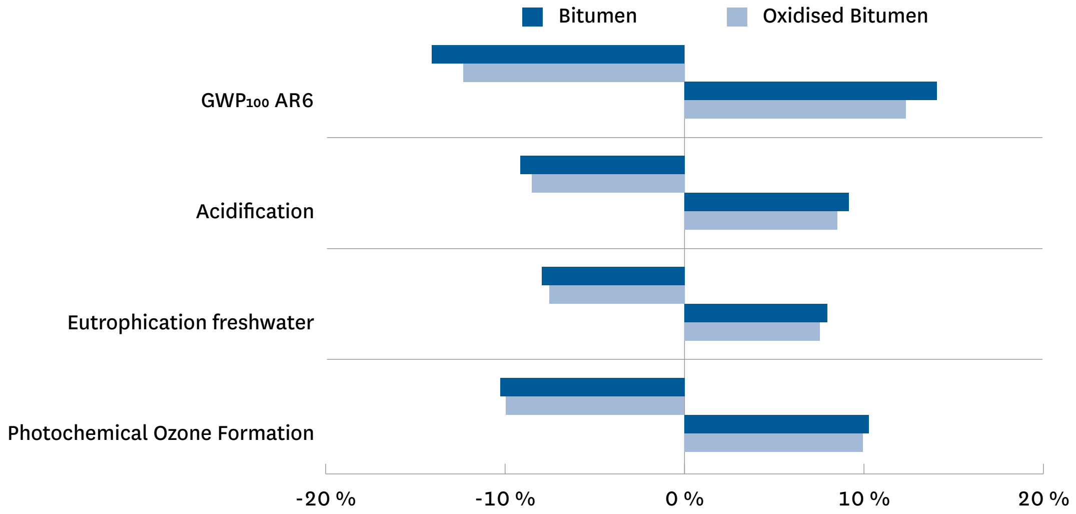

Figure 4-10. Influence of uncertainty in crude background data on overall results

A similar uncertainty analysis has been done to understand the influence of shorter or longer transport distances for the feedstock supply. Although for most crude oil origins the logistics are well defined and transport distances can be determined with precision, geopolitical events, natural disasters, accidents or droughts with an effect on the Suez and Panama Canal, detours due to market situations or pipeline closures might lead to longer transport distances in reality. To get a better understanding of the possible uncertainty in transport distances, the transport distances for the 3-year average feedstock supply presented in Table 3-2 have been increased and decreased by 20 %, resulting in the distances below in Table 4-4.

Table 4-4. Transport distances for uncertainty analysis

Origin of crude oil	Pipeline (oilfield to terminal/refinery) [km]	Oil tanker (export terminal to import terminal/refinery) [km]	Pipeline (import terminal to refinery) [km]
Baseline (3-year average)	780	4 550	50
+20 %	940	5 460	60
-20 %	620	3 640	40

The illustration of the uncertainty analysis in Figure 4-11 reveals that the GWP_{100} indicators is affected only little by the ±20 % variation of the transport distances (maximum variation is ±2 %). In contrast, the indicators acidification and photochemical ozone formation are more sensible for higher or lower transport distances mainly due to the NOX emissions and partly due to SO_2 emissions (sulphur content in the fuel oil of the oil tanker is 0,5 %) caused by the combustion of fuel oil in the ship engines, as well as the supply of electricity.

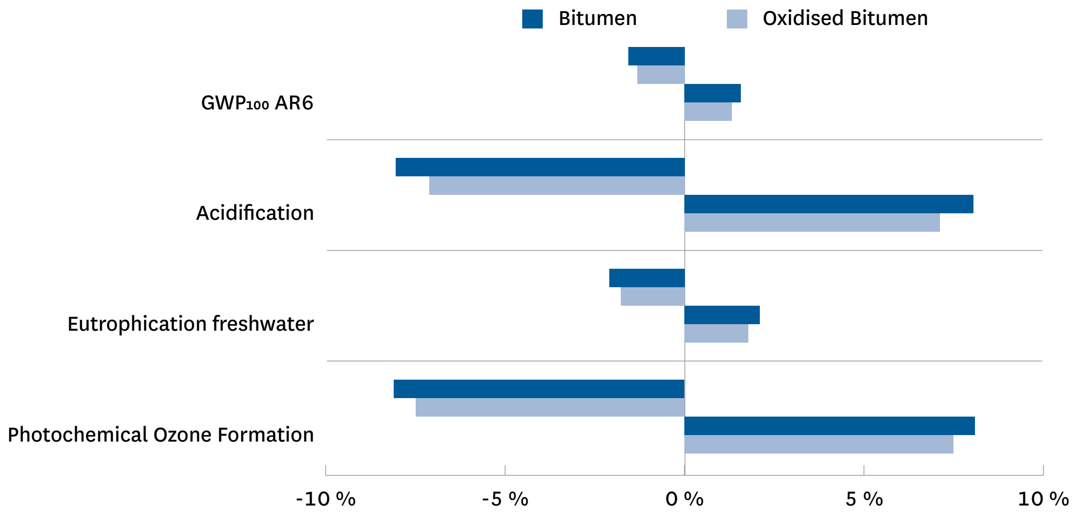

Figure 4-11. Influence of uncertainty in transport distances on overall results

Finally, the exergy value for steam used in the allocation of the refinery's CHP plant has been increased by 20 % from 0,33 MJ to 0,4 MJ to understand the influence and possible uncertainty of the assumption on the overall environmental impacts of the bitumen. The results are illustrated in Figure 4-12. The 20 % higher exergy value for steam results in a 0,4 % higher overall GWP_{100} (AR6) value for bitumen. For oxidised bitumen the GWP_{100} increases by 0,9 %, due to the distinct higher steam demand in the oxidation process. The influence on other impact categories is less relevant.

