

thinkstep

Life Cycle Assessment of Asphalt Binder

On behalf of the Asphalt Institute
March 2019



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Critical Review Statement

Review of the Report “Life Cycle Assessment of Asphalt Binder” (version March 14, 2019), Conducted for the Asphalt Institute by thinkstep AG

April 17, 2019

The review of this report has found that:

- the approach, described in the report, used to carry out the LCA is consistent with the ISO 14040:2006 principles and framework and the ISO 14044:2006 requirements and guidelines,
- the methods used in the LCA are scientifically and technically valid as much as the peer-reviewers were able to determine without having access to the LCA model and the data collection information,
- the interpretations of the results reflect the limitations identified in the goals of the study, and
- the report is transparent concerning the study steps and consistent for the purposes of the stated goals of the study.

This review statement only applies to the report and version named in the title, but not to any other report versions, derivative reports, excerpts, press releases, and similar documents.

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List of Acronyms

AI	Asphalt Institute
ADP	Abiotic Depletion Potential
AP	Acidification Potential
CHP	Combined heat and power
EoL	End-of-Life
EP	Eutrophication Potential
EPD	Environmental Product Declaration
FF	Fossil Fuel consumption
GaBi	Ganzheitliche Bilanzierung (German for “holistic balancing”)
GHG	Greenhouse Gas
GTR	Ground Tire Rubber
GWP	Global Warming Potential
IPCC AR5	Intergovernmental Panel on Climate Change 5 th Assessment Report
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NAPA	National Asphalt Pavement Association
NMVOC	Non-Methane Volatile Organic Compound
ODP	Ozone Depletion Potential
PED	Primary Energy Demand
PPA	Polyphosphoric Acid
POCP	Photochemical Ozone Creation Potential
PCR	Product Category Rule
SBS	Styrene Butadiene Styrene
SFP	Smog Formation Potential
TRACI	Tool for the Reduction and Assessment of Chemical and Other Environmental Impacts
VOC	Volatile Organic Compound



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, section 3.1). 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)

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)

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)

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)

Functional unit

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

Declared unit

“The declared unit is used instead of the functional unit when the precise function of the product ... is not stated or is unknown. The declared unit provides a reference by means of which the material flows of the information module of a ... product are normalised (in a mathematical sense) to produce data, expressed on a common basis. ... The declared unit shall relate to the typical applications of products.” (EN 15804, section 6.3.2)

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)

Closed-loop and open-loop allocation of recycled material

“An open-loop allocation procedure applies to open-loop product systems where the material is recycled into other product systems and the material undergoes a change to its inherent properties.”



“A closed-loop allocation procedure applies to closed-loop product systems. It also applies to open-loop product systems where no changes occur in the inherent properties of the recycled material. In such cases, the need for allocation is avoided since the use of secondary material displaces the use of virgin (primary) materials.”

(ISO 14044:2006, section 4.3.4.3.3)

Foreground system

“Those processes of the system that are specific to it ... and/or directly affected by decisions analyzed in the study.” (JRC 2010, 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 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....” (JRC 2010, 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).

Primary data

Data provided by the participants of the LCA and collected by the practitioner of the study. Generally, primary data should be used for the foreground system.

Secondary data

Existing data from literature or other sources, such as LCI data used to model upstream fuel and material inputs. Generally, secondary data are used for the background system.



1. Goal of the Study

Industries across all sectors and points in the value chain are being asked to supply information about the potential environmental impacts of their products. Life cycle assessment (LCA) is a method used to quantify these potential impacts, accounting for burdens throughout the supply chain for a given product. Driven by green building standards (e.g., LEED, Living Building Challenge, IgCC) and other green initiatives, the availability of accurate life cycle inventory (LCI) and life cycle impact assessment (LCIA) data have become a market demand for products used in the construction sector, including pavements. Transportation agencies such as the Illinois Toll Road Authority and the California Transportation Department are starting to look at how they can use such information in their project plans and designs (Ozer and Al-Qadi 2017, California Department of Transportation 2018).

With this study, the Asphalt Institute (AI) provides an industry-average LCI dataset on asphalt binders to provide data that are representative of North American industry conditions. This was achieved through the collection of primary data from North American refineries and a distinct method of allocation that accounts for the inherent difference between those refinery products that are used as fuels and those used as materials. Along with aggregate, asphalt binder is the major component of asphalt mixtures. As environmental profiles for asphalt mixture are being developed, AI wants to ensure that the background data for the asphalt binder are as accurate as possible. This is especially relevant as the National Asphalt Pavement Association (NAPA) has completed its Environmental Product Declaration (EPD) program for asphalt mixtures, using the Product Category Rule (PCR) for asphalt mixtures it helped develop (NAPA 2017). The NAPA EPD program is planning to use the datasets produced by this study, once available. The declared unit and reported impact categories have been selected to align with the requirements of this program, which in turn aligns with EN15804 (CEN 2013).

The target audience includes a broad cross section of internal and external stakeholders with concerns and interests pertaining to the potential life cycle environmental impacts of asphalt and its applications. Internal stakeholders include AI member companies who participated in the study, non-participating companies, and NAPA member companies. Producers and industry associations of other petroleum products may also be interested in the allocation methodology used within this study as they look to do their own LCAs.

This industry-wide cradle-to-gate LCA covers four asphalt binder products: asphalt binder without additives, asphalt binder with styrene butadiene styrene (SBS), asphalt binder with ground tire rubber (GTR), and asphalt with polyphosphoric acid (PPA).

The final report will be made publicly available along with the LCI datasets for full transparency with the reporting requirements of ISO 14044:2006, clause 5.2, and in order to facilitate the widespread adoption of the data by the LCA community.

This LCA study has been conducted in accordance with the International Standards ISO 14040:2006 and ISO 14044:2006. A critical review, though not required by ISO 14044 for non-comparative studies, has been conducted on both the initial Goal & Scope document and the final report to further scrutinize the results. The resulting datasets are intended to be distributed publicly for use in future LCAs. The critical review statement can be found at the beginning of this document.



2. Scope of the Study

The following sections describe the general 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 functions, declared unit and reference flows, the system boundary, allocation procedures, and cut-off criteria of the study.

2.1. Product System

This study covers several asphalt binders manufactured by AI members in North America. The products considered in this study are:

- Asphalt binder without additives
- Asphalt binder with styrene-butadiene-styrene (SBS)
- Asphalt binder with ground tire rubber (GTR) (terminal blend)
- Asphalt binder with polyphosphoric acid (PPA)

This industry-average assessment is based on information supplied by twelve AI member refineries (from nine companies) and eleven terminals (from four companies) in the U.S. and Canada. The participating companies are listed in Table 2-1.

Table 2-1: Participating companies

Company	Refineries	Terminals
BP P.L.C.	Whiting, IN, USA	-
Ergon, Inc.	-	Nashville, TN, USA Ennis, TX, USA Bainbridge, GA, USA
ExxonMobil Corp.	Joliet, IL, USA Billings, MT, USA	-
Husky Energy Inc.	Lloydminster, AB, CAN	-
Imperial Oil Limited	Strathcona, AB, CAN Nanticoke, ON, CAN	-
Jebro Inc.	-	Sioux City, IA, USA Waco, TX, USA Cheyenne, WY, USA Corson, SD, USA
Marathon Petroleum Corporation	Garyville, LA, USA	-
McAsphalt Industries Limited	-	Hamilton, ON, CAN
San Joaquin Refining Co., Inc.	Bakersfield, CA, USA	-
Shell Oil Company	St. Rose, LA, USA	-
U.S. Oil and Refining Co., Inc.	Tacoma, WA, USA	-
Valero Energy Corporation	Corpus Christi, TX, USA Wilmington, CA, USA	Houston, TX, USA St. James, LA, USA



At the twelve refineries, the asphalt is produced via straight-run distillation of crude oil. During this process, the residue from the atmospheric distillation of crude oil is further distilled in a vacuum tower to produce asphalt.

2.2. Declared Unit

Because of their varied attributes and additives, asphalt binders serve a wide array of uses in various market sectors, including building and construction, transportation, and as coatings and sealants (Asphalt Institute; Eurobitume 2015). Some specific uses in these market sectors include:

- **Building and construction:** roofing, waterproofing, reservoir and pool lining, dams, etc.
- **Transportation:** pavements for roads, airport runways, parking lots, etc.
- **Other applications:** waterproofing, pipe coatings, paints, sealants, sound deadening, etc.

The declared unit of these four products (asphalt binder without additives, asphalt binder with SBS, asphalt binder with GTR terminal blend, and asphalt binder with PPA) is **1 kilogram of asphalt binder**. Asphalt binder is also referred to as liquid asphalt or bitumen. Material specifications are dependent on the intended use of the asphalt binder, such as AASHTO M320 for paving asphalts and ASTM D312 for roofing asphalts (AASHTO 2016, ASTM 2016). This assessment includes all types of asphalt produced during petroleum refining.

2.3. System Boundary

The scope of this cradle-to-gate study includes raw material sourcing and extraction, transportation to refineries, refining of crude oil into asphalt, transport to the terminal, and final blending of the asphalt binders at the terminal. A process diagram is shown in Figure 2-1 and the inclusions and exclusions of the system boundary are listed in Table 2-2. Only processes at the refinery associated with asphalt production were included. As with many LCAs, capital goods, infrastructure, human labor and employer transport were excluded from the scope of the study due to their anticipated irrelevance for the results.

The region and method of extraction of all crude oil inputs to the refineries was used to select the most representative background inventories available in the GaBi databases.¹ If refineries were unable to provide details on method of extraction, an average mix of extraction technologies for the region was used. Details on the mode and distance of the transport of crude oil was also provided by refineries.

¹ This includes all commercially available LCI data as well as the underlying, disaggregated LCA models available to thinkstep which accurately represent crude oil extraction by region and extraction method.

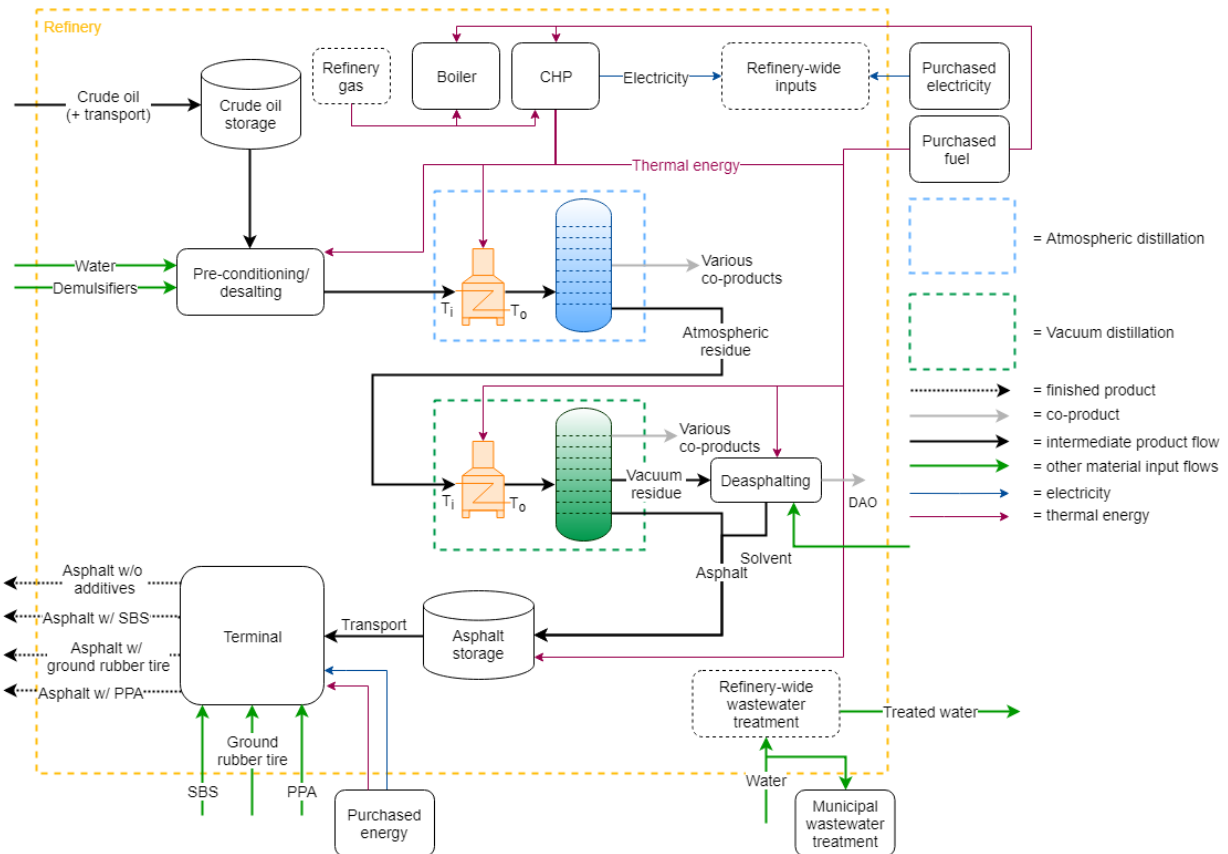


Figure 2-1: Cradle-to-gate system boundary

**Table 2-2: System Boundaries**

Included	Excluded
<ul style="list-style-type: none"> ✓ Raw material extraction and intermediate processing, including crude oil ✓ Upstream electricity generation and fuel production ✓ Inbound transportation of raw materials, including crude oil ✓ Product manufacturing and packaging ✓ Use of water, energy, and minor auxiliary materials (surfactants, H₂S scavengers) during manufacturing ✓ Emissions to air, water, and soil during manufacturing ✓ Internal transportation (within a refinery) ✓ Thermal energy for heating throughout process ✓ Crude oil storage, pre-conditioning/desalting, atmospheric distillation, vacuum distillation, de-asphalting, asphalt storage ✓ Transport to terminal ✓ Terminal operations 	<ul style="list-style-type: none"> ✗ Construction of capital equipment ✗ Maintenance and operation of support equipment (e.g., employee facilities, etc.) ✗ Packaging of raw materials ✗ Human labor and employee commute ✗ Transport of finished products to site and application of product ✗ Use stage ✗ Deconstruction, transport to EoL, and waste processing ✗ Disposal and recycling credits ✗ Processes at the refinery not associated with asphalt production or general operations

2.3.1. Time Coverage

The data are intended to represent asphalt production during the 2015 and 2016 calendar years. As such, each participating AI member company provided primary data for 12 consecutive months during the 2015 and 2016 calendar years, but only for those runs when asphalt was produced. The twelve participating refineries do not produce asphalt in every run. The data submitted only capture the inputs and outputs across those 12 months when asphalt is one of the products being produced at that refinery. These data were then used to calculate average production values for each company.

2.3.2. Technology Coverage

This study is intended to be representative of the four types of asphalt binders as produced in North America. All foreground data was collected from members for their facilities to represent average asphalt binders and their technologies. Special attention was given to background data for crude oil extraction as the method and location of extraction will influence the final results.

2.3.3. Geographical Coverage

This LCA is intended to represent the Asphalt Institute members' products produced in North America. Background data are representative of the respective countries (USA, Canada).



Regionally specific datasets are used to represent each manufacturing location's energy consumption, but proxy datasets are used as needed for raw material inputs to address lack of data for a specific material or for a specific geographical region. These proxy datasets are chosen for their technological representativeness of the actual materials.

2.4. Allocation

2.4.1. Previous Methodologies

There have been a variety of allocation methods used for LCAs of petroleum refineries. Eurobitume's LCI study allocates between refinery products based on economic factors calculated from European market averages over 7 years, grouping the outputs of each tower as residues and distillates (Eurobitume 2012). The GaBi refinery model allocates crude oil inputs by energy content and electricity, thermal energy, and emissions by mass (thinkstep 2016). Both these assessments rely on theoretical refinery models supplemented by industry average values as opposed to primary data collected directly from refineries where each refinery is modeled separately.

PRELIM (the Petroleum Refinery Life Cycle Inventory Model) estimates energy use and GHG emissions for crude oil products. The tool, which models separate unit processes for different refinery setups and crude assays, allows the user to choose between mass, energy, market value, and hydrogen contents for allocation at the sub-process level. (Abella, et al. 2016)

The NAPA EPD Program is currently using the NREL USLCI data for crude oil at refinery, allocated based on a Master's thesis by Rebecca Yang (NREL 2003, Yang 2014). Yang's allocation considers both the economic values of the refinery co-products as well as the mass yield of those co-products, allocating at the refinery level. Alternatively, the user of the USLCI data could choose to allocate the NREL data based on mass or energy content.

With the exception of Eurobitume's LCI, all these studies use an average crude slate representative of crude oil consumption in the US for all refinery products, not just asphalt. In contrast, this study aimed to collect data only when asphalt was being produced at the refinery.

2.4.2. Background Data

Allocation of background data (energy and materials) taken from the GaBi 2017 LCI database is documented online at <http://www.gabi-software.com/support/gabi/gabi-database-2018-lci-documentation>. A report published by the Joint Research Commission has additional information on the energy datasets found in GaBi (Garrain, de la Rua and Lechon 2013).

2.4.3. Co-Product and Multi-Input Allocation

Since asphalt is one product stream in a complex, multi-product system, it is crucial that the allocation methodology appropriately captures and allocates the total impacts of the system. For this study, the main material and energy inputs to be allocated are crude oil input, thermal energy consumption and associated emissions, and electricity. A scenario analysis is included as part of the study to validate the approach. Baseline and scenario allocation methodologies are shown in Table 2-3.

**Table 2-3: Proposed and scenario allocation/subdivision methodologies**

Input or Output	Proposed baseline methodology	Allocation Scenario 1	Allocation Scenario 2	Allocation Scenario 3
Electricity	Mass allocation	<i>(no other method deemed applicable)</i>		
Crude oil	Energy content allocation (net calorific value)	Mass allocation	<i>(Same as baseline)</i>	Mass allocation
Thermal energy	Subdivision calculated as sensible heat of asphalt, accounting for inefficiencies	<i>(Same as baseline)</i>	Energy content of allocation (using net calorific value)	Energy content of allocation (using net calorific value)
Direct emissions	Allocated based on thermal energy use	<i>(Same as baseline)</i>	Energy content of allocation (using net calorific value)	Energy content of allocation (using net calorific value)

Electricity

Mass allocation was selected for electricity in both the baseline and scenario analyses because the density of products is directly related to the electrical demand for pumping the products. No other allocation method is deemed an appropriate scenario for electricity. This methodology also aligns with existing GaBi datasets of refinery products (European Commission 2013, thinkstep 2016).

Crude oil input

Energy content of the co-products (using the net calorific value) is the baseline allocation methodology selected for crude oil input. This is an appropriate methodology because lighter refinery products with a higher net calorific value are preferred due to their higher market value and demand. Also, since this methodology aligns with existing GaBi datasets of refinery products, we ensure a consistent methodology with fuel datasets (European Commission 2013, thinkstep 2016). Because asphalt is a construction material and not purchased for its energy content, the scenario analysis will investigate the mass allocation for the crude oil input.

Thermal Energy

Thermal energy requirements for asphalt is based on the sensible heat² of asphalt in the system. It is calculated from the temperature differential between the crude tank to the asphalt rundown line and the specific heat capacity of the asphalt, while accounting for the heating system's inefficiencies.