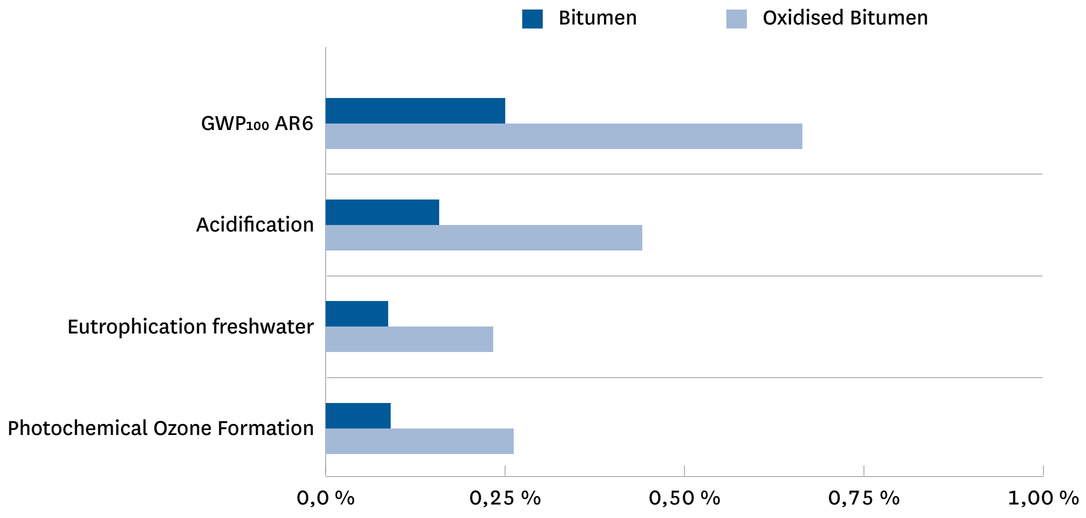

Figure 4-12. Influence of steam exergy on overall results

5. Interpretation

5.1 Identification of Relevant Findings

The present LCA study has developed life cycle inventory data and life cycle environmental impact results on the cradle-to-gate production of bitumen, and oxidised bitumen representative of the production of Eurobitume's members in the European Union and UK. To this end, primary data was collected from 17 refineries within the region, covering ~76 % of the total bitumen production by Eurobitume member refineries. An LCA model was created using the collected primary data alongside background datasets in Sphera's LCA FE software system for life cycle engineering that calculated the potential environmental impact results for each bitumen product. 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).

GWP_{100} impact (excluding climate carbon feedback, including biogenic carbon and calculated according to IPCC's AR6 methodology) for bitumen is 530 kg CO_2 eq./t bitumen. GWP_{100} for the same product but calculated according to IPCC's AR5 characterisation factors is 531 kg CO_2 eq./t bitumen. The major contributor to GWP_{100} impact is the supply of crude oil (70 % contribution), dominated by methane emissions (61 %). There is a significant increase in GWP_{100} for bitumen with respect to Eurobitume's previous study 'LCI for Bitumen 3.1' [6], which calculated a GWP_{100} impact of 216 kg CO_2 eq./t bitumen, considering IPCC's AR5 characterisation factors. The 145 % increase in GWP_{100} is related to a change in the background data used to calculate the environmental impact of the crude oil supply.

In Eurobitume's previous 'LCI for Bitumen 3.1' report, IOGP inventory data was used for energy supply, venting, flaring and fugitive emissions of crude production in various regions, in combination with LCI background data. The observation has been made that the calculated environmental impacts for crude supply in the previous report have been underestimated, especially methane emissions from crude oil production.

The present study updates upon its predecessor by using Sphera's MLC country-specific databases for crude oil extraction technologies, which in turn use data from the IEA Global Methane Tracker [33] to estimate the methane emissions of crude oil production. When benchmarking the GWP_{100} impacts from Sphera's MLC crude oil supply datasets against those from other credible literature sources, e.g., Masnadi et al [34], the environmental impacts for crude oil extraction are consistent.

The collection of primary data from Eurobitume's member refineries instead of using theoretical thermodynamic models or assumptions have also resulted in an increased energy consumption for some refinery units (with respect to previous versions of the report), e.g., distillation and bitumen storage, but has also increased the reliability of results. While the increased energy demand also factors in the aforementioned GWP_{100} increment with respect to Eurobitume's previous study 'LCI for Bitumen 3.1,' at the same time sourcing energy use calculations on primary data improves upon the reliability and accuracy of the study's results.

The collected data also revealed the impact of geopolitical conflicts on the environmental profile of refined bitumen products. Given the relevance of the crude oil supply operations for refined bitumen's GWP_{100}, changes in this supply chain are clearly reflected in refined bitumen's GWP metrics. For example, through sensitivity analysis was shown how the import ban on Russian crude oil to the European Union, starting in June 2022, resulted in a 6 % decrease in bitumen's $GWP_{100}$when applying the 2023 feedstock supply compared to the 3-year average feedstock supply (due to substitution with crudes with lower carbon intensity).

The assessment of the environmental impacts of oxidised bitumen products is also a novel addition to this report. Oxidation adds 86 kg CO_2 eq. /t of bitumen calculated according to IPCC's AR6 methodology. Therefore, the GWP_{100} of oxidised bitumen products is 616 kg CO_2 eq. /t of bitumen

Results of other environmental impact indicators are consistent with Eurobitume's previous study 'LCI for Bitumen 3.1'. Acidification potential is mainly caused by crude oil supply operations (46 % for bitumen, and 42 % for oxidised bitumen) and its subsequent transportation to the refinery (40 %, and 35 %, respectively). Freshwater eutrophication potential is mainly driven by the NO_x, ammonia, nitrates, and other emissions from crude oil supply (40 % for bitumen, and 38 % for oxidised bitumen) and from refinery overhead operations (29 %, and 25 %, respectively). In terms of photochemical ozone formation potential, the relevance of the refinery is rather low, since NMVOC emissions from crude supply (51 % for bitumen, and 50 % for oxidised bitumen) and NO_x emissions from feedstock transportation (40 %, and 37 %, respectively) are the main contributors. Finally, the use of fossil fuel resources is dominated by the feedstock (95 % bitumen, and 92 % for oxidised bitumen).

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

This study has been carried out on behalf of Eurobitume with the goal of understanding the potential environmental impacts of bitumen, and oxidised bitumen representative of the production of Eurobitume's members in the European Union and UK. The results from this analysis are specifically representative of the two aforementioned products and are not intended to be applied to other bitumen-derived products, other product specifications, other geographical regions, and/or assemble of refineries. 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 focused on the recent historical data of the feedstock supply basket of the refineries and their bitumen-related process operating conditions, and input and output data. Primary data collected for the 3-year and 5-year average feedstock supply mix refer to the period 2021-2023 and 2019-2023, respectively, while data collected for specific refinery units is referenced to the year 2023. Not all data requested was available for all refineries, and for some processes (e.g., specific types of emissions of the refinery) data was rather scarce, imposing limitations in the use of some of the results (e.g., toxicity indicators). This also applies for other environmental impact indicators, e.g., ozone depletion potential or water scarcity, for which limitations in the background data increase uncertainty of the results. Another example of data scarcity is that corresponding to energy flows like steam, supply of heat, and heat recovery via refinery network, which could not be collected and analysed for the entire refinery. On the other hand, 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. In the specific case of waste flows, information about the type and treatment of wastes was rather limited. Finally, other sources of uncertainty are related to the crude oil data being based on overall country data and not being specific to the countries' crudes used for bitumen production. Moreover, the challenges and complexities of collecting and assessing data from complex refineries that are very different from each other rises additional sources of uncertainty.

With regards to energy data, some inaccuracies may occur, e.g., in cases when recovered energy is used in a different refinery unit and the recovered energy is not considered in the relevant units (heat output and credit for the unit in which the heat is recovered and heat input with impact for the unit in which it is used).Additionally, since the modelling of the entire refinery is not within the scope of this study, the supply of internally generated fuels, e.g., refinery gas, is modelled using MLC background databases that are not necessarily specific to the refineries participating in this study. In terms of energy consumption of overhead operations, no primary data was available and therefore expert judgement of Eurobitume members was employed to approximate it.

Impacts from infrastructure have been analysed in a sensitivity analysis; however, assumptions needed to be done with regards to infrastructure utilisation given the limited availability of data.

Methane emissions are significant contributors to the GWP_{100} of crude oil supply and its modelling is subject to uncertainty. The LCA model uses country-specific average crude oil production background datasets that might smooth methane emissions data peaks from crude extraction operations. The use of more specific field-level methane emissions models/datasets may impact GWP_{100} results in any direction.

System boundaries of the study are cradle-to-refinery gate. Storage of bitumen outside the refinery is not included and the collected data and calculated impact is specific for this study and is not necessarily representative for any other bitumen storage outside the refinery due to different tank size, throughput etc.

5.3 Results of Sensitivity, and Uncertainty Analysis

5.3.1 Sensitivity Analysis

Feedstock supply

A sensitivity analysis was performed in which the baseline 3-year average feedstock was compared with (a) a 5-year average 2019-2023, and (b) with the 2023 average crude oil supply basket. For the two bitumen products, GWP_{100} increases, on average, 4 % with respect to the 3-year average baseline when the crude oil mix supply is averaged over the 5-year period 2019-2023. In general, extending the time period of the assessment compensates for possible fluctuations within the feedstock supply mix which might be not representative for a longer term. On the other hand, when the feedstock supply mix is averaged over the year 2023, GWP_{100} of the refined bitumen products decreases, on average, 6 % with respect to the baseline 3-year feedstock supply. This analysis shows the impact on refined bitumen's GWP_{100} of the very strong reduction of Russian crude oil imports to the EU/UK region since June 2022. The impact is especially highlighted as the refineries included in the study do not import Russian crude oil anymore after 2022 and have substituted it with crude oils mainly from the Middle East and North America. As discussed in this study, the GWP_{100} impact of crude oil supply varies significantly depending on the country of origin.. Additionally, changes in the crude oil supply of the refineries also have an impact on the type of crude oil transport required.

Allocation vs. Sensible Heat Method

A second sensitivity analysis was performed to evaluate the impact of the different multifunctionality approaches on the refined bitumen products GWP_{100}. When allocation by mass was applied, the GWP_{100} of the refined bitumen products increased, on average, 3 % with respect to the baseline results (allocation by energy content). When the sensible heat method was applied as an alternative approach to multifunctionality and to allocation, the GWP_{100} of the refined bitumen products decreased by 2 % (on average) with respect to baseline results (energy-based allocation). The sensible heat method was used in version 3.1 of the Eurobitume LCI for bitumen with distinct lower impacts for the distillation process. In contrast to version 3.1, electricity consumption of the distillation units has been accounted for in the present study to make the approach more complete. Although the multifunctionality approach that uses primary data and energy content-based allocation have been judged as more precise and has been chosen as baseline approach to overcome the limitations of the previous report, the sensible heat method still is an interesting approach with a different angle on the impact assessment of the bitumen.