Each oil refinery is different and complex, with heat integration between production processes and utilities. All refinery energy usage must be accounted for across the refinery co-products through a defined allocation method. One approach would be a rigorous heat and material balance around the many process units relevant to asphalt production using a process simulation software (e.g. Aspen HYSYS, Petro-SIM). This software can be used to create a complex model using thermodynamic equations to calculate the energy flow associated with each co-product at the process level thus tracking the energy required for

² Sensible heat is the energy required to change the temperature of a substance with no phase change (retrieved from: <http://climate.ncsu.edu/edu/health/health.Isheat>, July 17, 2017)



each co-product. However, each refinery's model is proprietary and could not be utilized in the LCA due to the complexity and confidentiality. This would greatly reduce transparency and it could not be guaranteed that models were consistent across refineries.

While lighter products are vaporized and sometimes condensed as part of their production from crude oil, asphalt is never vaporized nor condensed, which made employing a simpler method possible. The energy input to produce asphalt in refining is therefore calculated as the net sensible heat input (i.e., the energy required to raise the temperature of a material) into the asphalt fraction of the crude oil based on the temperature difference between the crude tank outlet and the asphalt storage tank rundown line, adjusted for the efficiency of the heaters, piping losses, and storage energy losses. This will be referred to as the *sensible heat method* and is described in further detail below.

The basic asphalt production process starts with crude in a crude tank. The crude is partially heated and mixed with water to dissolve salts. The water is separated from the crude and removed, removing the salts. The very low salt crude is heated again and distilled, with all products lighter than heavy gas oil vaporizing in the crude tower, leaving atmospheric residue, also known as reduced crude, at the tower bottom. The energy required for vaporization is attributable to the lighter products and hence excluded from consideration. The atmospheric residue is then heated again and further distilled under a vacuum, vaporizing all gas oils and any remaining diesel, with asphalt remaining as a hot liquid in the bottom of the vacuum distillation tower. The hot asphalt is exchanged with other refinery feeds, mostly in the crude and vacuum distillation units, to return heat to the process, before going to the asphalt rundown line and to asphalt storage. Thus, the net energy consumed by the asphalt is the net sensible heat input into the asphalt molecules from the crude tank to the asphalt rundown line. The total energy consumed to produce the asphalt then is the net sensible heat in the asphalt plus any energy losses in the heating system (heater, piping, and vessel losses). All additional energy consumption is attributed to the other co-products.

The sensible heat method multiplies the change in temperature of the asphalt by its heat capacity, divided by the average efficiency of the heaters. Then, the estimated piping and vessel losses were added. The initial temperature is that of the crude entering the process and the final temperature is after asphalt run down where heat is recovered – therefore, the calculation accounts for the heat recovered from the asphalt.

$$\frac{C \times \Delta T}{\eta} + L = \text{Thermal energy required}$$

Where,

C = heat capacity (J/K)

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

η = efficiency of heating system (unitless)

L = losses (J)

It should be noted that even with very conservative estimate for losses used for these calculations, loss still accounted for less than 1% of the energy required.

The described method was developed jointly with the Asphalt Institute and validated by two refineries operated by the same company. The validation process compared the results of the sensible heat method to a complex thermodynamic model from a process simulation software. To assess the accuracy of using the sensible heat method, the complex model was modified so that 10,000 barrels of asphalt product were removed from the total output while all the other co-products and their production volumes remained unaltered. Then the model was run to establish the difference between the energy requirements of the



original model and the modified model, which is the energy associated with producing those 10,000 barrels of asphalt. In both cases, it was found that the result calculated with the complex model was within one percent of the energy consumption calculated using the sensible heat method.

Direct emissions

Direct emissions were allocated based on the fraction of total thermal energy use (excluding recovered heat) calculated for asphalt. While process-specific emissions are generally preferred, in some cases only site-wide emissions from fuel combustion will be available from participating refineries. Process-specific emissions were allocated based on the fraction of total thermal energy for the process and site-wide emissions were allocated based on the fraction of total thermal energy for the site.

Note that in refining, other process units may react or distill asphalt materials further, with part of the products then being blended back into asphalt. These additional units will be ignored for the purpose of determining the energy input into and direct emissions of asphalt production as any additional energy utilized in or direct emissions from these processes are for the purpose of producing other, higher-value products and should be attributed as such. For example, energy and emissions from the de-asphalting process are not attributed to the asphalt product, but rather to the de-asphalted oil. The only burden attributed to asphalt produced from de-asphalting is from the upstream vacuum residue and atmospheric residue contributions.

2.4.4. End-of-Life Allocation

End-of-Life (EoL) allocation generally follows the requirements of ISO 14044, Section 4.3.4.3. As the system boundary doesn't include use or EoL, this section addresses the treatment of waste produced during the production of asphalt binder.

In cases where materials are sent to waste incineration, they are linked to an inventory that accounts for waste composition and heating value as well as for regional efficiencies and heat-to-power output ratios. Substitution credits are assigned for power and heat outputs using the regional grid mix and thermal energy from natural gas. The latter represents the cleanest fossil fuel and therefore results in a conservative estimate for the substituted inventory in the sense of a low credit. It is also the most common fuel for thermal energy generation in North America (U.S. Energy Information Administration 2018).

In cases where materials are sent to landfills, they are linked to inventories that account for waste composition, regional leachate rates, landfill gas capture as well as utilization rates (flaring vs. power production), as far as available. A substitution credit is assigned for power output using the regional grid mix.

2.5. Cut-off Criteria

No cut-off criteria are defined for this study. As summarized 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 were applied based on best assumptions regarding geographical, technological, and temporal representative and representing conservative assumptions for environmental impacts. For details on the cut-off criteria of background data, see the *GaBi Modelling Principles* (thinkstep 2017, 39-40).



The selections of proxy data are documented and the influence of these proxy data on the results of the assessment were analyzed.

2.6. Selection of LCIA Methodology and Impact Categories

The impact assessment categories and other metrics considered to be of high relevance to the goals of the project are shown in Table 2-4 and Table 2-5. TRACI 2.1 has been selected as it is currently the only impact assessment methodology framework that incorporates US average conditions to establish characterization factors (Bare 2012, EPA 2012). Results will additionally be reported using the CML methodology, version 4.7 published in January 2016 (Guinée, et al. 2002), to align with the results reported by the NAPA EPD program and to capture European conditions. Other metrics that are not required for the NAPA EPD program are discussed in the additional environmental information section.

Global Warming Potential and Non-Renewable Primary Energy Demand were chosen because of their relevance to climate change and energy efficiency, which are strongly interlinked and of high public and institutional interest. The global warming potential impact category is assessed based on the Intergovernmental Panel on Climate Change 5th Assessment Report (IPCC AR5) characterization factors taken from (IPCC 2013) for a 100-year timeframe (GWP100) as this is currently the most commonly used metric. It should be noted that there is no scientific justification for selecting 100 years over other timeframes. GWP expresses the radiative forcing of a greenhouse gas integrated over time in relation to that of CO₂. IPCC publishes characterization factors for both the 20- and 100-year timeframes. Short-lived climate forcers, such as methane, have a much higher GWP 20 value than GWP100 as their radiative forcing tails off quickly after an initial peak. Therefore, GWP20 values are also assessed to determine the influence of long- and short-lived climate forcers emitted over the life cycle of the product.

Eutrophication, Acidification, and Photochemical Ozone Creation Potentials were chosen because they are closely connected to air, soil, and water quality and capture the environmental burden associated with commonly regulated emissions such as NO_x, SO₂, VOC, and others.

Ozone depletion potential was chosen because of its high political relevance, which eventually led to the worldwide ban of more active ozone-depleting substances; the phase-out of less active substances is due to be completed by 2030. Current exceptions to this ban include the application of ozone depleting chemicals in nuclear fuel production. The indicator is therefore included for reasons of completeness.

Water consumption, i.e., the anthropogenic removal of water from its watershed through shipment, evaporation, or evapotranspiration also been selected due to its high political relevance. Around two billion people on the planet live in areas of water scarcity, and two thirds of the world's biggest groundwater systems are already in distress (UN Water 2007, Richey, et al. 2015). Note that water consumption in this assessment is calculated solely as inputs minus outputs of blue water, which is not a water footprint and therefore does not align with ISO 14046 (ISO 2014).

The present study includes the assessment of fossil and elemental resource depletion in order to align with the NAPA EPD program and required reporting requirements of EN15804 (CEN 2013). However, it should be noted that, despite 20 years of research, there remains no robust, globally agreed upon method - or even problem statement - for assessing mineral resource inputs in life cycle impact assessment (Drielsmaa, et al. 2016). One may further argue that the concern regarding the depletion of scarce resources is not as much an 'environmental' one, but rather about the vulnerability of markets to supply shortages. These shortages, in return, are driven by various factors that are not captured well by current metrics. Accordingly, resource criticality has emerged as a separate tool to assess resource consumption (Nassar, et al. 2012, Graedel and Reck 2015).

**Table 2-4: Impact category descriptions**

Impact Category	Description	Unit	Reference
Global Warming Potential, incl. biogenic carbon (GWP100 & GWP20)	A measure of greenhouse gas emissions, such as CO ₂ and methane. 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	IPCC AR5, (IPCC 2013); TRACI 2.1, (Bare 2012) ³ ; CML Jan 2016, (Guinée, et al. 2002)
Eutrophication Potential (EP)	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.	kg N equivalent (TRACI 2.1) kg PO ₄ ³⁻ equivalent (CML)	TRACI 2.1, (Bare 2012, EPA 2012); CML Jan 2016 (Guinée, et al. 2002)
Acidification Potential (AP)	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.	kg SO ₂ equivalent (TRACI, CML)	
Photochemical Ozone Creation Potential (POCP)	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 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 C ₂ H ₄ equivalent (CML)	
Smog Formation Potential (SFP)		kg O ₃ equivalent (TRACI)	
Ozone Depletion Potential (ODP)	A measure of air emissions that contribute to the depletion of the stratospheric ozone layer. Depletion of the ozone leads to higher levels of UVB ultraviolet rays reaching the earth's surface with detrimental effects on humans and plants.	kg CFC-11 equivalent (TRACI, CML)	
Human Health Particulate Effects (PM)	A measure of the risk to human health associated with particulate matter and selected inorganic emissions	kg PM 2.5 equivalent	

³ IPCC AR5 is the most up-to-date data source for GWP factors, but TRACI's GWP (which uses IPCC AR4) is also included for completeness.



Impact Category	Description	Unit	Reference
Abiotic depletion potential, fossil resources (ADPf)	A measure of the consumption of non-renewable energy resources that leads to a decrease in the future availability of the functions supplied by these resources.	MJ surplus energy (TRACI) MJ (CML)	TRACI 2.1, (Bare 2012, EPA 2012)
Abiotic depletion potential, elemental (ADPe)	A measure of the consumption of non-renewable elemental resources that leads to a decrease in the future availability of the functions supplied by these resources.	kg Sb equivalent (CML)	CML (van Oers, et al. 2002)

Table 2-5: Other environmental indicators

Indicator	Description	Unit	Reference
Primary Energy Demand (PED)	A measure of the total amount of primary energy extracted from the earth. PED is expressed in energy demand from non-renewable resources (e.g. petroleum, natural gas, etc.) and energy demand from renewable resources (e.g. hydropower, wind energy, solar, etc.). Efficiencies in energy conversion (e.g. power, heat, steam, etc.) are taken into account.	MJ (lower heating value)	(Guinée, et al. 2002)
Water Consumption (Water)	A measure of the net intake and release of fresh water across the life of the product system. This is not an indicator of environmental impact without the addition of information about regional water availability. Blue water consumption does not include the input of rain water.	Liters of water	(thinkstep 2018)

As one of the goals of this study is to provide data for use in the NAPA EPD program, additional environmental indicators listed in Table 2-6 will be reported to align with EN 15804 and the NAPA PCR (CEN 2013, NAPA 2017).

Table 2-6: Additional environmental indicators required for the NAPA EPD program

Impact Category / Indicator	Unit	Reference
Renewable primary energy as energy carrier (PERE)	MJ (LHV)	(CEN 2013)
Renewable primary energy resources as material utilization (PERM)	MJ (LHV)	
Total use of renewable primary energy resources (PERT)	MJ (LHV)	
Non-renewable primary energy as energy carrier (PENRE)	MJ (LHV)	
Non-renewable primary energy as material utilization (PENRM)	MJ (LHV)	
Total use of non-renewable primary energy resources (PENRT)	MJ (LHV)	
Use of secondary material (SM)	kg	
Use of renewable secondary fuels (RSF)	MJ (LHV)	
Use of non-renewable secondary fuels (NRSF)	MJ (LHV)	
Hazardous waste disposed (HWD)	kg	



Impact Category / Indicator	Unit	Reference
Non-hazardous waste disposed (NHWD)	kg	
Radioactive waste disposed (RWD)	kg	
Components for re-use (CRU)	kg	
Materials for recycling (MFR)	kg	
Materials for energy recovery (MER)	kg	
Exported energy (EE) [electric and thermal]	MJ (LHV)	

It shall be noted that all above 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 declared unit (relative approach). LCIA results are therefore relative expressions only and do not predict actual impacts, the exceeding of thresholds, safety margins, or risks.

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 steps, materials, and/or emissions 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 in relation to creating a dataset representative of industry, 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 modeling 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 modeling 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 measured or calculated industry-specific 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 will be provided in section 5 of the final report.

2.9. Type and format of the report

In accordance with the ISO requirements (ISO 2006) 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 GaBi ts software system for life cycle engineering, developed by thinkstep AG. The GaBi 2017 LCI database provides the secondary life cycle inventory data for the background system (raw materials, fuels, transportation, EoL, etc.).

2.11. Critical Review

A critical review of both the initial Goal & Scope document and the completed study report will be conducted by the following panel members:

- Arpad Horvath – Consultant, Berkeley, California (Chair)
- Mike Southern – Eurobitume
- Amit Kapur – Phillips 66

The review will be performed according to Clause 7.3.3 of ISO 14040 (2006), Clause 6.3 of ISO 14044 (2006), and ISO/TS 14071 (2014). The Critical Review Statement can be found at the beginning of this document. The analysis and the verification of the GaBi software model used and the individual background datasets are outside the scope of this review. The Critical Review Report containing the comments and recommendations of the independent experts as well as the practitioner's responses is available upon request from the study commissioner.



3. Life Cycle Inventory Analysis

3.1. Data Collection Procedure

All primary data were collected using customized data collection templates, which were sent out by email to the respective data providers in the participating companies. Data required for this study include both refinery-level, terminal-level, and process-level information, as well as data points required to calculate the sensible heat of asphalt. Process-level data need to describe pre-conditioning, atmospheric distillation, vacuum distillation, deasphalting, asphalt storage, and on-site combined heat and power units (CHP). For each of these processes, data on thermal energy input, co-product properties (including specific gravity and net calorific value), and furnace inlet and outlet temperatures for heaters associated with distillation towers were collected. Refinery-level and terminal-level data included total electricity consumption for pumps and compressors, combustion emissions, and total thermal energy consumption.

Details on the crude slates used for asphalt production runs, including region, crude name, location of port/well, and mode of transport were also collected. Participating facilities were either a refinery or a terminal. No data were collected for terminals co-located with refineries since none of the terminals that participated fell into this category. Additionally, no data were available on the fraction of production volume produced at co-located terminals.

Upon receipt, each questionnaire was cross-checked for completeness and plausibility using mass balance, stoichiometry, as well as internal and external benchmarking. Benchmarking was performed using descriptive statistics. The industry data was ranked into quartiles and outliers were determined using boundaries determined by the interquartile range (IQR). Bounds were calculated using the formulas in Equation 1 where Q_1 equals first quartile and Q_3 equals third quartile.

$$\text{Lower bound} = Q_1 - 1.5(IQR)$$

$$\text{Upper bound} = Q_3 + 1.5(IQR)$$

Equation 1: Equations for upper and lower bounds of data for determining outliers

Companies were also given the quartile benchmarks to compare their individual company data to the industry data. If gaps, outliers, or other inconsistencies occurred, thinkstep engaged with the data provider to resolve any open issues. No data were interpreted as a zero-value unless specifically reported as zero by the company.

3.2. Product System

3.2.1. Overview of Product System

Asphalt Institute member companies produce or manufacture petroleum asphalt binders. This study focuses on four asphalt binder products: asphalt binder without additives, asphalt binder with SBS, asphalt binder with GTR, and asphalt with PPA. The product boundary begins with crude oil input to the refinery



and ends at the asphalt terminal. Refining steps relevant to the production of asphalt binder include atmospheric distillation, vacuum distillation, and deasphalting⁴.

Some companies included in the study produce a mix of products while others are primarily asphalt manufacturers. Both follow the same process steps. For companies that are not primarily asphalt producers, data were collected for asphalt runs only. Impacts from storage, preconditioning, the asphalt terminal, and CHP are also included within the scope of this study.

Terminals are included in this study since they are typically necessary for the distribution of the product. Asphalt binder requires heated shipping and since refineries are not located in all areas, terminals are utilized to blend and modify binders to specific specification and grade requirements, as well as widen availability to meet end market needs. Some refineries have co-located terminals for retail sales distribution.

Modified asphalt binder is commonly used in North America. SBS, PPA, and GTR are included in this study as they are the most widely used modifiers and represent a range of different product requirements for the different climate and traffic conditions present in North America. Additionally, these modifiers are typically added at a terminal, not an asphalt mixture plant or at a refinery.

SBS and GTR provide improved rut resistance and crack resistance. PPA is used to increase the high temperature performance grading (PG) grade, which improves rut resistance. In many instances, PPA is used in combination with SBS as a cross-linking agent.

3.2.2. Crude Oil Slate

The production stage starts with extraction of crude oil and delivery to the refinery. Crude oil is modelled based on the GaBi crude oil supply model, which considers the whole supply chain of crude oil, i.e. extraction, production, processing, the long-distance transport and the regional distribution to the refinery. More information on the crude oil model can be found in Appendix A. The specific crude slate used within a refinery is vertically combined with that refinery's operations. The refineries are then combined as a production weighted average. Therefore, the average crude slate entering the refineries will differ from the production weighted average crude slate used in the study, specifically due to some sites sending vacuum residue to the coker instead of it being used as asphalt

Companies were asked to provide crude name, region, extraction technology, and mode of transportation. In many cases, primary information on the extraction technology was not available, in which case it was selected and modeled based on crude name. When no such information was available for the crude slate based on name, it was modeled using the region of origin's average crude slate mix as a proxy.

The resulting average crude oil slate for North American asphalt binder is used for this report and represents a mix of conventional (primary, secondary and tertiary production) and unconventional (oil sands, in-situ) extraction technologies. Tertiary extraction includes steam, CO₂, nitrogen, and natural gas injection and comprises 13% of the crude slate. The production-weighted crude slate by crude extraction method is shown in Table 3-1.

⁴ There is no deasphalting included in the model as it was not a step in the asphalt production process for the participating companies. If a company were to have had a deasphalting step, note that energy and emissions from the deasphalting process would not have been attributed to the asphalt produced, only the de-asphalted oil (DAO). The only burden attributed to asphalt produced from deasphalting would have been from the upstream vacuum residue and atmospheric residue contribution.