5.3.2 Uncertainty Analysis

Several analyses have been done to better understand the impact of possible uncertainty in background and foreground data as well as in the applied methodology.

Due to the high relevance of the feedstock supply on the LCA results of the bitumen products a possible underestimation or overestimation of impacts in the LCI background data of crude oil production would have an almost direct impact on the LCA results of the bitumen. An additional uncertainty regarding the crude oil data is related to it being based on average country data and not specific to the countries' crudes used for bitumen production.

Uncertainty in the calculated transport distances for the refinery feedstock would be of minor importance for the GWP_{100} indicators, for the acidification and photochemical ozone formation the relevance would be higher.

5.4 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 were used. The LCI datasets from Sphera's MLC v. 2024.1 database are widely distributed and used with Sphera's LCA For Expert (LCA FE) software. The datasets have been used in LCA models worldwide in industrial and scientific applications in internal as well as in many critically reviewed and published studies. In the process of providing these datasets they are cross-checked with other databases and values from industry and science. The data quality assessment and rating were conducted based on the European Commission's ILCD handbook on LCA [3]. Table 5-1 gives an overview of the different quality levels and ratings and their definition.

Table 5-1. Definition of quality levels and ratings for the data quality indicators

Quality level	Quality rating	Definition
Very good	1	'Meets the criterion to a very high degree, having no relevant need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to a hypothetical ideal data quality.'
Good	2	'Meets the criterion to a high degree, having little yet significant need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to a hypothetical ideal data quality.'
Fair	3	'Meets the criterion to a still sufficient degree, while having the need for improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to a hypothetical ideal data quality. '
Poor	4	'Does not meet the criterion to a sufficient degree, having the need for relevant improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to a hypothetical ideal data quality.'
Very poor	5	'Does not at all meet the criterion, having the need for very substantial improvement. This is to be judged in view of the criterion's contribution to the data set's potential overall environmental impact and in comparison to a hypothetical ideal data quality.'

5.4.1 Precision and Completeness

- ✓ **Precision:** Measured primary data are considered to be of the highest precision, followed by calculated data, literature data and estimated data. 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, precision is considered to be high. The data collection has been designed especially for the goal and scope of the study. Seasonal variations in refinery operations and variations across different refineries were balanced out by using yearly and weighted averages. All background data were sourced from Sphera's MLC with the documented precision (please see section 3.4 for information about the background data). Achieved data quality level (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 (rating): good (2).

5.4.2 Consistency and Reproducibility

- ✓ **Consistency:** To ensure data consistency, all primary data were collected with the same level of detail, while all background data were sourced from Sphera's MLC. Additional secondary sources have been used to set up infrastructure models, using the same LCI background data source as for the rest of the model. Achieved data quality level and 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, a disclosure of the country specific feedstock supply is not possible.

5.4.3 Representativeness

- ✓ **Temporal:** For the refinery specific feedstock supply crude oil by country-of-origin data were collected for the years 2019 to 2023 to be able to analyse and understand the usage of different time periods or reference years on the overall LCA results. Primary data for the refinery units 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 for information about the 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 (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. Proxy data for the crude oil supply has been used for around 1 % of the crude supply, for HFO the European (RER) dataset has been used for all EU countries. Geographical representativeness is considered to be very high with regard to the goal and scope of this study. Achieved data quality level (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.

5.4.4 Overall data quality

Based on 'formula 3' (provided in Figure 5-1) and the definition of the overall data quality ratings (provided in Table 5-2) of section '12 Annex A: Data quality concept and approach' of the European Commission's ILCD handbook on LCA [3], the overall data quality rating (DQR) was calculated and is presented in Table 5-3.

$$DQR = \frac{TeR + GR + TiR + C + P + M + X_w * 4}{i + 4}$$

DQR = Data Quality Rating
TeR, GR, TiR, C, P, M: Please see Table 5-3
X_w *= Weakest quality level obtained (i.e. highest numeric value) among the data quality indicators*
i = Number of data quality indicators

Figure 5-1. Formula for the calculation of the overall data quality rating

Table 5-2. Overall data quality definition (JRC, 2010)

Overall data quality rating (DQR)	Overall data quality level
≤1,6	'High quality'
>1,6 to ≤3	'Basic quality'
>3 to ≤4	'Data estimate'

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

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

5.5 Model Completeness and Consistency

5.5.1 Completeness

All relevant process steps for each product system were considered and modelled to represent each specific situation. The process chain is considered sufficiently complete and detailed with regards to the goal and scope of this study.

5.5.2 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 and with the study's goal and scope. Differences in background data quality were minimised by using LCI data from Sphera's MLC, based on a consistent methodology and set of modelling principles. This approach ensures, as far as possible, that the different product systems are equivalent and that differences in the results reflect actual differences between the product systems and are not due to inconsistencies in modelling choices, data sources, emission factors, or other artefacts.

5.6 Conclusions, Limitations, and Recommendations

5.6.1 Conclusions

An updated LCA study on the production of bitumen and oxidised bitumen products by Eurobitume's member refineries within the EU and the UK was developed to provide LCI data and environmental impact results with improved representativeness.

The present study updates Eurobitume's 2021 LCI report version 3.1 with reviewed data and methodology, aiming to enhance accuracy and reliability of environmental impact results. The main results of this assessment are the update of refined bitumen products' LCI data and life cycle environmental impact results, particularly GWP_{100} and other impact categories required by standard EN 15804+A2:2019 for the development of EPDs. Contribution analysis, sensitivity and uncertainty analyses complemented the assessment.

The collection of representative LCI data for the modelling of bitumen production covered ~76 % of the bitumen produced by Eurobitume members in the EU/UK region. It is important to consider that the bitumen that has not been covered in this study is also produced in refineries using similar set-ups to those of the 17 refineries included in this study, with similar energy consumption and emissions. Therefore, it is not expected that the LCA results for the bitumen not covered in this study would be considerably different. The same holds true for bitumen produced in the EU by companies which are not member of Eurobitume. The study can be therefore considered as a very good approximation for the entire bitumen production in the EU.

Among the most relevant findings was a different magnitude of GWP_{100} for bitumen compared to that of version 3.1, which was related to the background data used in the modelling of the crude oil supply. The assessment of a baseline 3-year average feedstock supply and other time periods in the sensitivity analysis gives good indication of the impact of several possible midterm developments (e.g., ongoing import ban on Russian oil, Russian oil comes back in the supply mix). Key limitations of the previous study (e.g., data for calculation of crude oil impact and almost no primary data involved) have been overcome. Nonetheless, the use of the 3-year average baseline scenario is recommended as a more robust option compared to a single-year feedstock supply scenario. In any specific year, the supply can be influenced by many factors not limited to the question of Russian oil alone, e.g., natural disasters, geopolitical crisis, or a reorganisation in the supply chain of a specific refinery. The use of a baseline scenario using a 3-year average feedstock supply is preferable to avoid the impact of events specific to 2023 and is a more robust reference for the next 3-5 years before the study is potentially updated.

Finally, with the publication of this report, potential users of the LCI or LCIA results for bitumen should use the values of this latest study (version 4.0) in new studies or updates and no longer the results from version 3.1 of Eurobitume’s LCI for bitumen study [6] & [14].

5.6.2 Limitations

The full list of EN 15804+A2:2019 indicators has been provided to allow for producers of bitumen-containing products/services to use the bitumen LCI data as background data in future EPDs, but results of some of these indicators have limitations or higher uncertainty with regard to LCI background data, coverage of emissions in the foreground system, as well as the LCIA methodologies as such, e.g., toxicity indicators or ozone depletion potential.

On the other hand, the life cycle inventories for bitumen and oxidised bitumen have been provided to Eurobitume in ILCD format. Before any use of the data, it should be considered that the study and ILCD datasets have been conducted with EF3.1 flow nomenclature. When using LCIA methodologies other than EF3.1 or an potential update of EF3.1, the interoperability of the flow nomenclature needs to be guaranteed before the usage.

5.6.3 Recommendations

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

- Continue the periodical update of the LCI for bitumen, as it has been performed in the past.
- Provide special consideration to the update of methane emissions in the LCI background data used to calculate the impacts of the feedstock supply as major contributor of the overall GWP_{100}.
- Increase the study’s coverage of European refined bitumen production by adding more refineries to future updates.

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Annex A: Critical Review Statement

Critical Review Report about the LCA report

“The Eurobitume Life Cycle Assessment for Bitumen Version 4.0”

V 4.0.3 dated 22nd of January 2025

ISO 14 040 & ISO 14 044
ISO/TS 14071

SOL 24-476.2

24th of January 2025

v2

for

Eurobitume

1 Introduction

Sphera has prepared a third-party report “The Eurobitume Life Cycle Assessment for Bitumen Version 4.0” dated January 2025, supporting two ILCD datasheets that will be communicated about bitumen and oxidized bitumen production within the EU and the UK produced by Eurobitume’s members.

The goal of the third-party report was to “to provide life cycle inventory data and life cycle environmental impact results on the production of bitumen and oxidized bitumen representative of production within the European Union (EU) and the United Kingdom (UK) produced by Eurobitume’s members.”. This work is an update of previous LCA studies which have also been prepared by Sphera and verified with a critical review (CR).

This current LCA study states that ISO 14040:2006 and ISO 14044:2006 requirements have been applied in order to get reliable and transparent results. Eurobitume has requested a CR expert to conduct a CR of the third-party report (this “third-party report” is called “the LCA report” in the following text).

The present CR report is the “Final CR report”, including the detailed tables prepared by the CR expert. This CR report is dedicated to being integrated, as a whole, within the final LCA report of Eurobitume and Sphera.

2 The CR expert

The CR expert was Philippe Osset, independent from the overall study content, and external to Eurobitume, Sphera and the related business interests. Philippe Osset is Dipl. Eng., CEO of Solinnen, LCA expert and practitioner since 1994 (France). He is mandated expert to represent France at ISO/TC 207/SC 3, SC 5 and SC 7. He has significant experience of the practice of LCA applied to oil and its co-products.

3 Nature of the CR work, CR process and limitations

The CR expert has worked according to the requirements of ISO 14040:2006 and 14044:2006 concerning CR. They have considered ISO/TS 14071 requirements too. Additionally, the expectations of the ILCD data sheets reviews set in the reference report by DG ENV have been applied and reported in the ILCD review template.

According to ISO 14044, the CR process has been undertaken to check if:

- the methods used to carry out the LCA in the LCA report are consistent with ISO 14044 requirements,
- the methods used to carry out the LCA are scientifically and technically valid,
- the data used are appropriate and reasonable in relation to the goal of the study,
- the interpretations reflect the limitations identified in the study and the goal of the study, and
- the study report is transparent and consistent.