**Table 3-1: Crude oil extraction method of AI asphalt binder**

Category of extraction technology	Percentage (by mass)
Crude from oil sands	44%
Primary extraction	22%
Secondary extraction	16%
Tertiary extraction, steam injection	15%
Tertiary extraction, CO ₂ injection	1%
Tertiary extraction, nitrogen injection	1%
Tertiary extraction, natural gas injection	1%
Other (refinery products)	<1%

The crude slate used specifically for the production of the AI asphalt binder was also compared to the 2016 refinery net inputs for the average North American slate used to produce all refinery products (i.e., not specific to asphalt production). This assessment was based on the US and CA refinery net imports (EIA 2018c, Government of Canada 2017, Enerdata 2018) and the quality of imports (EIA 2018a, EIA 2018b, Government of Canada 2018). Average data were not available based on extraction method, therefore the API gravity was used for comparison purposes. API gravity is commonly used as an indicator of quality when purchasing crudes and is grouped as heavy, medium, or light.⁵ The difference between the AI crude slate and NA average is largely driven by the higher percentage of crude slate from oil sands (heavy) as compared to the NA average.

Table 3-2: Quality of crude slate, AI versus NA average

Quality of crude	AI Quality of crude slate Percentage (by mass)	NA average Quality of crude slate Percentage (by mass)
Heavy	55%	36%
Medium	35%	29%
Light	9%	35%
Other	1%	-

AI member's asphalt binder products are manufactured in Canada and the United States, with 85% of crude oil sourced from those nations. Table 3-3 shows the crude source breakdown by country for both domestic and international sources.

Table 3-3: Country of crude oil origin of average asphalt binder

Country of origin	Percentage (by mass)
Canada	53%
United States	26%
Saudi Arabia	6%

⁵ Another method for comparison to the average could be the breakdown between sweet and sour crudes, but this data was not collected as part of this study.



Country of origin	Percentage (by mass)
Kuwait	4%
Colombia	4%
Venezuela	3%
Iraq	2%
Mexico	1%
Brazil	<1%
Ecuador	<1%

Crude is then transported to the refinery by pipeline, ocean-going tanker, coastal tanker or some combination of these modes. Companies were asked to provide method of transportation for each crude slate. When these data were not available, transport method was determined based on the average transport mix for that region. Transport distance was either provided by the company or calculated based on origin, destination, and transport method.

Dilbit, Synbit, and Synthetic Crude

Crude oil extracted from oil sands, or crude bitumen⁶, is a heavy crude oil containing as much as 2% water and solids depending on the extraction method and does not meet pipeline specifications for long distance transport (Oil Sands Magazine 2018). Specifications for pipeline transportability indicate that crude oil shipments not exceed a density of 940 kg/m³ and a viscosity of 350 cSt (Transportation Research Board and National Research Council 2013). A few methods are used to prepare the crude bitumen so it meets the pipeline specifications. Crude bitumen can either be upgraded or diluted with a fluid of lower viscosity, either a distillate or a lighter crude oil. This project considers crude bitumen that has been upgraded (“synthetic crude”) as well as crude bitumen that has been diluted, both “dilbit” and “synbit”.

Synthetic crude is a light sweet crude that is the product of upgrading. Dilbit is crude bitumen that has been diluted with distillates, typically natural gas condensate or naphtha in the order of 30 to 40% by volume. Synbit is crude bitumen that has been diluted with synthetic crude in the order of 50% by volume (Oil Sands Magazine 2017, Transportation Research Board and National Research Council 2013).

Crudes were identified as synthetic, dilbit, or synbit based on the crude names (Oil Sands Magazine 2017). Assumptions were cross checked with the participating companies. Synthetic crude was modeled as crude bitumen from oil sands with upgrading, dilbit as crude bitumen from oil sands with 30% naphtha diluent, and synbit as 50% crude bitumen from oil sands with no upgrading and 50% crude bitumen from oil sands with upgrading. Table 3-4 shows the breakdown of the three oil sands products within the model and the North American average from oil sands magazine (Oil Sands Magazine 2018).

Table 3-4: Oil sands (crude bitumen) crude oil products by mass

Crude bitumen product	Percentage (by mass)	Percentage (by mass)
	AI Model	NA Average
Dilbit	80%	~60%
Synthetic	16%	~40%
Synbit	3%	N/A

⁶ Crude oil from oil sands is called crude bitumen to distinguish it from the alternate nomenclature of bitumen for the asphalt product.



3.2.3. Asphalt Production

Crude oil refinery activities begin with the input of crude oil. Crude is fed to the desalter where it is partially heated and mixed with water to dissolve salts. The water is separated and removed. Next, the crude oil enters the atmospheric distillation unit, where it is heated and distilled. All products lighter than heavy gas oil vaporize, and as discussed in the allocation methodology section (2.4.2), the energy required for vaporization is fully attributable to those lighter products. The residue from the atmospheric distillation is introduced to the vacuum distillation unit. The atmospheric residue is heated and further distilled under a vacuum, vaporizing all gas oils and any remaining diesel, with asphalt remaining as a hot liquid in the bottom of the vacuum distillation tower. The hot asphalt passes through heat exchangers alongside other refinery feeds, mostly in the crude and vacuum distillation units, to return heat to the process, before going to the asphalt rundown line and to asphalt storage (thinkstep 2016).

The combination and sequence of refinery processes is specific to the characteristics of the crude oil input and the products output. Refinery production is also influenced by market demand for the products, crude oil pricing and availability, and requirements of the various petroleum products as monitored by authorities (thinkstep 2016). Because of these factors, primary refinery data were collected only for runs that produce asphalt. Limitations of this approach are addressed in Section 5.6.2.

The lower heating value (LHV) for each output was requested in the data from the refineries. Where primary data were not available, the LHV was taken from either the GaBi datasets or research from sites such as the U.S Energy Information Agency (EIA). In the few cases where an output did not match with one of the standard outputs, it was included with the output that most closely matched the energy content of that stream.

Table 3-5, Table 3-6, Table 3-7, and Table 3-8 present the unallocated unit processes for preconditioning, atmospheric distillation, vacuum distillation, and asphalt storage, per 1 kg of asphalt produced at the refinery. Thermal energy required (calculated using the sensible heat approach discussed previously) is not separated by unit process but is instead reported on a total basis in Table 3-11. After allocation the amount of crude oil required per kg of asphalt is 1 kg.

Table 3-5: Unit process preconditioning, per 1 kg of asphalt produced at refinery

Type	Flow	Value	Unit
Inputs	Crude oil	4.98	kg
Outputs	Crude oil	4.98	kg

Table 3-6: Unit process atmospheric distillation unit, per 1 kg of asphalt produced at refinery

Type	Flow	Value	Unit	LHV [MJ/kg]
Inputs	Crude oil	4.98	kg	
Outputs	Atmospheric residue	2.70	kg	44.0
	Gas oil	0.361	kg	43.0
	Heavy distillates	0.273	kg	38.0
	Kerosene	0.416	kg	43.0
	Liquefied petroleum gas	0.037	kg	46.2
	Naphtha	0.936	kg	44.0
	Misc. refinery products	0.211	kg	43.7

**Table 3-7: Unit process vacuum distillation unit, per 1 kg of asphalt produced at refinery**

Type	Flow	Value	Unit	LHV [MJ/kg]
Inputs	Atmospheric residue	2.70	kg	
Outputs	Asphalt binder (no additives)	1.00	kg	38.7
	Cracker feed	0.0266	kg	38.1
	Vacuum gas oil (heavy, medium, light)	1.24	kg	38.6
	Vacuum residue (including residual fuel oil and flux)	0.596	kg	38.5

Despite repeated efforts for clarification, some companies were unable to resolve the mass imbalance reported at their ADU and VDU units. This may partially be due to conversion of annual data from volume to mass with a single density value and not accounting for density changes with temperature. As a result, the ADU has 6% more material coming in than leaving, while the VDU has 10% more material leaving than entering.

Table 3-8: Unit process asphalt storage

Type	Flow	Value	Unit
Inputs	Asphalt binder (no additives)	1	kg
Outputs	Asphalt binder (no additives)	1	kg

3.2.4. Product Composition

At the terminal the additive contents were based on expert judgement about commonly used mixtures (Table 3-9). While there can be significant variation depending on the terminal, the decision was made by the industry to select commonly used additive amounts.

Table 3-9: Material composition of the four products

	Asphalt binder w/o additives	Asphalt binder w/ SBS	Asphalt binder w/ GTR	Asphalt binder w/ PPA
Asphalt binder	100%	96.5%	92.0%	99.5%
Styrene-butadiene-styrene (SBS)	-	3.5%	-	-
Ground tire rubber (GTR)	-	-	8.0%	-
Polyphosphoric acid (PPA)	-	-	-	0.5%

3.2.5. Refinery level

While process-specific electricity, thermal energy, water usage, and emission would have been preferred, this data were not available. Therefore, refinery-level data were collected for site-wide consumption of electricity and thermal energy as well as direct emissions. Purchased energy and energy generated on-site were included.

Electricity was allocated based on the total mass of the co-products. Thermal energy was allocated based on the sensible heat method described in section 2.4.2. Direct emissions from refinery processes including fuel combustion were allocated based on the total thermal energy use calculated for asphalt production.



Some sites were not able to provide refinery-wide data for just asphalt runs, therefore, the product yields here do not align with those from the previous process steps. Given that electricity and water are allocated by mass, this would not significantly affect the final results.

Table 3-10: Unit process refinery level

Type	Flow	Value	Unit	LHV [MJ/kg]
Inputs	Electricity (includes CHP electricity)	1.95	MJ	
	Ground water	0.674	kg	
	River water	8.64	kg	
	Water (municipal)	7.64	kg	
Outputs	Asphalt binder (no additives)	1.00	kg	38.7
	Diesel	1.13	kg	43.0
	Proprietary products	0.456	kg	38.0
	Fuel oil	0.412	kg	39.5
	Gasoline	3.87	kg	43.9
	Kerosene	0.969	kg	43.0
	Liquefied petroleum gas	0.155	kg	46.2
	Lubricating oil	0.231	kg	38.0
	Naphtha	0.221	kg	44.0
	Petrol coke	0.401	kg	31.4
	Refinery gas	0.222	kg	48.2
	Sulphur	0.0712	kg	9.26
	Vacuum gas oil	0.470	kg	38.6
	Misc. refinery products	0.0784	kg	42.5
	Hazardous waste for further processing	3.57E-04	kg	
	Hazardous waste for incineration	7.64E-05	kg	
	Hazardous waste for land-filling	3.40E-04	kg	
	Water treated on-site, released to watershed	13.3	kg	
	Non-hazardous waste for further processing	5.44E-03	kg	
	Non-hazardous waste for land-filling	1.94E-03	kg	
	Waste for incineration without energy recovery	1.91E-04	kg	
	Waste water to treatment	2.84	kg	
	Water vapor	0.680	kg	

The thermal energy input presented in Table 3-11 was calculated using the formula presented in 2.4.3. Below is an example of the calculation using sample values only, as each refinery was modeled individually and then combined to create the production-weighted average. The specific heat value (C) used here is an example only, as each refinery provided their own data on this value. If a company was not able to provide the specific heat of asphalt, an average of the values reported by other sites was used.



$$C = 2763 \text{ J/kg-K [0.66 Btu/lb-F]}$$

$$T1 = 296 \text{ K [73°F]}$$

$$T2 = 445 \text{ K [342°F]}$$

$$\Delta T = T2 - T1 = 149 \text{ K [269°F]}$$

$$\eta = 0.88$$

$$\frac{\frac{2,763}{1,000,000} \times 149}{0.88} = 0.47 \text{ MJ/kg}$$

Table 3-11: Calculated thermal energy required per 1 kg of asphalt produced at refinery and emissions

Type	Flow	Value	Unit
Inputs	Thermal energy (mix of natural and refinery gas)	0.484	MJ
Outputs	Asphalt binder (at refinery)	1.00	kg
Emissions to air	Ammonia	3.25E-07	kg
	Arsenic (+V)	1.20E-10	kg
	Benzene	9.50E-08	kg
	Cadmium	1.35E-10	kg
	Carbon dioxide	3.33E-02	kg
	Carbon monoxide	3.24E-05	kg
	Chromium	6.41E-10	kg
	Cobalt	1.26E-10	kg
	Copper	5.38E-10	kg
	Cyanide	5.26E-07	kg
	Dust (PM2.5 - PM10)	9.41E-06	kg
	Hydrocarbons	1.33E-05	kg
	Hydrogen sulphide	2.78E-07	kg
	Lead	1.45E-09	kg
	Manganese	1.44E-10	kg
	Mercury	1.46E-10	kg
	Methane	1.28E-05	kg
	Molybdenum	1.05E-10	kg
	Nickel	7.67E-09	kg
	Nitrogen oxides	1.64E-05	kg
	Nitrous oxide	5.99E-07	kg
	NM VOC (unspecified)	1.37E-05	kg
	Polycyclic aromatic hydrocarbons (PAH, unspec.)	1.72E-09	kg
	Selenium	2.52E-10	kg
	Sulphur dioxide	6.13E-05	kg
	Vanadium	8.97E-09	kg



Type	Flow	Value	Unit
	Zinc	1.24E-08	kg
Emissions to water	Arsenic (+V)	1.16E-06	kg
	Biological oxygen demand (BOD)	4.46E-05	kg
	Cadmium	5.87E-11	kg
	Chemical oxygen demand (COD)	2.18E-05	kg
	Cobalt	1.68E-10	kg
	Copper	5.63E-09	kg
	Fluoride	6.63E-06	kg
	Lead	1.57E-09	kg
	Mercury	1.77E-11	kg
	Nickel	2.15E-08	kg
	Selenium	2.52E-10	kg
	Sulphide	1.86E-07	kg
	Vanadium	5.10E-08	kg
	Zinc	2.73E-08	kg
Emissions to soil	Hydrocarbons (unspecified)	1.13E-07	kg

Some emissions were removed from Table 3-11 if only fewer than three companies reported values.

Though other companies did report zero values for these emissions (leading to more than 5 data points for each value), due to the proprietary concerns associated with the collected data, the study practitioners erred on the side of caution and removed these emissions. Of the reported results, the removed emissions only affected EP, but by less than 1%.

3.2.6. Asphalt terminal

The processes within each refinery was vertically aggregated first and then combined into one production-weighted average each. The average asphalt production process then provided the input of asphalt to the average terminal process. No further effort was made to model supplier-specific inputs of asphalt to each terminal as the energy consumption of the terminal is expected to vary insignificantly across different suppliers. Inputs and outputs were collected for each terminal and were not differentiated between the products with different amounts of additives.

At the asphalt terminal, hot liquid asphalt is stored, additives (ground tire rubber, styrene-butadiene-styrene, or polyphosphoric acid) are mixed or milled into the asphalt, and hot liquid asphalt is further distributed. Energy reported is used for these purposes, with electricity mainly used for milling and thermal energy used for storage. Table 3-12 presents the unit process per 1 kg of product. Terminals can be either co-located with the refinery or off-site. For this study, all participating companies were located off-site. No data were available for co-located terminals. Inbound transportation from the refinery to the terminal is a production weighted average of the distances and modes collected from the companies. Site run-off



water has to be sent through treatment, therefore the input of rain water is calculated as the difference between water sent to treatment and the ground or municipal water inputs.

Note that this study only represents off-site terminals, which will likely be an overestimate for refineries with co-located terminals since they can take advantage of the heat already required for asphalt production. In contrast, off-site terminals need to re-heat the asphalt due to heat loss during transport. Additionally, co-location of a terminal with a refinery would also minimize the transport distance.

The input of the ground tire rubber (GTR) itself is burden-free, while the energy required to grind the tires is included (US EPA 2016). GTR is also considered as a non-renewable energy carrier, as seen in Table 4-5, Table 4-6, Table 4-7, and Table 4-8.

Table 3-12: Unit process asphalt terminal, per 1 kg asphalt binder

Type	Flow	Asphalt binder	w/ GTR	w/ PPA	w/ SBS	Unit	Mode	Dist [km]
Inputs	Asphalt binder (from refinery)	1.00	0.92	0.995	0.965	kg	Rail Ship Truck	707 159 200
	GTR	-	0.08	-	-	kg	Truck	930
	PPA	-	-	0.005	-	kg	Truck	230
	SBS	-	-	-	0.035	kg	Rail Ship Truck	357 11,376 383
	Ground water		0.00123			kg		
	Rain water		0.272			kg		
	Water (municipal water)		0.0258			kg		
	H ₂ S scavenger		1.62E-04			kg		
	Electricity		0.135			MJ		
	Thermal energy from natural gas ⁷		1.04			MJ		
	Thermal energy from propane ⁷		1.69E-04			MJ		
	Asphalt binder		1.00			kg		
	Asphalt binder		1.00			kg		
Emissions to air	Benzene		4.81E-07			kg		
	Carbon monoxide		2.28E-05			kg		
	Dust (PM2.5 - PM10)		1.20E-05			kg		
	Hazardous waste		7.42E-06			kg		
	Hydrogen sulphide		6.55E-08			kg		
	Nitrogen oxides		3.13E-05			kg		
	NM VOC (unspecified)		1.65E-04			kg		
	Non-haz waste for land-filling		0.00142			kg		

⁷ Background data for thermal energy from natural gas and propane include fuel combustion emissions. As this table only includes the primary data collected from participants, not GHG emissions are reported here.



Type	Flow	Asphalt binder	w/ GTR	w/ PPA	w/ SBS	Unit	Mode	Dist [km]
	Polycyclic aromatic hydrocarbons		1.29E-07			kg		
	Sulphur dioxide		2.37E-06			kg		
	Water (waste water, treated)		0.288			kg		
	Water vapour		0.0112			kg		
Emissions to water	Biological oxygen demand		1.07E-07			kg		
	Chemical oxygen demand		7.09E-07			kg		
	Zinc		2.41E-09			kg		

3.3. Background Data

3.3.1. Fuels and Energy

National or regional averages for fuel inputs and electricity grid mixes were obtained from the GaBi 2017 databases. Table 3-13 and Table 3-14 show the most relevant LCI datasets used in modeling the product systems and the upstream crude oil. Electricity consumption was modeled using regional grid mixes that account for imports from neighboring countries and regions. The exception to this is the Canadian grid mixes for the provinces of Ontario⁸ and Alberta⁹.

Documentation for all GaBi datasets can be found online (thinkstep 2018).