The first task of the CR was *to provide Sphera* with detailed comments to allow Sphera to improve its work. These comments have covered methodology choice, data used, results and reporting. The CR expert has checked the *plausibility* of the results through comparisons with existing (past) publications. Additionally, this final CR report *provides the future reader* of the LCA report and user of the LCI with information that will help understand the LCA report, its results, and the LCI data used in this study.

The CR was performed after completion of a draft study. The analysis and the verification of individual datasets were outside the scope of the CR. The CR work started in December 2024 and ended in January 2025. During this period, various oral and written exchanges have been held between the CR expert, Eurobitume and Sphera, including clarification exchanges regarding the CR initial comments, and the production of one set of detailed comments by the CR expert, and a new version of the LCA report (the final LCA report) by Sphera.

The CR expert prepared 50 comments on the LCA report during the various exchanges. They covered the following areas:

- General (10 comments),
- Methodology (9 key comments),
- Technical (5 key comments),
- Data (16 comments),
- Other miscellaneous comment (10 comments).

Sphera has considered the comments and modified and improved their LCA report. This final CR report is the synthesis of the final comments by the reviewers. Selected detailed comments are provided within this final CR report, together with the full detailed exchanges as appendices.

This final CR report is delivered to Eurobitume by the CR expert. The CR expert cannot be held responsible for the use of its work by any third party. The conclusions of the CR expert cover the full LCA report from Eurobitume. They do not cover any other report, summary, extract, extrapolation, or publication which may eventually been done. The

CR expert's conclusions have been made given the current state of the art and the information which has been received for the covered topics in the LCA report. These CR expert conclusions could have been different in a different context.

4 Conclusions of the Review – Critical Review Statement

The CR expert considers that the requirements of the reference standards have been met by the final LCA report and the generation and content of the two ILCD data sheets.

The final LCA report answers the goal which has been set up, within the scope of the limitations that are mentioned in the LCA report, and the detailed CR expert comments which are provided in the next chapter. Improvements have been made to the work, following the recommendations of the previous CR report.

As a reminder, according to ISO 14044, the CR expert warns users that these cradle to gate LCI shall not be compared directly with cradle to gate LCI of other products fulfilling the same function (cf. SOL 20).

5 Detailed comments

The following lines bring some highlights that a reader of the final LCA report may use to assist his reading and understanding of the LCA report. Some CR detailed comments do not appear here. The reading of the detailed comments and answers (see the table in appendices at Chapter 6) is recommended.

5.1 Consistency of methods used with ISO 14044 requirements

The final structure of the LCA report is presented according to the content of the ISO standard requirements. The methods that have been selected for reference calculations are clearly presented.

The content of the LCA report is a cradle to gate report. This approach is adapted to fulfil the goal of the study.

5.2 Scientific and technical validity

The production route of bitumen and oxidized bitumen reflects the current state of the art. The limitations are clearly indicated in the LCA report.

The model used by Sphera has been reviewed and corresponds to what is presented in the LCA report in terms of methodology and values. Horizontal averaging of site data with appropriate weighting has been done before implementation in the "LCA for Experts" software of Sphera to reflect the actual production routes (SOL 32).

The uncertainty analysis chapter presents the appropriate information that LCA practitioners will need when using the Eurobitume data in their LCA.

5.3 Appropriateness of data used in relation to the goal of the study

The list of the 17 European sites which have provided foreground data for bitumen and oxidized bitumen has been made available to the CR expert and is not provided in the LCA report due to confidentiality. Their representativeness is mentioned in the report: it is approximately 76% of volume produced in Europe (SOL 47) by Eurobitume members, and approx. 45% of the whole production. The sensitivity analyses made in the report concluded that the results presented in the report are representative of the whole European production of Eurobitume members, and furthermore the whole European production of bitumen (see chapter 5.6.1 of the LCA report).

The background data used in the report are appropriate to generate the LCI. It can be noted that Sphera will continue to update the background data (SOL 12 and answer), but no significant influence on the LCI is expected in the next years (otherwise, the LCI should be updated).

European averages (RER) have been used as indicated to model LCI of European countries (SOL 18 & 24 and answers). It is a reasonable approach which is commonly used to answer the goal of such study – the use of the average of the specific supply of each site might not have had a significant influence on the results. A more specific approach has been used for fossil feedstock supply (such as "oil") since this choice had an influence.

The quality of data is high and significantly improved as compared to the LCI dated 2021 "The Eurobitume Life-Cycle Inventory for Bitumen" version 3.1.

5.4 Validity of interpretations in the scope of the limitations of the study

An appropriate set of sensitivity analyses has been done to support the conclusions of the study, which are presented together with the limitations born from those sensitivity analyses. The interpretations presented in the LCA report support in an appropriate manner the ILCD format LCI which will be provided by Eurobitume.

5.5 Transparency and consistency

The overall level of transparency and consistency of the LCA report is high, and in line with the ISO 14044:2006 expectations. A (small number) of confidential information has been shared with the CR expert during the CR process.

6 Appendices

The detailed CR tables exchanged during the CR are the appendices of the present CR report. They recap the detailed exchanges between the CR expert, Eurobitume and Sphera.