Table 3-13: Key energy datasets used in refinery and terminal inventory analysis

Energy	Location	Dataset	Data Provider	Reference Year
Electricity	CA	Electricity from biomass (solid)	ts	2013
Electricity	CA	Electricity from hard coal	ts	2013
Electricity	CA	Electricity from heavy fuel oil (HFO)	ts	2013
Electricity	CA	Electricity from hydro power	ts	2013
Electricity	CA	Electricity from natural gas	ts	2013
Electricity	US	Electricity from natural gas via CHP (w/o supply)	ts	2013
Electricity	CA	Electricity from nuclear	ts	2013
Electricity	CA	Electricity from photovoltaic	ts	2013
Electricity	CA	Electricity from wind power	ts	2013
Electricity	US	Electricity grid mix – CAMX	ts	2012

⁸ Ontario production grid mix: <http://www.ieso.ca/en/corporate-ieso/media/year-end-data/2015>

⁹ Alberta production grid mix: <http://www.auc.ab.ca/pages/annual-electricity-data.aspx>; Distribution loss source: <https://www.aeso.ca/grid/loss-factors/previous-loss-factors-and-calibration-factors/>



Energy	Location	Dataset	Data Provider	Reference Year
Electricity	US	Electricity grid mix – ERCT	ts	2012
Electricity	US	Electricity grid mix – MROW	ts	2012
Electricity	US	Electricity grid mix – NWPP	ts	2012
Electricity	US	Electricity grid mix – RFCW	ts	2012
Electricity	US	Electricity grid mix – RMPA	ts	2012
Electricity	US	Electricity grid mix – SRMV	ts	2012
Electricity	US	Electricity grid mix – SRSO	ts	2012
Electricity	US	Electricity grid mix – SRTV	ts	2012
Fuel	CA	Natural gas mix	ts	2013
Fuel	US	Natural gas mix	ts	2013
Fuel	US	Refinery gas at refinery	ts	2013

Table 3-14: Key energy datasets used in background data on crude oil extraction

Energy	Location	Dataset	Data Provider	Reference Year
Electricity	CA	Electricity from natural gas	ts	2013
Electricity	BR	Electricity grid mix	ts	2013
Electricity	CA	Electricity grid mix	ts	2013
Electricity	CL	Electricity grid mix	ts	2013
Electricity	IQ	Electricity grid mix	ts	2013
Electricity	KW	Electricity grid mix	ts	2013
Electricity	MX	Electricity grid mix	ts	2013
Electricity	SA	Electricity grid mix	ts	2013
Electricity	US	Electricity grid mix	ts	2013
Electricity	VE	Electricity grid mix	ts	2013
Fuel	EU-28	Bunker oil at refinery	ts	2013
Fuel	IN	Diesel at refinery	ts	2013
Fuel	BR	Diesel mix at refinery	ts	2013
Fuel	EU-28	Diesel mix at refinery	ts	2013
Fuel	US	Diesel mix at refinery	ts	2013
Fuel	US	Gasoline mix (premium) at refinery	ts	2013
Fuel	US	Kerosene / Jet A1 at refinery	ts	2013
Fuel	EU-28	Light fuel oil at refinery	ts	2013
Fuel	US	Light fuel oil at refinery	ts	2013
Fuel	CA	Natural gas mix	ts	2013
Fuel	US	Propane at refinery	ts	2013



Energy	Location	Dataset	Data Provider	Reference Year
Fuel	US	Refinery gas at refinery	ts	2013
Thermal energy	CA	Thermal energy from natural gas	ts	2013

3.3.2. Raw Materials and Processes

Data for upstream and downstream raw materials and unit processes were obtained from the GaBi 2017 database. All data for crude oil extraction and transport was generated using GaBi background data, customized to the region and extraction methods specified by each company. Table 3-15 shows the most relevant LCI datasets used in modeling the product systems. Documentation for all GaBi datasets can be found online (thinkstep 2018).

Table 3-15: Key material and process datasets used in inventory analysis

Material / Process	Geographic Reference	Dataset	Data Provider	Ref Year	Proxy?
Crude oil	Customized	Crude oil (customized based on information provided by companies)	ts	2016	Some
PPA	US	Phosphoric acid (highly pure)	ts	2016	Y
SBS	US	Styrene-butadiene rubber (SBR)	ts	2016	N
Water	US	Tap water from groundwater	ts	2016	N
H ₂ S Scavenger	US	Wax / Paraffins at refinery	ts	2013	Y
Landfill	US	Glass/inert on landfill	ts	2016	N
Hazardous waste	GLO	Hazardous waste (non-specific) (C rich, worst case scenario incl. landfill)	ts	2016	N
Waste water treatment	US	Municipal waste water treatment (mix)	ts	2016	N

3.3.3. Transportation

Average transportation distances and modes of transport are included for the transport of the raw materials, operating materials, and auxiliary materials to refineries and terminals.

The GaBi 2017 database was used to model transportation. Truck transportation within the United States was modeled using the GaBi US truck transportation datasets. The vehicle types, fuel usage, and emissions for these transportation processes were developed using a GaBi model based on the most recent US Census Bureau Vehicle Inventory and Use Survey (2002) and US EPA emissions standards for heavy trucks in 2007. The 2002 VIUS survey is the latest available data source describing truck fleet fuel consumption and utilization ratios in the US based on field data (Langer 2013), and the 2007 EPA emissions standards are considered to be the appropriate data available for describing current US truck emissions, leading to conservative truck transportation results. Fuels were modeled using the geographically appropriate datasets.

**Table 3-16: Transportation and road fuel datasets**

Mode / fuels	Geographic Reference	Dataset	Data Provider	Reference Year
Container ship	GLO	Container ship, 27500 dwt payload capacity, ocean going	ts	2016
Rail	GLO	Rail transport cargo - average, average train, gross tonne weight 1000t / 726t payload capacity	ts	2016
Truck	US	Truck - Heavy Heavy-duty Diesel Truck / 53,333 lb payload - 8b	ts	2016
Fuel	US	Diesel mix at filling station (100% fossil)	ts	2013
Fuel	US	Heavy fuel oil at refinery (0.3wt.% S)	ts	2013
Pipeline	GLO	Crude oil pipeline XX-02 (customized by region)	ts	2016
Oil tanker	GLO	Oil tanker / 10.000-300.000 dwt / Ocean-going	ts	2012

3.4. Life Cycle Inventory Analysis Results

ISO 14044 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, Table 3-17 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 for asphalt binder, no additives. Results for the other three products can be found in Appendix B.

Table 3-17: LCI results of asphalt binder, per 1 kg of product

Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
Inputs							
Non-renewable energy resources [MJ]	Crude oil (resource) ¹⁰	4.23E+01	1.51E-01	3.21E-01	2.75E-01	3.42E-02	4.31E+01
	Hard coal (resource)	1.03E-01	5.37E-02	1.04E-01	8.38E-02	1.07E-01	4.52E-01
	Lignite (resource)	2.23E-02	9.99E-03	1.62E-02	5.37E-03	3.62E-02	9.00E-02
	Natural gas (resource)	7.15E+00	5.71E-02	6.49E-01	7.92E-02	1.43E+00	9.37E+00
	Peat (resource)	3.46E-05	2.52E-06	1.79E-06	6.01E-07	3.30E-06	4.28E-05
	Uranium (resource)	5.12E-02	3.83E-02	5.42E-02	4.17E-02	5.68E-02	2.42E-01
Renewable energy	Primary energy from geothermics	9.91E-04	1.06E-03	1.57E-03	1.51E-03	4.85E-05	5.17E-03

¹⁰ Crude oil (resource) includes crude used as a feedstock and as an energy resource. The split between the two can be found in Table 4-5



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
resources [MJ]	Primary energy from hydro power	4.62E-02	2.49E-02	6.84E-03	7.34E-03	4.63E-03	8.99E-02
	Primary energy from solar energy	1.86E-02	4.71E-03	7.82E-03	6.01E-03	4.31E-03	4.15E-02
	Primary energy from waves	4.28E-15	6.40E-16	9.90E-16	9.01E-16	5.95E-16	7.41E-15
	Primary energy from wind power	8.37E-03	6.21E-03	1.51E-02	7.76E-03	2.80E-02	6.54E-02
Non-renewable elements [kg]	Antimony	3.71E-10	1.17E-11	2.64E-11	1.54E-11	3.44E-11	4.59E-10
	Chromium	2.08E-07	1.07E-07	5.44E-08	4.34E-08	6.50E-08	4.77E-07
	Lead	4.60E-05	1.50E-07	2.40E-06	6.03E-07	5.03E-06	5.42E-05
	Silver	4.89E-08	2.01E-10	2.59E-09	6.91E-10	5.37E-09	5.77E-08
	Zinc	2.98E-05	1.22E-07	1.57E-06	4.22E-07	3.26E-06	3.51E-05
Non-renewable resources [kg]	Colemanite ore	2.91E-05	1.21E-08	5.09E-08	3.07E-08	4.95E-08	2.92E-05
	Sodium chloride (rock salt)	5.88E-04	3.86E-06	8.51E-05	2.23E-06	3.56E-05	7.15E-04
Water resources [kg]	Ground water	9.99E-02	7.49E-03	1.66E+00	8.16E-03	6.39E-02	1.84E+00
	Lake water	5.58E-02	2.53E-04	5.21E-03	4.09E-03	1.08E-03	6.64E-02
	Lake water to turbine	1.23E+01	6.66E+00	1.72E+00	1.87E+00	1.20E+00	2.37E+01
	Rain water	2.76E-01	2.16E-02	4.56E-02	2.78E-02	3.16E-01	6.87E-01
	River water	1.76E+01	7.69E-01	2.58E+00	6.51E-01	1.16E+00	2.28E+01
	River water to turbine	4.17E+01	2.17E+01	6.34E+00	6.42E+00	4.36E+00	8.06E+01
	Sea water	1.35E+00	2.06E-01	5.16E-01	2.43E-01	4.14E-01	2.72E+00
Renewable resources [kg]	Carbon dioxide	1.74E-03	3.85E-04	7.46E-04	4.97E-04	4.13E-04	3.78E-03
	Nitrogen	6.26E-14	9.84E-15	1.60E-14	1.46E-14	8.53E-15	1.12E-13
	Oxygen	2.26E-04	6.88E-06	5.05E-05	6.62E-03	1.20E-04	7.03E-03
Outputs							
Deposited goods [kg]	Hazardous waste (deposited)	1.08E-08	6.11E-11	2.40E-09	1.87E-10	4.90E-10	1.40E-08
	Overburden (deposited)	5.98E-02	1.81E-02	3.72E-02	1.97E-02	5.14E-02	1.86E-01
	Slag (deposited)	5.20E-14	1.83E-14	1.45E-14	2.46E-14	8.44E-15	1.18E-13
	Spoil (deposited)	1.91E-02	4.12E-04	2.36E-03	4.12E-04	5.42E-03	2.77E-02
	Tailings (deposited)	4.20E-01	8.89E-05	1.94E-03	1.83E-03	3.32E-04	4.24E-01
	Waste (deposited)	7.44E-04	4.78E-05	2.90E-03	6.31E-05	2.55E-03	6.30E-03
Inorganic emissions to air	Aluminium	1.89E-11	6.65E-12	5.39E-12	9.12E-12	3.13E-12	4.31E-11
	Ammonia	1.46E-06	8.18E-08	1.48E-06	4.82E-07	1.09E-06	4.60E-06
	Carbon dioxide	3.59E-01	9.40E-03	7.14E-02	3.17E-02	9.30E-02	5.64E-01
	Carbon dioxide (aviation)	4.31E-08	2.21E-08	4.13E-08	2.78E-08	6.78E-08	2.02E-07
	Carbon dioxide (biotic)	1.07E-03	3.84E-04	2.34E-03	1.13E-03	9.19E-04	5.84E-03
	Carbon dioxide (land use change)	2.14E-04	3.12E-06	1.04E-05	6.10E-06	1.12E-05	2.45E-04



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
	Carbon dioxide (peat oxidation)	1.66E-10	4.17E-11	1.05E-06	5.56E-11	7.42E-11	1.05E-06
	Carbon monoxide	3.55E-04	4.22E-06	5.47E-05	4.44E-05	5.66E-05	5.15E-04
	Chlorine	6.00E-09	6.80E-11	1.23E-07	1.04E-10	5.23E-08	1.81E-07
	Hydrogen chloride	8.85E-07	5.19E-07	6.91E-07	4.22E-07	4.30E-07	2.95E-06
	Hydrogen sulphide	2.66E-06	4.43E-07	1.39E-06	6.42E-07	3.57E-07	5.49E-06
	Nitrogen dioxide	6.65E-08	2.75E-09	8.17E-09	2.61E-08	1.94E-08	1.23E-07
	Nitrogen monoxide	6.54E-07	1.62E-08	1.49E-07	3.26E-07	9.02E-08	1.24E-06
	Nitrogen oxides	1.01E-03	1.73E-05	6.82E-05	1.92E-04	1.19E-04	1.41E-03
	Nitrogen, total	7.26E-14	9.32E-14	2.56E-09	1.16E-13	1.42E-13	2.56E-09
	Nitrogen trifluoride	9.16E-14	5.11E-14	1.07E-13	6.32E-14	1.85E-13	4.98E-13
	Nitrous oxide	7.35E-06	1.76E-07	1.91E-07	3.74E-07	2.57E-07	8.35E-06
	Sulphur dioxide	5.02E-04	4.20E-05	1.05E-04	6.59E-05	4.56E-05	7.60E-04
	Sulphur hexafluoride	1.29E-14	1.38E-14	2.05E-14	1.96E-14	6.32E-16	6.74E-14
	Sulphur trioxide	1.51E-09	2.39E-10	7.73E-10	3.17E-10	3.82E-10	3.22E-09
	Sulphuric acid	3.35E-09	1.12E-11	1.76E-10	4.40E-11	3.69E-10	3.95E-09
Organic emissions to air [kg]	Methane	1.83E-03	1.62E-05	1.57E-04	3.94E-05	2.68E-04	2.31E-03
	Methane (biotic)	9.20E-07	9.52E-08	2.61E-05	1.06E-07	8.21E-06	3.55E-05
Halogenated organic emissions to air [kg]	Chloromethane (methyl chloride)	3.82E-15	7.88E-16	2.00E-11	1.08E-15	1.47E-15	2.00E-11
	R 114 (dichlorotetrafluoroethane)	4.80E-12	4.11E-12	6.37E-12	4.96E-12	6.40E-12	2.66E-11
	R 22 (chlorodifluoromethane)	3.57E-13	2.28E-13	2.68E-13	2.03E-13	3.12E-13	1.37E-12
NM VOC (organic) emissions to air [kg]	NM VOC (unspecified)	1.10E-04	2.86E-07	1.69E-05	1.03E-05	1.70E-04	3.07E-04
Heavy metals to air [kg]	Antimony	2.20E-10	6.45E-11	1.94E-10	9.27E-11	1.57E-10	7.28E-10
	Arsenic	3.69E-14	4.17E-16	1.63E-15	5.15E-16	2.66E-15	4.21E-14
	Arsenic (+V)	1.84E-09	7.38E-10	1.32E-09	1.00E-09	1.44E-09	6.35E-09
	Arsenic trioxide	7.46E-13	2.33E-15	3.89E-14	9.67E-15	8.17E-14	8.79E-13
	Cadmium	3.66E-10	4.09E-11	5.79E-10	7.66E-11	1.01E-10	1.16E-09
	Chromium	7.62E-09	1.37E-10	1.30E-09	2.27E-10	1.07E-09	1.04E-08
	Chromium (+III)	1.47E-10	7.05E-13	7.91E-12	2.11E-12	1.08E-11	1.69E-10
	Chromium (+VI)	1.54E-15	1.79E-17	9.09E-17	2.84E-17	1.81E-16	1.86E-15
	Cobalt	4.41E-10	6.81E-11	2.41E-10	5.98E-11	9.75E-11	9.08E-10
	Copper	8.93E-09	1.69E-10	1.61E-09	2.88E-10	1.38E-09	1.24E-08
	Hydrogen arsenic (arsine)	6.19E-11	1.93E-13	3.23E-12	8.03E-13	6.78E-12	7.30E-11
	Iron	1.83E-07	8.23E-10	1.24E-08	3.22E-09	1.99E-08	2.19E-07
	Lanthanum	1.21E-17	1.29E-17	1.91E-17	1.83E-17	5.94E-19	6.31E-17
	Lead	1.27E-07	1.06E-09	1.07E-08	2.39E-09	1.53E-08	1.56E-07
	Manganese	2.51E-07	1.51E-09	1.80E-08	4.21E-09	3.04E-08	3.05E-07



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
	Mercury	8.39E-10	1.20E-10	1.64E-08	1.26E-10	8.49E-10	1.83E-08
	Molybdenum	2.31E-10	5.78E-12	1.27E-10	1.65E-11	8.81E-12	3.89E-10
	Nickel	6.81E-09	2.43E-09	8.32E-09	4.36E-10	5.54E-10	1.86E-08
	Palladium	6.67E-18	7.09E-18	1.05E-17	1.01E-17	3.26E-19	3.47E-17
	Rhodium	6.44E-18	6.85E-18	1.02E-17	9.75E-18	3.14E-19	3.35E-17
	Scandium	6.19E-18	6.57E-18	9.80E-18	9.40E-18	3.04E-19	3.23E-17
	Selenium	2.57E-09	1.98E-09	3.14E-09	2.62E-09	3.35E-09	1.37E-08
	Silver	1.89E-11	6.65E-12	5.39E-12	9.12E-12	3.13E-12	4.31E-11
	Tellurium	1.38E-11	6.39E-14	6.48E-13	2.02E-13	8.45E-13	1.55E-11
	Thallium	9.41E-11	4.36E-13	5.63E-12	1.40E-12	8.87E-12	1.10E-10
	Tin	2.31E-09	6.39E-10	1.36E-09	1.01E-09	1.52E-09	6.83E-09
	Titanium	3.49E-09	1.60E-11	2.32E-10	5.18E-11	3.95E-10	4.19E-09
	Vanadium	2.68E-08	9.23E-09	1.17E-08	1.78E-09	1.71E-09	5.12E-08
	Zinc	2.01E-08	1.34E-09	1.69E-08	2.97E-09	4.78E-09	4.61E-08
Particles to air [kg]	Dust (> PM10)	2.34E-06	1.28E-06	2.52E-06	1.85E-06	2.89E-06	1.09E-05
	Dust (PM10)	5.17E-08	5.22E-10	6.81E-09	1.98E-06	1.01E-08	2.05E-06
	Dust (PM2.5 - PM10)	3.06E-05	8.20E-07	1.29E-05	5.09E-07	1.25E-05	5.73E-05
	Dust (PM2.5)	2.11E-05	3.70E-07	1.62E-06	4.53E-06	2.38E-06	2.99E-05
	Silicon dioxide (silica)	1.78E-12	6.26E-13	5.08E-13	8.58E-13	2.94E-13	4.06E-12
Inorganic emissions to freshwater [kg]	Ammonia	1.18E-07	2.35E-08	3.99E-08	2.70E-08	4.51E-08	2.53E-07
	Ammonium	1.88E-07	1.34E-08	4.59E-06	2.03E-08	1.85E-06	6.67E-06
	Nitrate	4.90E-06	5.74E-07	8.41E-06	8.05E-07	4.17E-06	1.89E-05
	Nitrogen organic bound	1.89E-06	6.03E-08	2.82E-05	1.40E-07	4.81E-07	3.08E-05
	Phosphate	4.04E-07	1.47E-08	1.53E-06	3.05E-08	3.48E-08	2.02E-06
	Phosphorus	2.42E-08	9.85E-10	2.36E-06	1.37E-09	1.02E-06	3.41E-06
Heavy metals to fresh water [kg]	Antimony	3.73E-12	3.64E-12	1.89E-10	5.81E-12	7.02E-12	2.10E-10
	Arsenic	7.81E-14	6.23E-16	3.35E-15	7.28E-16	5.59E-15	8.84E-14
	Arsenic (+V)	2.71E-06	7.78E-10	1.20E-06	2.60E-08	5.32E-09	3.93E-06
	Cadmium	1.18E-06	5.25E-10	2.74E-08	1.14E-08	1.29E-08	1.24E-06
	Chromium	1.31E-05	9.99E-08	1.46E-06	1.93E-07	3.48E-06	1.83E-05
	Chromium (+III)	1.02E-09	1.80E-10	2.91E-10	2.03E-10	3.00E-10	1.99E-09
	Chromium (+VI)	1.04E-10	2.47E-12	4.49E-09	3.66E-12	1.91E-09	6.52E-09
	Cobalt	7.55E-12	1.73E-13	4.93E-10	2.56E-13	1.30E-10	6.31E-10
	Copper	1.32E-06	1.18E-09	3.88E-08	1.48E-08	3.28E-08	1.41E-06
	Iron	3.08E-05	1.83E-05	2.97E-05	9.94E-06	6.73E-05	1.56E-04
	Lead	9.79E-07	2.49E-09	3.13E-08	1.16E-08	4.34E-08	1.07E-06
	Manganese	8.61E-09	5.09E-09	2.83E-08	6.80E-09	1.69E-08	6.57E-08
	Mercury	8.80E-09	2.18E-11	3.96E-10	1.19E-10	2.86E-10	9.62E-09
	Molybdenum	3.46E-09	2.28E-09	2.86E-09	2.18E-09	3.30E-09	1.41E-08
	Nickel	1.61E-06	1.14E-09	5.09E-08	1.66E-08	1.69E-08	1.70E-06
	Selenium	5.74E-10	2.88E-10	7.40E-08	3.26E-10	4.39E-10	7.56E-08
	Silver	1.52E-11	1.51E-12	6.02E-10	2.16E-12	2.57E-10	8.78E-10
	Tantalum	3.63E-17	2.39E-17	5.75E-17	2.88E-17	1.05E-16	2.51E-16
	Thallium	2.62E-11	8.17E-14	1.37E-12	3.39E-13	2.87E-12	3.08E-11
	Tin	9.58E-16	4.13E-16	4.40E-17	1.76E-17	2.34E-16	1.67E-15
	Titanium	7.78E-10	3.23E-10	4.39E-10	3.14E-10	4.81E-10	2.33E-09
	Tungsten	1.47E-12	4.78E-13	1.14E-12	6.12E-13	1.86E-12	5.56E-12
	Vanadium	1.50E-09	4.11E-10	5.16E-08	4.67E-10	5.95E-10	5.45E-08



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
	Zinc	1.15E-07	9.27E-10	5.60E-08	2.60E-09	1.97E-08	1.94E-07
Water quality metrics [kg]	Adsorbable organic halogen compounds (AOX)	9.83E-09	3.63E-09	3.72E-07	5.15E-09	9.23E-08	4.83E-07
	Biological oxygen demand (BOD)	1.01E-05	1.67E-08	5.09E-05	1.41E-07	3.12E-06	6.43E-05
	Chemical oxygen demand (COD)	2.31E-04	1.19E-05	2.58E-04	1.55E-05	3.03E-05	5.47E-04
	Nitrogenous Matter	2.19E-07	1.02E-09	1.61E-08	3.23E-09	2.51E-08	2.64E-07
	Solids (dissolved)	2.98E-08	2.47E-08	4.58E-08	3.55E-08	4.22E-08	1.78E-07
	Total dissolved organic bound carbon (TOC)	4.52E-12	2.01E-12	4.26E-13	2.08E-13	1.86E-12	9.03E-12
	Total organic bound carbon (TOC)	9.95E-06	1.42E-08	4.81E-05	1.31E-07	4.65E-07	5.86E-05
Other emissions to fresh water ¹¹ [kg]	Collected rainwater to river	5.39E-04	3.41E-05	5.24E-03	4.49E-05	4.98E-03	1.08E-02
	Cooling water to river	1.66E+01	7.31E-01	1.46E+00	5.78E-01	1.09E+00	2.04E+01
	Processed water to groundwater	2.51E-03	1.11E-04	1.84E+00	1.74E-04	1.30E-03	1.84E+00
	Processed water to river	2.04E-01	6.09E-03	6.92E-01	1.65E-02	3.12E-01	1.23E+00
	Turbined water to river	5.47E+01	2.79E+01	8.07E+00	8.28E+00	5.55E+00	1.05E+02
Water releases to sea water [kg]	Cooling water to sea	1.33E+00	2.03E-01	5.13E-01	2.42E-01	4.11E-01	2.70E+00
	Processed water to sea	9.45E-03	3.12E-06	8.76E-05	4.11E-05	7.90E-05	9.67E-03

¹¹ If process water is sent to treatment, the output of treated water is included here.



4. LCIA Results

This chapter contains the results for 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 (a) followed the underlying impact pathway and (b) met 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

4.1.1. Impact assessment results

The life cycle impact results for the various asphalt products are presented in Table 4-1 through Table 4-4.

Table 4-1: Impact assessment, asphalt no additives, per kg (IPCC 2013, Guinée, et al. 2002, EPA 2012)

Impact Category	Unit	Asphalt binder, Crude oil	Asphalt binder, Transport	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
IPCC AR5							
Global warming potential [GWP100]	kg CO ₂ eq	0.403	0.0225	0.0769	0.0330	0.101	0.637
Global warming potential [GWP20]	kg CO ₂ eq	0.503	0.0243	0.0870	0.0351	0.117	0.766
CML 2001 (v4.1)							
Ozone depletion potential	kg CFC-11 eq	4.53E-12	3.87E-12	6.40E-12	4.67E-12	6.03E-12	2.55E-11
Acidification potential	kg SO ₂ eq	7.49E-04	4.26E-04	1.66E-04	1.78E-04	1.17E-04	1.64E-03
Eutrophication potential	kg PO ₄ ³⁻ eq	4.38E-04	4.20E-05	5.25E-05	2.74E-05	2.50E-05	5.85E-04
Photochemical ozone creation potential	kg C ₂ H ₄ eq	3.33E-04	2.30E-05	1.71E-05	1.34E-05	3.76E-05	4.24E-04
Abiotic depletion potential for non-fossil resources	kg Sb eq	4.07E-07	2.67E-09	2.19E-08	5.75E-09	4.27E-08	4.80E-07
Abiotic depletion potential for fossil resources	MJ	49.6	0.272	1.09	0.443	1.61	53.0
TRACI 2.1							
Ozone depletion potential	kg CFC-11 eq	4.81E-12	4.11E-12	6.79E-12	4.97E-12	6.41E-12	2.71E-11
Acidification potential	kg SO ₂ eq	8.28E-04	4.46E-04	1.68E-04	2.04E-04	1.36E-04	1.78E-03
Eutrophication potential	kg N eq	5.04E-05	1.50E-05	7.30E-05	9.85E-06	1.76E-05	1.66E-04
Smog formation potential	kg O ₃ eq	0.0181	7.90E-03	1.76E-03	4.82E-03	3.44E-03	0.0360
Fossil fuel consumption	MJ	4.88	0.0308	0.142	0.0499	0.220	5.32
Human health particulate effects	kg PM _{2.5} eq	5.38E-05	4.08E-05	2.21E-05	1.14E-05	1.93E-05	1.47E-04



Table 4-2: Impact assessment, asphalt with 8% GTR, per kg (IPCC 2013, Guinée, et al. 2002, EPA 2012)

Impact Category	Unit	Asph. bind GTR, Crude oil	Asph. bind GTR, Transport to refinery	Asph. bind GTR, Refinery	Asph. bind GTR, Transport to terminal	Asph. bind GTR, Terminal	Total
IPCC AR5							
Global warming potential [GWP100]	kg CO ₂ eq	0.371	0.0207	0.0707	0.0362	0.122	0.621
Global warming potential [GWP20]	kg CO ₂ eq	0.463	0.0223	0.0800	0.0385	0.141	0.745
CML 2001 (v4.1)							
Ozone depletion potential	kg CFC-11 eq	4.16E-12	3.56E-12	5.89E-12	4.35E-12	6.04E-12	2.40E-11
Acidification potential	kg SO ₂ eq	6.89E-04	3.92E-04	1.53E-04	1.83E-04	1.30E-04	1.55E-03
Eutrophication potential	kg PO ₄ ³⁻ eq	4.03E-04	3.86E-05	4.83E-05	3.01E-05	2.75E-05	5.48E-04
Photochemical ozone creation potential	kg C ₂ H ₄ eq	3.07E-04	2.11E-05	1.57E-05	1.43E-05	3.96E-05	3.97E-04
Abiotic depletion potential for non-fossil resources	kg Sb eq	3.75E-07	2.46E-09	2.02E-08	6.25E-09	5.27E-08	4.56E-07
Abiotic depletion potential for fossil resources	MJ	45.6	0.250	1.00	0.494	1.96	49.3
TRACI 2.1							
Ozone depletion potential	kg CFC-11 eq	4.43E-12	3.79E-12	6.24E-12	4.63E-12	6.42E-12	2.55E-11
Acidification potential	kg SO ₂ eq	7.62E-04	4.10E-04	1.55E-04	2.13E-04	1.52E-04	1.69E-03
Eutrophication potential	kg N eq	4.64E-05	1.38E-05	6.71E-05	1.07E-05	1.86E-05	1.57E-04
Smog formation potential	kg O ₃ eq	0.0166	7.27E-03	1.62E-03	5.28E-03	3.90E-03	0.0347
Fossil fuel consumption	MJ	4.49	0.0283	0.130	0.0575	0.273	4.98
Human health particulate effects	kg PM2.5 eq	4.95E-05	3.75E-05	2.04E-05	1.18E-05	2.01E-05	1.39E-04

Table 4-3: Impact assessment, asphalt with 0.5% PPA, per kg (IPCC 2013, Guinée, et al. 2002, EPA 2012)

Impact Category	Unit	Asph. bind PPA, Crude oil	Asph. bind PPA, Transport to refinery	Asph. bind PPA, Refinery	Asph. bind PPA, Transport to terminal	Asph. bind PPA, Terminal	Total
IPCC AR5							
Global warming potential [GWP100]	kg CO ₂ eq	0.401	0.0224	0.0765	0.0329	0.121	0.654
Global warming potential [GWP20]	kg CO ₂ eq	0.501	0.0242	0.0865	0.0350	0.139	0.786
CML 2001 (v4.1)							
Ozone depletion potential	kg CFC-11 eq	4.50E-12	3.85E-12	6.37E-12	4.65E-12	7.43E-12	2.68E-11
Acidification potential	kg SO ₂ eq	7.45E-04	4.24E-04	1.65E-04	1.77E-04	3.25E-04	1.84E-03
Eutrophication potential	kg PO ₄ ³⁻ eq	4.36E-04	4.18E-05	5.23E-05	2.73E-05	3.13E-05	5.88E-04
Photochemical ozone creation potential	kg C ₂ H ₄ eq	3.32E-04	2.28E-05	1.70E-05	1.33E-05	4.90E-05	4.34E-04
Abiotic depletion potential for non-fossil resources	kg Sb eq	4.05E-07	2.66E-09	2.18E-08	5.73E-09	8.30E-08	5.19E-07



Impact Category	Unit	Asph. bind PPA, Crude oil	Asph. bind PPA, Transport to refinery	Asph. bind PPA, Refinery	Asph. bind PPA, Transport to terminal	Asph. bind PPA, Terminal	Total
Abiotic depletion potential for fossil resources	MJ	49.3	0.271	1.09	0.442	2.11	53.2
TRACI 2.1							
Ozone depletion potential	kg CFC-11 eq	4.79E-12	4.09E-12	6.75E-12	4.95E-12	7.90E-12	2.85E-11
Acidification potential	kg SO ₂ eq	8.24E-04	4.43E-04	1.67E-04	2.03E-04	3.18E-04	1.96E-03
Eutrophication potential	kg N eq	5.02E-05	1.49E-05	7.26E-05	9.83E-06	2.13E-05	1.69E-04
Smog formation potential	kg O ₃ eq	0.0180	7.86E-03	1.75E-03	4.81E-03	4.14E-03	0.0365
Fossil fuel consumption	MJ	4.85	0.0306	0.141	0.0498	0.287	5.36
Human health particulate effects	kg PM2.5 eq	5.35E-05	4.05E-05	2.20E-05	1.13E-05	4.62E-05	1.74E-04

Table 4-4: Impact assessment, asphalt with 3.5% SBS, per kg (IPCC 2013, Guinée, et al. 2002, EPA 2012)

Impact Category	Unit	Asph. bind SBS, Crude oil	Asph. bind SBS, Transport to refinery	Asph. bind SBS, Refinery	Asph. bind SBS, Transport to terminal	Asph. bind SBS, Terminal	Total
IPCC AR5							
Global warming potential [GWP100]	kg CO ₂ eq	0.389	0.0217	0.0742	0.0391	0.241	0.765
Global warming potential [GWP20]	kg CO ₂ eq	0.486	0.0234	0.0839	0.0415	0.284	0.918
CML 2001 (v4.1)							
Ozone depletion potential	kg CFC-11 eq	4.37E-12	3.73E-12	6.18E-12	4.64E-12	1.12E-11	3.01E-11
Acidification potential	kg SO ₂ eq	7.22E-04	4.11E-04	1.60E-04	3.47E-04	3.03E-04	1.94E-03
Eutrophication potential	kg PO ₄ ³⁻ eq	4.23E-04	4.05E-05	5.07E-05	4.53E-05	5.63E-05	6.16E-04
Photochemical ozone creation potential	kg C ₂ H ₄ eq	3.22E-04	2.22E-05	1.65E-05	2.27E-05	6.93E-05	4.52E-04
Abiotic depletion potential for non-fossil resources	kg Sb eq	3.93E-07	2.58E-09	2.11E-08	6.62E-09	1.41E-07	5.65E-07
Abiotic depletion potential for fossil resources	MJ	47.8	0.263	1.05	0.522	5.19	54.9
TRACI 2.1							
Ozone depletion potential	kg CFC-11 eq	4.65E-12	3.97E-12	6.55E-12	4.94E-12	1.19E-11	3.20E-11
Acidification potential	kg SO ₂ eq	7.99E-04	4.30E-04	1.62E-04	3.82E-04	3.42E-04	2.12E-03
Eutrophication potential	kg N eq	4.87E-05	1.45E-05	7.04E-05	1.59E-05	3.27E-05	1.82E-04
Smog formation potential	kg O ₃ eq	0.0174	7.62E-03	1.70E-03	8.16E-03	7.78E-03	0.0427
Fossil fuel consumption	MJ	4.70	0.0297	0.137	0.0606	0.726	5.66
Human health particulate effects	kg PM2.5 eq	5.19E-05	3.93E-05	2.14E-05	2.08E-05	3.28E-05	1.66E-04



4.1.2. Resource use results

The resource use results for the various asphalt products are presented in Table 4-5 through Table 4-8. Note that water consumption values at the terminal are negative when rain is excluded due to the storm water runoff that is sent to municipal waste water treatment.

Table 4-5: Resource use, asphalt binder no additives, per kg

Resource	Unit	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
Renewable primary energy as energy carrier	MJ	0.0743	0.0368	0.0313	0.0226	0.0370	0.202
Renewable primary energy resource as material utilization	MJ	-	-	-	-	-	-
Total use of renewable primary energy resources	MJ	0.0743	0.0368	0.0313	0.0226	0.0370	0.202
Non-renewable primary energy as energy carrier	MJ	7.43	1.56	1.14	0.485	1.66	12.3
Non-renewable primary energy as material utilization	MJ	41.0	-	-	-	-	41.0
Total use of non-renewable primary energy resources	MJ	48.4	1.56	1.14	0.485	1.66	53.2
Use of secondary materials	kg	-	-	-	-	-	-
Use of renewable secondary fuels	MJ	-	-	-	-	-	-
Use of non-renewable secondary fuels	MJ	-	-	-	-	-	-
Use of net fresh water (excl. rain water)	L	0.744	0.113	0.244	0.0721	-0.165	1.01
Use of net fresh water (incl. rain water)	L	1.019	0.135	0.284	0.100	0.147	1.68

Table 4-6: Resource use, asphalt with 8% GTR, per kg

Resource	Unit	Asph. bind GRT, Crude oil	Asph. bind GRT, Transport to refinery	Asph. bind GRT, Refinery	Asph. bind GRT, Transport to terminal	Asph. bind GRT, Terminal	Total
Renewable primary energy as energy carrier	MJ	0.0683	0.0339	0.0288	0.0211	0.0373	0.189
Renewable primary energy resource as material utilization	MJ	-	-	-	-	-	-
Total use of renewable primary energy resources	MJ	0.0683	0.0339	0.0288	0.0211	0.0373	0.189
Non-renewable primary energy as energy carrier	MJ	6.83	1.44	1.05	0.533	2.02	11.9
Non-renewable primary energy as material utilization	MJ	37.7	-	-	-	2.64	40.3
Total use of non-renewable primary energy resources	MJ	44.5	1.44	1.05	0.533	4.66	52.2
Use of secondary materials	kg	-	-	-	-	0.080	0.080
Use of renewable secondary fuels	MJ	-	-	-	-	-	-
Use of non-renewable secondary fuels	MJ	-	-	-	-	-	-
Use of net fresh water (excl. rain water)	L	0.685	0.104	0.224	0.0676	-0.161	0.92
Use of net fresh water (incl. rain water)	L	0.937	0.124	0.261	0.094	0.154	1.57



Table 4-7: Resource use, asphalt with 0.5% PPA, per kg

Resource	Unit	Asph. bind PPA, Crude oil	Asph. bind PPA, Transport to refinery	Asph. bind PPA, Refinery	Asph. bind PPA, Transport to terminal	Asph. bind PPA, Terminal	Total
Renewable primary energy as energy carrier	MJ	0.0739	0.0367	0.0311	0.0225	0.0471	0.211
Renewable primary energy resource as material utilization	MJ	-	-	-	-	-	-
Total use of renewable primary energy resources	MJ	0.0739	0.0367	0.0311	0.0225	0.0471	0.211
Non-renewable primary energy as energy carrier	MJ	7.39	1.55	1.14	0.484	2.18	12.7
Non-renewable primary energy as material utilization	MJ	40.8	-	-	-	-	40.8
Total use of non-renewable primary energy resources	MJ	48.1	1.55	1.14	0.484	2.18	53.5
Use of secondary materials	kg	-	-	-	-	-	-
Use of renewable secondary fuels	MJ	-	-	-	-	-	-
Use of non-renewable secondary fuels	MJ	-	-	-	-	-	-
Use of net fresh water (excl. rain water)	L	0.740	0.113	0.242	0.0717	-0.109	1.06
Use of net fresh water (incl. rain water)	L	1.014	0.134	0.283	0.099	0.227	1.76

Table 4-8: Resource use, asphalt with 3.5% SBS, per kg

Resource	Unit	Asph. bind SBS, Crude oil	Asph. bind SBS, Transport to refinery	Asph. bind SBS, Refinery	Asph. bind SBS, Transport to terminal	Asph. bind SBS, Terminal	Total
Renewable primary energy as energy carrier	MJ	0.0717	0.0355	0.0302	0.0225	0.0803	0.240
Renewable primary energy resource as material utilization	MJ	-	-	-	-	-	-
Total use of renewable primary energy resources	MJ	0.0717	0.0355	0.0302	0.0225	0.0803	0.240
Non-renewable primary energy as energy carrier	MJ	7.17	1.51	1.10	0.563	5.30	15.6
Non-renewable primary energy as material utilization	MJ	39.5	-	-	-	-	39.5
Total use of non-renewable primary energy resources	MJ	46.7	1.51	1.10	0.563	5.30	55.2
Use of secondary materials	kg	-	-	-	-	-	-
Use of renewable secondary fuels	MJ	-	-	-	-	-	-
Use of non-renewable secondary fuels	MJ	-	-	-	-	-	-
Use of net fresh water (excl. rain water)	L	0.718	0.109	0.235	0.0721	0.304	1.44
Use of net fresh water (incl. rain water)	L	0.983	0.130	0.274	0.100	0.914	2.40



4.1.3. Output flow and waste categories results

The output flow and waste results for the various asphalt products are presented in Table 4-9 through Table 4-12.