Annex B: Additional Information

Table B-1. Average transport distances per region / continent (2019-2023)

Origin of crude oil	Pipeline (oilfield to terminal /refinery) [km]	Oil tanker (export terminal to import terminal / refinery) [km]	Pipeline (import terminal to refinery) [km]
Africa	210	5 790	100
Europe	110	380	50
Former Soviet Union (FSU)	3 510	2 770	50
Middle East	530	8 880	70
North America	120	9 190	100
South America	160	8 500	10
Other feedstock (mainly HFO)	0	2 920	0
Total	**970**	**4 330**	**50**

Table B-2. Average transport distances per region / continent (2023)

Origin of crude oil	Pipeline (oilfield to terminal /refinery) [km]	Oil tanker (export terminal to import terminal / refinery) [km]	Pipeline (import terminal to refinery) [km]
Africa	210	5 230	80
Europe	130	540	60
Former Soviet Union (FSU)	1 590	4 990	60
Middle East	540	9 280	60
North America	110	9 060	80
South America	100	8 170	30
Other feedstock (mainly HFO)	0	6 280	0
Total	**320**	**5 830**	**50**

Table B-3. Calculated average emission profile (excl. CO_2) for fuel combustion in refinery

Type	Emission	Value [g/MJ]
Emissions to air	Ammonia	1,80E-04
	Benzene	5,80E-04
	Carbon monoxide (CO)	2,52E-02
	Chloride	7,05E-05
	Cyanide	9,71E-04
	Methane (CH_4)	1,21E-02
	Nitrogen oxides (NO_x)	5,47E-02
	NMVOC	5,65E-02
	Nitrous oxide (N_2O)	1,30E-03
	Particulates ($<PM_{2,5}$)	4,06E-03
	Particulates ($PM_{2,5}$ - PM_{10})	1,14E-03
	Polycyclic aromatic hydrocarbons (PAH)	6,35E-07
	Sulphur dioxide (SO_2)	9,12E-02
	Hydrogen fluoride	4,93E-05

Type	Emission	Value [g/MJ]
Emission to air - Metals	Arsenic (+V)	6,00E-07
	Cadmium (+II)	4,91E-07
	Chromium	9,80E-07
	Cobalt	1,40E-07
	Copper (+II)	1,28E-06
	Lead (+II)	8,47E-07
	Mercury (+II)	1,30E-07
	Nickel (+II)	4,81E-06
	Selenium	6,01E-07
	Vanadium (+III)	1,38E-06
	Zinc (+II)	7,78E-06
Emissions to water*	Absorbable organic halogen compounds (AOX)	3,26E-05
	Chemical oxygen demand (COD)	1,65E-02
	Total organic bounded carbon	1,95E-03
	Chloride	1,86E-01
	Cyanide	9,01E-06
	Fluoride	3,09E-04
	Nitrogen organic bounded	2,73E-03
	Phosphate	9,13E-05
	Sulphate	1,92E-01
	Sulphide	3,30E-05
	PAH	1,80E-07
	Benzene	1,80E-07
	Toluene	1,80E-07
	Xylenes	1,80E-07
	Phenols	1,64E-06
	Benzo(g,h,i)perylene	6,84E-08
	Fluoranthene	5,69E-09
	Metals	
Emissions to water - Metals	Arsenic (+V)	8,60E-07
	Cadmium (+II)	4,77E-08
	Chromium	2,54E-07
	Copper (+II)	1,05E-06
	Iron	5,33E-05
	Lead (+II)	6,90E-07
	Mercury (+II)	5,95E-09
	Nickel (+II)	1,67E-06
	Vanadium (+III)	8,50E-06
	Zinc (+II)	1,22E-05

*Based on location of refineries and bitumen output, 70 % of emission to sea water and 30 % to fresh water.

Table B-4. Key material and process datasets used in inventory analysis

Material/ Process	Country	Dataset	Data Provider	Reference Year	Proxy?
Crude oil mix	United Arab Emirates	AE: Oil Production all Technologies	Sphera	2019	No
	Albania	IT: Oil Production all Technologies	Sphera	2019	Yes
	Algeria	DZ: Oil Production all Technologies	Sphera	2019	No
	Angola	AO: Oil Production all Technologies	Sphera	2019	No
	Argentina	AR: Oil Production all Technologies	Sphera	2019	No
	Austria	AT: Oil Production all Technologies	Sphera	2019	No
	Azerbaijan	AZ: Oil Production all Technologies	Sphera	2019	No
	Brazil	BR: Oil Production all Technologies	Sphera	2019	No
	Cameroon	CM: Oil Production all Technologies	Sphera	2019	No
	Canada	CA: Oil Production all Technologies	Sphera	2019	No
	Cuba	TT: Oil Production all Technologies	Sphera	2019	Yes
	Denmark	DK: Oil Production all Technologies	Sphera	2019	No
	France	FR: Oil Production all Technologies	Sphera	2019	No
	Gabon	GA: Oil Production all Technologies	Sphera	2019	No
	Germany	DE: Oil Production all Technologies	Sphera	2019	No
	Ghana	NG: Oil Production all Technologies	Sphera	2019	Yes
	Guyana	BR: Oil Production all Technologies	Sphera	2019	Yes
	Iraq	IQ: Oil Production all Technologies	Sphera	2019	No
	Israel	EG: Oil Production all Technologies	Sphera	2019	Yes
	Italy	IT: Oil Production all Technologies	Sphera	2019	No
	Kazakhstan	KZ: Oil Production all Technologies	Sphera	2019	No
	Kuwait	KW: Oil Production all Technologies	Sphera	2019	No
	Ivory Coast	NG: Oil Production all Technologies	Sphera	2019	Yes
	Libya	LY: Oil Production all Technologies	Sphera	2019	No
	Mexico	MX: Oil Production all Technologies	Sphera	2019	No
	The Netherlands	NL: Oil Production all Technologies	Sphera	2019	No
	Malaysia	MY: Oil Production all Technologies	Sphera	2019	No
	Nigeria	NG: Oil Production all Technologies	Sphera	2019	No
	Norway	NO: Oil Production all Technologies	Sphera	2019	No
	Oman	OM: Oil Production all Technologies	Sphera	2019	No
	Russia	RU: Oil Production all Technologies	Sphera	2019	No
	Saudi Arabia	SA: Oil Production all Technologies	Sphera	2019	No
	Great Britain	GB: Oil Production all Technologies	Sphera	2019	No
	Tunisia	TN: Oil Production all Technologies	Sphera	2019	No
	USA	US: Oil Production all Technologies	Sphera	2019	No
	Venezuela	VE: Oil Production all Technologies	Sphera	2019	No