Table 4-9: Waste, asphalt no binder, per kg

Resource	Unit	Asphalt binder, Crude oil	Asphalt binder, Transport	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
Hazardous waste disposed	MJ	-	-	1.46E-04	-	7.42E-06	1.53E-04
Non-hazardous waste disposed	MJ	-	-	7.09E-04	-	1.42E-03	2.13E-03
Radioactive waste disposed	MJ	-	-	-	-	-	-
Components for re-use	MJ	-	-	-	-	-	-
Materials for recycling	MJ	-	-	2.30E-03	-	-	2.30E-03
Materials for energy recovery	MJ	-	-	-	-	-	-

Table 4-10: Waste, asphalt with 8% GTR, per kg

Resource	Unit	Asph. bind GRT, Crude oil	Asph. bind GRT, Transport to refinery	Asph. bind GRT, Refinery	Asph. bind GRT, Transport to terminal	Asph. bind GRT, Terminal	Total
Hazardous waste disposed	MJ	-	-	1.34E-04	-	7.42E-06	1.41E-04
Non-hazardous waste disposed	MJ	-	-	6.52E-04	-	1.42E-03	2.07E-03
Radioactive waste disposed	MJ	-	-	-	-	-	-
Components for re-use	MJ	-	-	-	-	-	-
Materials for recycling	MJ	-	-	2.12E-03	-	-	2.12E-03
Materials for energy recovery	MJ	-	-	-	-	-	-

Table 4-11: Waste, asphalt with 0.5% PPA, per kg

Resource	Unit	Asph. bind PPA, Crude oil	Asph. bind PPA, Transport to refinery	Asph. bind PPA, Refinery	Asph. bind PPA, Transport to terminal	Asph. bind PPA, Terminal	Total
Hazardous waste disposed	MJ	-	-	1.45E-04	-	7.42E-06	1.52E-04
Non-hazardous waste disposed	MJ	-	-	7.05E-04	-	1.42E-03	2.13E-03
Radioactive waste disposed	MJ	-	-	-	-	-	-
Components for re-use	MJ	-	-	-	-	-	-
Materials for recycling	MJ	-	-	2.29E-03	-	-	2.29E-03
Materials for energy recovery	MJ	-	-	-	-	-	-

**Table 4-12: Waste, asphalt with 3.5% SBS, per kg**

Resource	Unit	Asph. bind SBS, Crude oil	Asph. bind SBS, Transport to refinery	Asph. bind SBS, Refinery	Asph. bind SBS, Transport to terminal	Asph. bind SBS, Terminal	Total
Hazardous waste disposed	MJ	-	-	1.40E-04	-	7.42E-06	1.48E-04
Non-hazardous waste disposed	MJ	-	-	6.84E-04	-	1.42E-03	2.10E-03
Radioactive waste disposed	MJ	-	-	-	-	-	-
Components for re-use	MJ	-	-	-	-	-	-
Materials for recycling	MJ	-	-	2.22E-03	-	-	2.22E-03
Materials for energy recovery	MJ	-	-	-	-	-	-

4.2. Detailed Results

Figure 4-1 presents the relative results of asphalt without additives leaving the terminal, broken down by crude oil extraction and transport, refinery operations, and terminal operations (including transport to the terminal). Crude oil extraction is the primary driver of burden for all categories except EP, where waste treatment at the refinery is the primary driver. Note that the best available waste water treatment data were based on all municipal waste water treatment in the US, therefore it has a higher organic content than would typically be associated with an industrial operation like a refinery. It is likely that the EP is therefore overestimated. Terminal operations can contribute as much as 20% of potential impacts, with the exception of the asphalt with SBS where the terminal can contribute up to 40% of potential impacts due to the high contribution of SBS (see Figure 4-4).

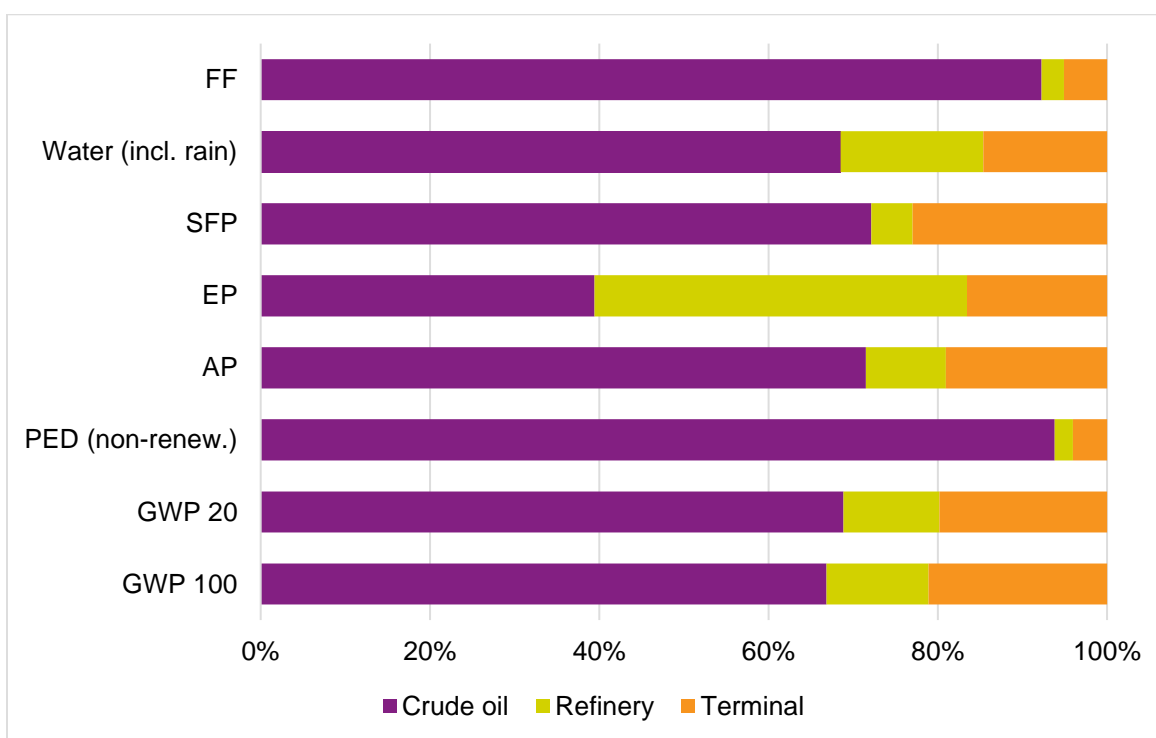


Figure 4-1: Overall impacts of asphalt binder, no additives [TRACI 2.1, except PED (non-renew.) and Water (incl. rain)]



Figure 4-2 presents the relative impacts for crude oil extraction and refinery operations (excluding the terminal). The crude oil is the primary driver of impact for GWP100, PED (non-renew.), SFP, and FF. Crude transport represents 1% to 20% of the impacts for all reported impact categories, with a 5% contribution to GWP100 and a 20% contribution to AP and SFP. For EP, the highest impacts for refinery operations are due to waste water treatment which contribute 46%.

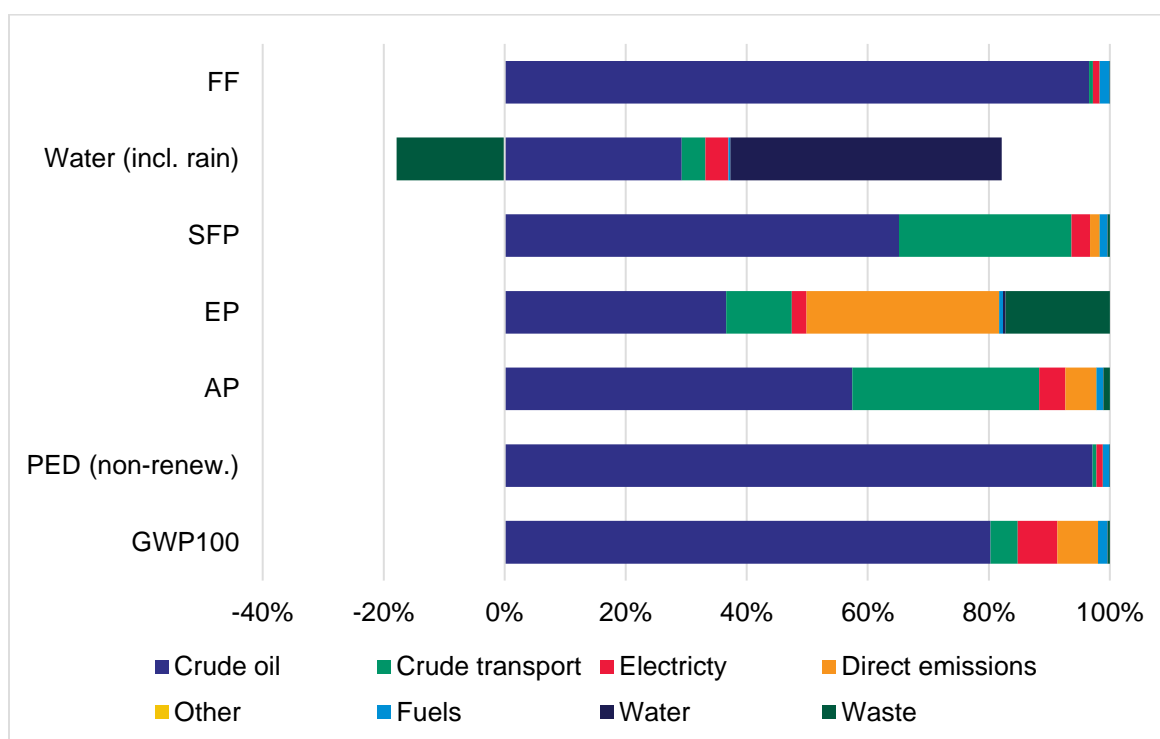


Figure 4-2: Crude oil and refinery impacts of asphalt binder, no additives [TRACI 2.1, except PED (non-renew.) and Water (incl. rain)]

Figure 4-3 presents the relative results for operations and inbound transport at the terminal, it does not include the upstream impact of the asphalt at refinery. As inputs and outputs are allocated by mass to each asphalt product coming out of the terminal, the trends below apply to the other products, though relative contributions will decrease if additives are included. It can be seen that thermal energy is the most significant driver for PED and GWP, while inbound transport is most significant for AP, EP, and SFP. A scenario analysis around the inbound transport of asphalt can be found in section 4.3.2.

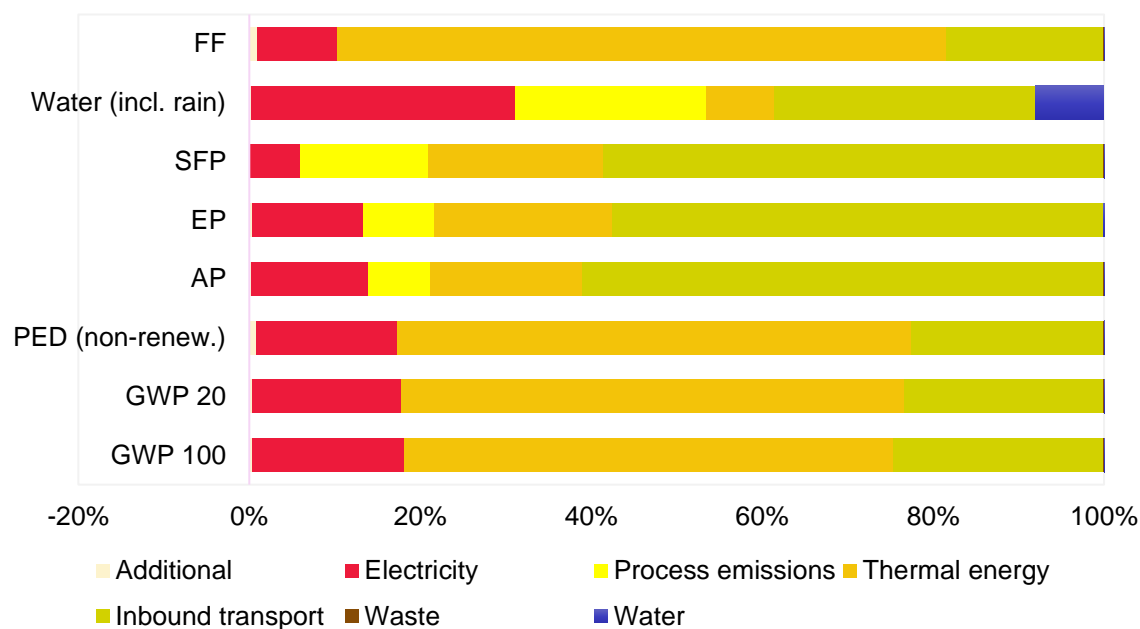


Figure 4-3: Relative results for terminal operations, excluding additives and refinery operations

Figure 4-4 shows absolute GWP100 results for the terminal only, for each product under study. The GWP100 per kg of SBS is 4 kg CO₂-eq, which means even a small SBS content in the asphalt blend increases impacts significantly. The GWP for PPA is also 4 kg CO₂-eq/kg but a much smaller amount is used. The GWP for GTR only accounts for the grinding of the tires, not the upstream burden of manufacturing the tires. Additional refers to any auxiliary materials, which were minor.

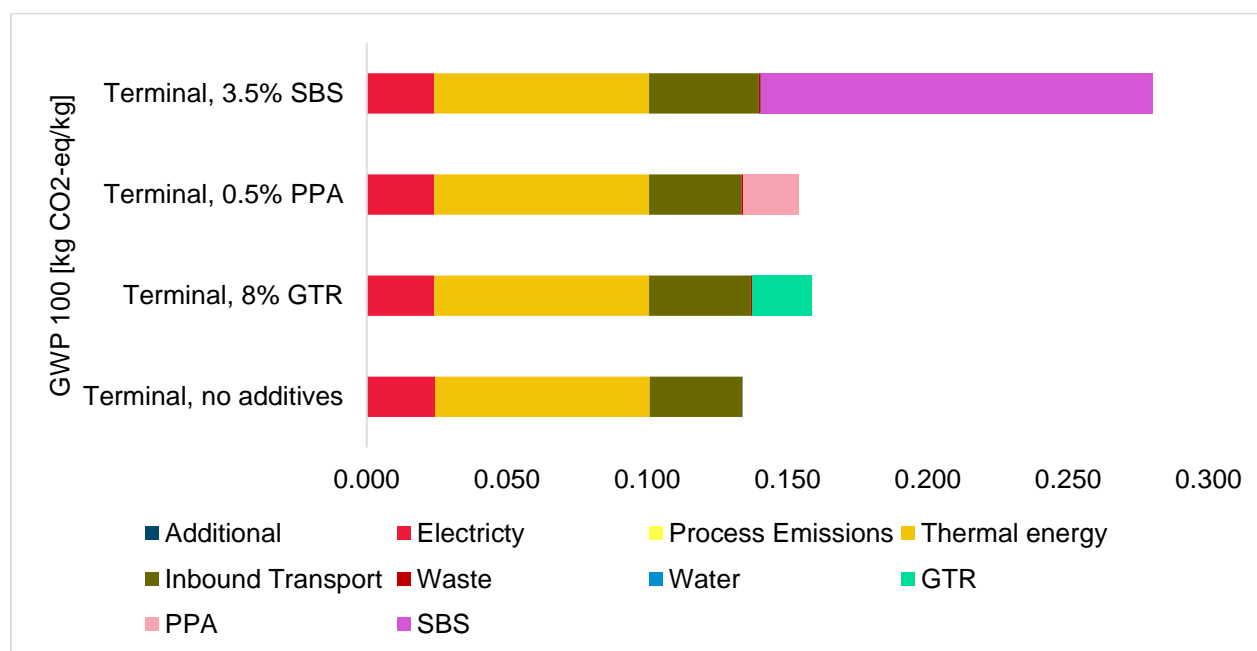


Figure 4-4: GWP100 impacts of terminal operations for all 4 products

4.2.1. Comparison of Crude Oil Extraction Methods in GaBi

To better understand the potential impacts associated with the upstream extraction of crude oil, Figure 4-5 presents the GWP of the crude slate of this study alongside the GaBi background data used to model the average crude slate. All datasets are from the GaBi 2017 database and include upstream production of energy and ancillary materials required for extraction. Production in Canada was selected as an example, as it is the region the majority of the average slate is extracted from. The crude slate breakdown by extraction method can be found in Table 3-1.

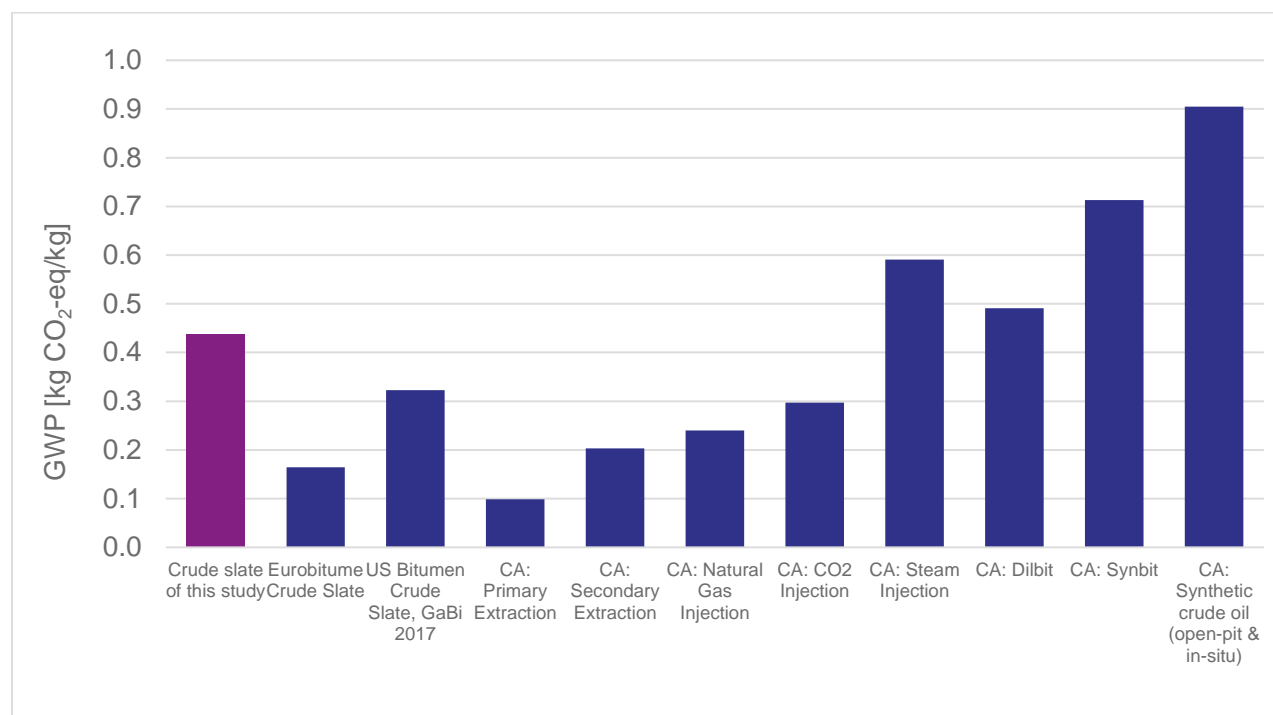


Figure 4-5: Crude oil extraction comparison [GWP]

4.3. Scenario Analyses

4.3.1. Allocation

A scenario analysis was done to assess the validity of the baseline scenario. The scenarios, as presented in Table 4-13, use mass allocation for crude oil and energy content for thermal energy and direct emissions.



Table 4-13: Allocation methodology scenarios

[TRACI 2.1]	Baseline	Crude oil (mass)	% Diff. from baseline	Thermal energy (NCV)	% Diff. from baseline	Thermal energy (NCV) & Crude oil (mass)	% Diff. from baseline
No additives							
GWP100 [kg CO ₂ eq.]	0.637	0.631	-1%	0.679	7%	0.673	6%
GWP20 [kg CO ₂ eq.]	0.766	0.759	-1%	0.812	6%	0.805	5%
PED, non renew. [MJ]	53.4	52.8	-1%	54.0	1%	53.3	0%
AP [kg SO ₂ eq.]	1.78E-03	1.76E-03	-1%	1.86E-03	5%	1.84E-03	4%
EP [kg N eq.]	1.66E-04	1.65E-04	-1%	1.85E-04	12%	1.84E-04	11%
SFP [kg O ₃ eq.]	0.0360	0.0356	-1%	0.0368	2%	0.0364	1%
Water consumption [kg]	1.01	1.00	-1%	1.01	0%	1.00	-1%
GTR							
GWP100 [kg CO ₂ eq.]	0.621	0.616	-1%	0.660	6%	0.654	5%
GWP20 [kg CO ₂ eq.]	0.745	0.738	-1%	0.787	6%	0.780	5%
PED, non renew. [MJ]	49.7	49.1	-1%	50.2	1%	49.6	0%
AP [kg SO ₂ eq.]	1.69E-03	1.67E-03	-1%	1.77E-03	5%	1.75E-03	3%
EP [kg N eq.]	1.57E-04	1.56E-04	-1%	1.74E-04	11%	1.73E-04	11%
SFP [kg O ₃ eq.]	0.0347	0.0343	-1%	0.0354	2%	0.0350	1%
Water consumption [kg]	0.92	0.91	-1%	0.92	0%	0.91	-1%
PPA							
GWP100 [kg CO ₂ eq.]	0.654	0.649	-1%	0.696	6%	0.690	6%
GWP20 [kg CO ₂ eq.]	0.786	0.779	-1%	0.831	6%	0.824	5%
PED, non renew. [MJ]	53.7	53.0	-1%	54.2	1%	53.6	0%
AP [kg SO ₂ eq.]	1.96E-03	1.94E-03	-1%	2.04E-03	4%	2.02E-03	3%
EP [kg N eq.]	1.69E-04	1.68E-04	-1%	1.88E-04	11%	1.87E-04	11%
SFP [kg O ₃ eq.]	0.0365	0.0361	-1%	0.0373	2%	0.0369	1%
Water consumption [kg]	1.06	1.05	-1%	1.06	0%	1.05	-1%
SBS							
GWP100 [kg CO ₂ eq.]	0.765	0.760	-1%	0.806	5%	0.800	5%
GWP20 [kg CO ₂ eq.]	0.918	0.911	-1%	0.962	5%	0.955	4%
PED, non renew. [MJ]	55.4	54.7	-1%	55.9	1%	55.3	0%
AP [kg SO ₂ eq.]	2.12E-03	2.10E-03	-1%	2.20E-03	4%	2.18E-03	3%
EP [kg N eq.]	1.82E-04	1.81E-04	0%	2.01E-04	10%	2.00E-04	10%
SFP [kg O ₃ eq.]	0.0427	0.0423	-1%	0.0435	2%	0.0431	1%
Water consumption [kg]	1.44	1.43	-1%	1.44	0%	1.43	0%



4.3.2. Terminal Location

No data were available on the amount of asphalt sold at independent terminals or those co-located with refineries. It is, however, not uncommon for a refinery to have its own terminal. This would reduce the impact of the inbound transport of the asphalt as well as the amount of heat required at the terminal, as no heat would be lost during transport. Table 4-14 presents the reduction in impact of the asphalt without additives if there were no inbound transport of the asphalt from the refinery, no thermal energy input at the terminal, or both. As no data on the potential energy savings due to co-location were available at the time of the study, the displayed reductions in impacts are best-case estimates, i.e., assuming no additional thermal energy is needed.

Table 4-14: Terminal location scenario analysis

[TRACI 2.1]	Baseline	No transport of asphalt to terminal	% Diff. from baseline	No thermal energy input at terminal	% Diff. from baseline	No transport or thermal energy	% Diff. from baseline
No additives							
GWP100 [kg CO ₂ eq.]	0.637	0.604	-5%	0.560	-12%	0.527	-17%
GWP20 [kg CO ₂ eq.]	0.766	0.731	-5%	0.677	-12%	0.642	-16%
PED, non renew. [MJ]	53.2	52.8	-1%	51.9	-2%	51.5	-3%
AP [kg SO ₂ eq.]	1.78E-03	1.58E-03	-11%	1.72E-03	-3%	1.52E-03	-15%
EP [kg N eq.]	1.66E-04	1.56E-04	-6%	1.62E-04	-2%	1.52E-04	-8%
SFP [kg O ₃ eq.]	0.0360	0.0312	-13%	0.0343	-5%	0.0295	-18%
Water consumption [kg]	1.01	0.94	-7%	1.00	-1%	0.92	-8%
GTR							
GWP100 [kg CO ₂ eq.]	0.621	0.591	-5%	0.545	-12%	0.514	-17%
GWP20 [kg CO ₂ eq.]	0.745	0.712	-4%	0.656	-12%	0.624	-16%
PED, non renew. [MJ]	49.6	49.1	-1%	48.3	-3%	47.8	-4%
AP [kg SO ₂ eq.]	1.69E-03	1.50E-03	-11%	1.63E-03	-4%	1.44E-03	-15%
EP [kg N eq.]	1.57E-04	1.47E-04	-6%	1.53E-04	-2%	1.44E-04	-8%
SFP [kg O ₃ eq.]	0.0347	0.0302	-13%	0.0330	-5%	0.0286	-18%
Water consumption [kg]	0.92	0.85	-7%	0.91	-1%	0.84	-9%
SBS							
GWP100 [kg CO ₂ eq.]	0.765	0.733	-4%	0.689	-10%	0.657	-14%
GWP20 [kg CO ₂ eq.]	0.918	0.884	-4%	0.829	-10%	0.795	-13%
PED, non renew. [MJ]	55.2	54.7	-1%	53.9	-2%	53.4	-3%
AP [kg SO ₂ eq.]	2.12E-03	1.92E-03	-9%	2.06E-03	-3%	1.86E-03	-12%
EP [kg N eq.]	1.82E-04	1.73E-04	-5%	1.79E-04	-2%	1.69E-04	-7%
SFP [kg O ₃ eq.]	0.0427	0.0380	-11%	0.0410	-4%	0.0363	-15%
Water consumption [kg]	1.44	1.37	-5%	1.43	-1%	1.36	-6%
PPA							
GWP100 [kg CO ₂ eq.]	0.654	0.621	-5%	0.578	-12%	0.545	-17%



[TRACI 2.1]	Baseline	No transport of asphalt to terminal	% Diff. from baseline	No thermal energy input at terminal	% Diff. from baseline	No transport or thermal energy	% Diff. from baseline
GWP20 [kg CO ₂ eq.]	0.786	0.751	-4%	0.697	-11%	0.662	-16%
PED, non renew. [MJ]	53.5	53.0	-1%	52.2	-2%	51.7	-3%
AP [kg SO ₂ eq.]	1.96E-03	1.75E-03	-10%	1.90E-03	-3%	1.69E-03	-13%
EP [kg N eq.]	1.69E-04	1.59E-04	-6%	1.65E-04	-2%	1.55E-04	-8%
SFP [kg O ₃ eq.]	0.0365	0.0317	-13%	0.0348	-5%	0.0300	-18%
Water consumption [kg]	1.06	0.99	-7%	1.05	-1%	0.97	-8%

4.4. Sensitivity Analyses

4.4.1. Additive Content

The amount of additive in the asphalt binder is dependent on the requirements of the hot asphalt mixture. Figure 4-6, Figure 4-7, and Figure 4-8 show how changes in the additive contents affect each impact category. It can be seen that water consumption is the most significantly affected when increasing SBS content, followed by GWP, AP, and SFP. For PPA, AP is by far the most sensitive impact category, followed by water and GWP. Finally, GTR, which does not affect results as significantly as the other two additives, mostly affects the water and PED impact categories.

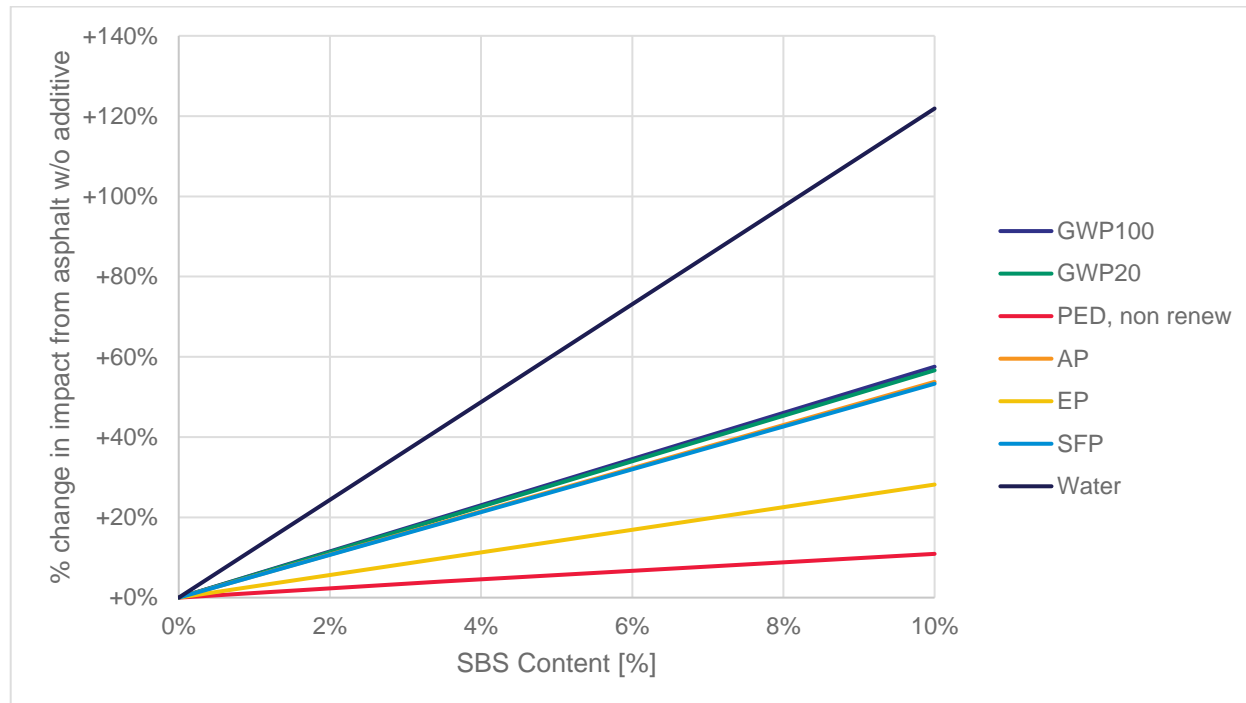


Figure 4-6: Sensitivity of results to SBS content

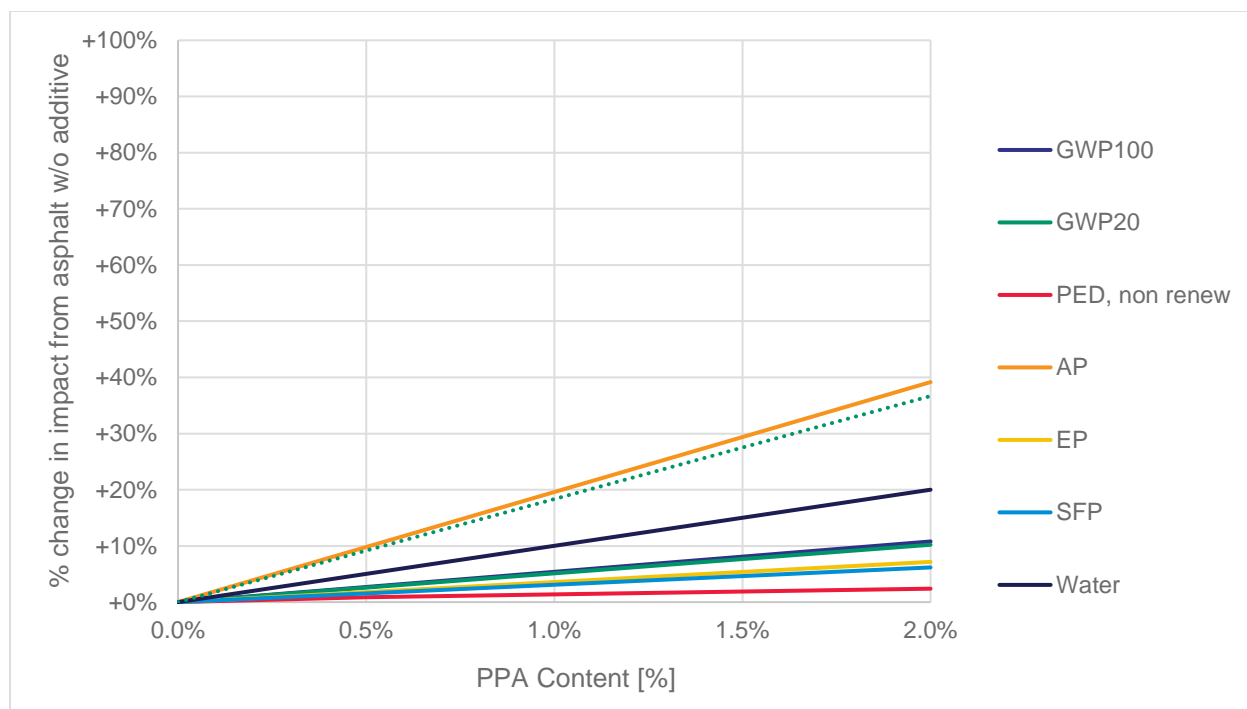


Figure 4-7: Sensitivity of results to PPA content

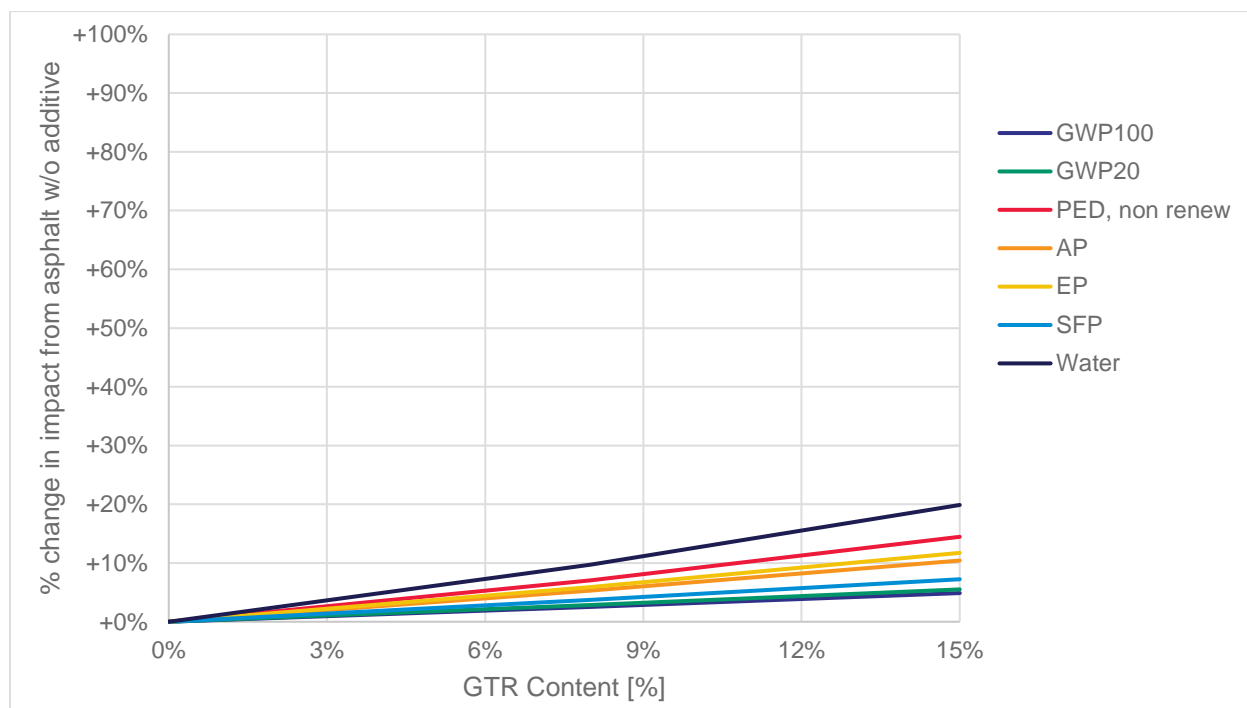


Figure 4-8: Sensitivity of results to GTR content



5. Interpretation

5.1. Identification of Relevant Findings

The extraction of the crude oil is the primary driver of all potential environmental impacts, due most significantly to the use of crude oil from oil sands or crudes extracted via a tertiary method. At the refinery itself, electricity is the most significant single driver of impact, followed by on-site thermal energy generation and associated direct emissions. Terminal operations can contribute up to 20% of potential environmental impacts without additives. When including additives like SBS (3.5%), they can contribute up to 40%. Within the terminal and apart from additives, thermal energy is the most significant driver of impact for GWP and PED, while inbound transport of the asphalt is the most significant driver for AP, SFP, and EP. Table 5-1 summarizes the largest drivers of the results.

Table 5-1: Main contributors to overall results by category and input / output

No additives			GTR		SBS		PPA	
	Category	Input/ output	Category	Input/ output	Category	Input/ output	Category	Input/ output
GWP100	Crude oil (67%)	CO ₂ (87%)	Crude oil (63%)	CO ₂ (89%)	Crude oil (54%)	CO ₂ (89%)	Crude oil (65%)	CO ₂ (89%)
GWP20	Crude oil (69%)	CO ₂ (74%)	Crude oil (65%)	CO ₂ (74%)	Crude oil (55%)	CO ₂ (74%)	Crude oil (67%)	CO ₂ (74%)
PED, non renew.	Crude oil (93%)	Crude oil (81%)	Crude oil (92%)	Crude oil (80%)	Crude oil (86%)	Crude oil (77%)	Crude oil (92%)	Crude oil (81%)
AP	Crude oil (72%)	NO _x (55%)	Crude oil (69%)	NO _x (56%)	Crude oil (58%)	NO _x (56%)	Crude oil (65%)	NO _x (55%)
EP	Crude oil (39%)	Nitrogen to water (18%)	Crude oil (38%)	Nitrogen to water (18%)	Crude oil (35%)	Nitrogen to water (17%)	Crude oil (39%)	Nitrogen to water (18%)
SFP	Crude oil (72%)	NO _x (97%)	Crude oil (69%)	NO _x (97%)	Crude oil (59%)	NO _x (97%)	Crude oil (71%)	NO _x (97%)

5.2. Assumptions and Limitations

Where companies could not provide specific details on the crude slates used, whatever information they could provide was used to estimate the required information to model the crude. For example, if extraction method was not available and the crude name was not specific enough to provide helpful details, the average mix of extraction methods for the region of extraction were used.

Refinery-level information had to be used for electricity, water use, emissions, and wastes. While process-specific data would have been available from some participating companies, the same calculation approach was applied to all refineries for consistency reasons.