Material/ Process	Country	Dataset	Data Provider	Reference Year	Proxy?
Atmospheric residue	Europe	RER: Heavy fuel oil at refinery (2,5wt.% S)	Sphera	2020	Yes
HFO		BR: Heavy fuel oil at refinery (2,5wt.% S)	Sphera	2020	Yes
		RER: Heavy fuel oil at refinery (2,5wt.% S)	Sphera	2020	No
		RU: Heavy fuel oil at refinery (2,5wt.% S)	Sphera	2020	No
		AU: Heavy fuel oil at refinery (2,5wt.% S)	Sphera	2020	Yes
Auxiliaries	Global	Process water from groundwater (for regionalization) - open input electricity and water	Sphera	2020	No
	Global	Process water from surface water (for regionalization) - open inputs electricity and water	Sphera	2020	No
	Global	Tap water from groundwater (for regionalization) - open inputs electricity and water	Sphera	2020	No
	Global	Tap water from surface water (for regionalization) - open input electricity and water	Sphera	2020	No
	Global	Municipal wastewater treatment (sludge 50 % agricultural/50 % incineration, for regionalization)	Sphera	2020	No
	DE	Slag (worst case, vitrification)	Sphera	2020	Yes
	RER	Hazardous waste (statistical average composition) in waste incineration plant	Sphera	2020	Yes
	DE	Slag (best case, inert landfill only)	Sphera	2020	Yes
	DE	Slag (worst case, vitrification)	Sphera	2020	Yes
	RER	Commercial waste in municipal waste incineration plant (0 % H_2O content)	Sphera	2020	Yes
	RER	Inert matter (Unspecific construction waste) on landfill	Sphera	2020	Yes
	RER	Sodium hydroxide (caustic soda) mix (100 %)	Sphera	2020	No
	RER	Water (desalinated; deionised)	Sphera	2020	No
	RER	Zinc stearate (stabilizer, approximation)	Sphera	2020	Yes
	GLO	Antifoaming agent (ethoxylate fatty alcohols)	Sphera	2020	Yes
	RER	Ethylenediaminetetraacetic acid (EDTA) (approximation)	Sphera	2020	Yes
	RER	Wax/Paraffins at refinery	Sphera	2020	No
	RER	Silane (approximation)	Sphera	2020	Yes

Table B-5. Key LCI datasets used for infrastructure models

Material/ Process	Country	Dataset	Data Provider	Reference Year	Proxy?
Material	RER	Steel cold rolled coil (BF route)	Sphera	2023	No
	RER	Stainless Steel - Cold Rolled Coil 1.4057 / X17CrNi16-2 / 431 (80 % Recycled Content)	Sphera	2023	No
	RER	Copper pipe mix, bare (A1-A3)	Sphera	2023	No
	RER	Copper wire (0,6 mm)	Sphera	2023	No
	GLO	Zinc mix	Sphera	2023	No
	RER	Aluminium ingot mix - consumption mix	Sphera	2023	No
	DE	Tin Bronze (CuSn10)	Sphera	2023	No
	RER	Cast iron part	Sphera	2023	No
	DE	Stone wool flat roof plate (100 mm)	Sphera	2023	No
	RER	Solvent paint white (EN 15804 A1-A3)	Sphera	2023	No
	DE	PVC part (injection moulding)	Sphera	2023	No
	RER	Cable 5 wire (EN 15804 A1-A3)	Sphera	2023	No
	RER	Plywood board (EN 15804 A1-A3)	Sphera	2023	No
	RER	Concrete C30/37 (Ready-mix concrete) (EN 15804 A1-A3)	Sphera	2023	No
Manufacturing	DE	Steel sheet deep drawing (adjustable)	Sphera	2023	No
	GLO	Welding seam 1 m (including welding wire)	Sphera	2023	No
	GLO	Steel sheet stamping and bending (5 % loss)	Sphera	2023	No
	RER	Electricity grid mix	Sphera	2020	No
	GLO	Diesel combustion in construction machine (18-36 kW; Stage IIIA)	Sphera	2023	No
	GLO	Steel high-alloyed machining (0,47 kg shavings per 1 kg part)	Sphera	2023	No
Auxiliaries	RER	Sand 0/2	Sphera	2023	No
	DE	Steel wire rod	Sphera	2023	Yes
	RER	Tap water from surface water	Sphera	2023	No
	RER	Polyvinyl chloride (PVC) in waste incineration plant (0 % H_2O content)	Sphera	2023	No
	RER	Inert matter (Unspecific construction waste) on landfill	Sphera	2023	No
	US	Wood product (OSB, particle board) waste in waste incineration plant (7,8 % H_2O content)	Sphera	2023	No
Transport	GLO	Truck-trailer, Euro 6 A-C, 34 - 40 t gross weight/ 27 t payload capacity	Sphera	2023	No
	RER	Diesel mix at filling station	Sphera	2020	No
	GLO	Bulk commodity carrier, average, coastal	Sphera	2023	No
	RER	Light fuel oil at refinery	Sphera	2020	No

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