The study does not include terminals co-located at refineries, which makes the presented results conservative estimates of the environmental profile of North American asphalt binder.



Only emissions measured and reported by the participating companies, both refineries and terminals, were included. It is not possible to know what emissions are released if a company is not required to measure them, or if they are too small to measure accurately. It is anticipated that this would have an insignificant effect on the reported results as the emissions would either be small or ones of low concern.

5.3. Results of Scenario and Sensitivity Analyses

5.3.1. Scenario Analyses

Scenario analyses were performed to compare results between different sets of assumptions or modeling choices. The first analysis showed that allocating thermal energy by the net calorific value of the outputs can increase overall impacts from 0% to 17%. If thermal energy were allocated between co-products at the ADU and the VDU based solely on energy content of the co-products, the results increased. However, this would include the heat required for phase changes of the lighter products as well as the recovered heat from heat exchangers the asphalt passes through, so the baseline results are considered more accurate than the alternative allocation approach. Allocating the crude oil by mass or energy content does not significantly impact the results.

The second analysis showed that co-location of terminals can reduce overall impacts by 3% to 17% depending on the category. Two factors contribute to this reduction, no inbound transport of the asphalt and no thermal energy due to heat savings from the refinery. When considering the lack of inbound transport alone, AP and SFP showed the most significant reductions, up to 12% depending on the product. When just the lack of thermal energy input was considered, only GWP was significantly impacted, with reductions up to 12% depending on product. Finally, when considering both factors, AP, SFP, and GWP impact reductions ranged from 11% to 17%.

5.3.2. Sensitivity Analysis

Results for asphalt binders with additives will increase linearly as the additive contents increase. For SBS, the most sensitive categories are water, GWP, AP, and SFP. For PPA, the most sensitive category by far is AP. Finally, GTR does not impact results as significantly as PPA and SBS, but it affects water and PED the most. It is therefore important to accurately represent the additive type and amount when selecting an asphalt binder dataset.

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 industry data in combination with consistent background LCA information from the GaBi 2017 database were used. The LCI datasets from the GaBi 2017 database are widely distributed and used with the GaBi ts 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.



5.4.1. Precision and Completeness

- ✓ **Precision:** As the majority of the relevant foreground data are measured data or calculated based on primary information sources of the owner of the technology, precision is considered to be high. Seasonal variations and variations across different manufacturers were balanced out by using yearly weighted averages. All background data are sourced from GaBi databases with the documented precision (thinkstep 2018).
- ✓ **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 are considered to be high. All background data are sourced from GaBi databases with the documented completeness (thinkstep 2018).

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 the GaBi databases.
- ✓ **Reproducibility:** Reproducibility is supported as much as possible through the disclosure of input-output data, dataset choices, and modeling approaches in this report, though it is limited by the availability of background data to the practitioner. With access to these background data and this report, any third party should be able to approximate results.

5.4.3. Representativeness

Temporal

All primary data were collected for the years 2015-2016. All secondary data come from the GaBi 2017 databases and are representative of the years 2012-2016. As the study intended to compare the product systems for the reference years 2015-2016, temporal representativeness is considered to be very good.

Geographical

All primary and secondary data were collected specific to the countries or regions under study. Where country-specific or region-specific data were unavailable, proxy data were used. To assess geographical representativeness the total asphalt and road oil capacity of the five US PADD regions and Canada (Population) were compared to the reported asphalt capacity of the participating facilities (Sample) based on (Koffler, Shonfield and Vickers 2016). All facility capacity data are publicly available (EIA 2017a, The Oil & Gas Journal 2017). As the weighted average deviation is 12% the geographical representativeness is considered to be good.

Table 5-2: Geographical representativeness

Region	Population	Sample	Absolute deviation
PADD 1	12%	0%	12%
PADD 2	33%	23%	10%
PADD 3	25%	43%	18%
PADD 4	10%	7%	3%
PADD 5	11%	10%	1%
Canada	8%	17%	8%
Weighted-average deviation			12%
Geographic representativeness			88%



Technological

All primary and secondary data were modeled to be specific to the technologies or technology mixes under study. Where technology-specific data were unavailable, proxy data were used. Technological representativeness is considered to be good. The representative asphalt data provided accounts for 24% of asphalt capacity in the United States and Canada as of the beginning of 2017 and 27% of annual production for 2016 (EIA 2017b, Government of Canada 2017).

In order to assess technological representativeness, the facility size distribution is evaluated as a proxy for overall efficiency based on reported asphalt and road oil production capacity. All facility capacity data are publicly available (EIA 2017a, The Oil & Gas Journal 2017). Table 5-3 presents the cluster sizes used, the population breakdown, the sample breakdown, and the overall deviation. As the weighted average deviation is 14% the technological representativeness is 86% and therefore considered to be good.

Table 5-3: Technological representativeness, by facility asphalt and road oil production capacity

Capacity [bbl/day]	Population	Sample	Absolute deviation
$\leq 4,000$	3%	2%	1%
$4,000 < X \leq 13,000$	29%	31%	3%
$13,000 < X \leq 23,000$	36%	15%	21%
$23,000 < X$	33%	52%	19%
Weighted-Average Deviation			14%
Technological representativeness			86%

The quality of the crude slate was also assessed. While the North American crude slate is approximately one-third heavy crude, the AI crude slate is approximately two-thirds heavy crude. This follows since data were collected only for runs where asphalt was produced.

5.5. Model Completeness and Consistency

5.5.1. Completeness

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

5.5.2. Consistency

All assumptions, methods and data are consistent with each other and with the study's goal and scope. Differences in background data quality were minimized by exclusively using LCI data from the GaBi 2017 databases. System boundaries, allocation rules, and impact assessment methods have been applied consistently throughout the study.



5.6. Conclusions, Limitations, and Recommendations

5.6.1. Conclusions

This study presented the results for four asphalt binder products: without additives, with SBS, with PPA, and with GTR. It was seen that crude oil extraction was the primary driver of impacts. In only accounting for asphalt runs we could isolate the crudes that are used for asphalt production, which tend to be heavier, typically from oil sands or requiring tertiary extraction methods. As discussed in section 2.4.1, many LCAs use all runs over a year. Given that the fraction of the crude impacts attributed to bitumen will vary depending on the residual yield of these crude baskets, it is difficult to know how this may affect results, it does, however, increase the accuracy of the results. This study is also unique as it includes primary data from North American refineries and specifically data from asphalt only refineries. The specific heat methodology, used to account for the fact that much of the energy required in distillation towers is to boil off lighter fractions of the crude, captures the thermal energy needed only for asphalt production and could be adapted to other refinery products. Its use resulted in slightly lower impacts than allocating thermal energy based on the net calorific value of the co-products. The study at hand is therefore considered to be the most accurate representation of the environmental impact profile of asphalt binder produced in North America.

5.6.2. Limitations

The results of this study only apply to asphalt produced in Canada and the United States.

Terminal impacts are overestimated as energy savings benefits from co-location of terminals with refineries are not captured in the study.

5.6.3. Recommendations

The Asphalt Institute can improve the precision of future assessments by collecting more detailed data on the employed extraction technologies of crude slates used for asphalt production. While these data are already considered high quality, and many companies could provide the optimal level of detail for these materials, any effort to remove assumptions from this area would improve this study.

The Asphalt Institute could also improve the representativeness of future assessment by including more companies, especially in the asphalt and road oil capacity range from $13,000 < X \leq 23,000$ bbl/day.

There is an inherent complexity in an LCA of any refinery product. By using the sensible heat method to estimate thermal energy consumption for asphalt production, this study more accurately accounts for the potential environmental impacts of asphalt binder, which in turn would also improve the accuracy of other refinery products. Future studies on refinery products may therefore benefit from using the same method to ensure consistency across the industry.

The selection of crudes utilized within a refinery is a complex process based on multiple variables, therefore, asphalt binder stakeholders have no opportunity to affect the crude slate profile used. Efforts should instead be focused on reducing impacts at the refinery and terminal, particularly electricity and thermal energy consumption, and associated emissions.



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Appendix A : The Crude Oil Supply Model in GaBi

The crude oil supply model set considers the whole supply chain of crude oil, i.e. extraction, production, processing, the long-distance transport and the regional distribution to the refinery.

Conventional crude oil production model

The production of crude oil, natural gas and NGL (natural gas liquids) in GaBi is modelled as a combined production (allocation by energy content (net calorific value) is applied). It is a generic model and comprises all relevant processes and process steps for the extraction, production and processing of crude oil, natural gas and NGL. The model enables the user to generate detailed Life Cycle Inventories (LCI) of the crude oil production according to oil field properties and technology characteristics (e.g. production technologies (primary, secondary, tertiary production / enhanced oil recovery (EOR)), onshore/offshore production, drilling depth, oil and gas composition). Table A-1 B-1 states the key parameters of the model and the data sources used. The model considers all relevant energy and resource flows as well as all emissions to air, water and soil (e.g. flaring, venting, waste water, waste).

Table A-1: Key parameters of the model and data sources

Key parameters	Data source(s)
Technology used (primary, secondary, tertiary production / EOR)	Oil & Gas Journal (OGJ), country-specific, public studies, expert judgements, estimations
Share of produced crude oil, natural gas and natural gas liquids (NGL)	U.S. Energy Information Administration (EIA), International Energy Agency (IEA)
Share of onshore/offshore production	Oil & Gas Journal (OGJ), country-specific, public studies, expert judgements, estimations
Drilling/reservoir depth	Oil & Gas Journal (OGJ)
Water-oil-ratio, wastewater and waste	International Association of Oil & Gas Producers (IOGP), country-specific, public studies, expert judgements, estimations
Flaring and venting	U.S. Energy Information Administration (EIA)
Energy consumption	Calculations based on the energy demand of all relevant production and processing units (e.g. pumps, injections pumps, separators) and the oil field properties and technology characteristics, variety of public studies, expert judgements, estimations

Based on information received from the client on “specific gravity”, “region/country”, “crude name”, “company name”, “extraction technology”, “location of port/well”, the average country-specific crude oil production and processing models in GaBi are adapted specifically for every crude oil (e.g. share of onshore/offshore



production, applied production technology, API gravity). In cases where absolutely no data are available, the average country-specific crude oil production and processing models in GaBi are used.

Crude oil transport model

Based on the crude oil transport model in GaBi, the following modelling is used for the crude oil transportation:

- Domestic production: For domestic production the transport from the oil production and processing field to the refinery is taken into account.
- Imports: Starting from the production and processing field the crude oil is either transported via pipeline directly to the border of the consumer country or via oil tankers. In case of import via tanker, the crude oil is transported via pipeline to the next crude oil tanker port terminal within the exporting country and then exported via large vessel to the consumer country. From the border of the consumer country or the tanker port the crude oil is transported via pipeline to the refinery.

Based on information received from the client on “region/country”, “crude name”, “company name”, “location of port/well”, “mode of transport” and “distance”, the pipeline distances for every crude oil are calculated based on the global crude oil pipeline network. The oil tanker distances are calculated using the Sea Distances / Port Distances - online tool for calculation distances between sea ports (online available: <https://www.sea-distances.org>). In cases where no transport information is available, average country-specific distances and transport modes are used. Crude oil losses during transportation are assumed to be negligible and not taken into account.



Appendix B : Life Cycle Inventory of Binders with Additives

Table B-1: LCI Asphalt binder GTR

Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
Inputs							
Non-renewable energy resources [MJ]	Crude oil (resource) ¹²	3.89E+01	1.39E-01	2.95E-01	2.53E-01	1.17E-01	3.97E+01
	Hard coal (resource)	9.46E-02	4.94E-02	9.61E-02	7.71E-02	1.09E-01	4.27E-01
	Lignite (resource)	2.05E-02	9.20E-03	1.49E-02	4.94E-03	3.64E-02	8.59E-02
	Natural gas (resource)	6.58E+00	5.25E-02	5.97E-01	7.29E-02	1.79E+00	9.09E+00
	Peat (resource)	3.18E-05	2.32E-06	1.65E-06	5.53E-07	4.17E-06	4.05E-05
	Uranium (resource)	4.71E-02	3.52E-02	4.99E-02	3.84E-02	5.75E-02	2.28E-01
Renewable energy resources [MJ]	Primary energy from geothermics	9.11E-04	9.75E-04	1.44E-03	1.39E-03	6.73E-05	4.78E-03
	Primary energy from hydro power	4.25E-02	2.29E-02	6.29E-03	6.75E-03	4.85E-03	8.33E-02
	Primary energy from solar energy	1.72E-02	4.33E-03	7.19E-03	5.53E-03	4.65E-03	3.89E-02
	Primary energy from waves	3.94E-15	5.88E-16	9.10E-16	8.29E-16	7.10E-16	6.98E-15
	Primary energy from wind power	7.70E-03	5.71E-03	1.39E-02	7.14E-03	2.81E-02	6.25E-02
Non-renewable elements [kg]	Antimony	3.41E-10	1.08E-11	2.43E-11	1.42E-11	3.87E-11	4.29E-10
	Chromium	1.91E-07	9.81E-08	5.01E-08	3.99E-08	6.64E-08	4.45E-07
	Lead	4.23E-05	1.38E-07	2.21E-06	5.55E-07	6.37E-06	5.16E-05
	Silver	4.50E-08	1.85E-10	2.38E-09	6.35E-10	6.80E-09	5.50E-08
	Zinc	2.74E-05	1.12E-07	1.45E-06	3.88E-07	4.13E-06	3.35E-05
Non-renewable resources [kg]	Colemanite ore	2.67E-05	1.11E-08	4.68E-08	2.82E-08	5.48E-08	2.69E-05
	Sodium chloride (rock salt)	5.41E-04	3.55E-06	7.82E-05	2.05E-06	3.71E-05	6.62E-04
Water resources [kg]	Ground water	9.19E-02	6.89E-03	1.53E+00	7.50E-03	6.84E-02	1.70E+00
	Lake water	5.13E-02	2.33E-04	4.79E-03	3.76E-03	2.38E-03	6.25E-02
	Lake water to turbine	1.13E+01	6.12E+00	1.58E+00	1.72E+00	1.25E+00	2.20E+01
	Rain water	2.54E-01	1.99E-02	4.20E-02	2.56E-02	3.21E-01	6.62E-01

¹² Crude oil (resource) includes crude used as a feedstock and as an energy resource. The split between the two can be found in Table 4-5



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
Renewable resources [kg]	River water	1.62E+01	7.08E-01	2.37E+00	5.98E-01	1.19E+00	2.11E+01
	River water to turbine	3.84E+01	2.00E+01	5.84E+00	5.90E+00	4.60E+00	7.47E+01
	Sea water	1.24E+00	1.89E-01	4.75E-01	2.24E-01	4.20E-01	2.55E+00
	Carbon dioxide	1.60E-03	3.55E-04	6.86E-04	4.58E-04	4.43E-04	3.54E-03
	Nitrogen	5.76E-14	9.05E-15	1.47E-14	1.35E-14	1.02E-14	1.05E-13
	Oxygen	2.08E-04	6.33E-06	4.65E-05	6.09E-03	6.74E-04	7.03E-03
Outputs							0.00E+00
Deposited goods [kg]	Hazardous waste (deposited)	9.98E-09	5.63E-11	2.21E-09	1.72E-10	6.20E-10	1.30E-08
	Overburden (deposited)	5.50E-02	1.67E-02	3.42E-02	1.81E-02	5.26E-02	1.77E-01
	Slag (deposited)	4.78E-14	1.68E-14	1.34E-14	2.26E-14	9.69E-15	1.10E-13
	Spoil (deposited)	1.75E-02	3.79E-04	2.17E-03	3.79E-04	6.74E-03	2.72E-02
	Tailings (deposited)	3.87E-01	8.18E-05	1.79E-03	1.69E-03	9.19E-04	3.91E-01
	Waste (deposited)	6.84E-04	4.39E-05	2.66E-03	5.80E-05	2.61E-03	6.06E-03
Inorganic emissions to air	Aluminium	1.74E-11	6.12E-12	4.96E-12	8.39E-12	3.59E-12	4.04E-11
	Ammonia	1.34E-06	7.53E-08	1.37E-06	4.43E-07	1.40E-06	4.63E-06
	Carbon dioxide	3.30E-01	8.65E-03	6.57E-02	2.91E-02	1.18E-01	5.52E-01
	Carbon dioxide (aviation)	3.96E-08	2.03E-08	3.80E-08	2.55E-08	6.87E-08	1.92E-07
	Carbon dioxide (biotic)	9.83E-04	3.53E-04	2.15E-03	1.04E-03	1.14E-03	5.66E-03
	Carbon dioxide (land use change)	1.97E-04	2.87E-06	9.53E-06	5.61E-06	1.35E-05	2.29E-04
	Carbon dioxide (peat oxidation)	1.52E-10	3.84E-11	9.65E-07	5.12E-11	7.72E-11	9.66E-07
	Carbon monoxide	3.26E-04	3.88E-06	5.03E-05	4.09E-05	7.34E-05	4.95E-04
	Chlorine	5.52E-09	6.26E-11	1.13E-07	9.60E-11	5.24E-08	1.71E-07
	Hydrogen chloride	8.14E-07	4.78E-07	6.36E-07	3.88E-07	4.39E-07	2.75E-06
	Hydrogen sulphide	2.45E-06	4.07E-07	1.28E-06	5.91E-07	3.84E-07	5.11E-06
	Nitrogen dioxide	6.12E-08	2.53E-09	7.52E-09	2.40E-08	2.80E-08	1.23E-07
	Nitrogen monoxide	6.02E-07	1.49E-08	1.37E-07	3.00E-07	1.94E-07	1.25E-06
	Nitrogen oxides	9.29E-04	1.59E-05	6.28E-05	1.77E-04	1.71E-04	1.36E-03
	Nitrogen, total	6.68E-14	8.57E-14	2.35E-09	1.06E-13	1.43E-13	2.35E-09
	Nitrogen trifluoride	8.43E-14	4.70E-14	9.86E-14	5.81E-14	1.87E-13	4.75E-13
	Nitrous oxide	6.77E-06	1.62E-07	1.76E-07	3.44E-07	3.76E-07	7.82E-06
	Sulphur dioxide	4.61E-04	3.86E-05	9.69E-05	6.06E-05	5.03E-05	7.08E-04
	Sulphur hexafluoride	1.19E-14	1.27E-14	1.88E-14	1.80E-14	8.77E-16	6.23E-14
	Sulphur trioxide	1.39E-09	2.20E-10	7.11E-10	2.92E-10	4.07E-10	3.02E-09
	Sulphuric acid	3.08E-09	1.03E-11	1.62E-10	4.05E-11	4.67E-10	3.76E-09
	Methane	1.68E-03	1.49E-05	1.45E-04	3.62E-05	3.33E-04	2.21E-03



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
Organic emissions to air [kg]	Methane (biotic)	8.46E-07	8.75E-08	2.40E-05	9.77E-08	8.23E-06	3.33E-05
Halogenated organic emissions to air [kg]	Chloromethane (methyl chloride)	3.52E-15	7.25E-16	1.84E-11	9.90E-16	1.55E-15	1.84E-11
	R 114 (dichlorotetrafluoroethane)	4.41E-12	3.78E-12	5.86E-12	4.57E-12	6.46E-12	2.51E-11
	R 22 (chlorodifluoromethane)	3.29E-13	2.09E-13	2.47E-13	1.87E-13	3.16E-13	1.29E-12
NMVOC (organic) emissions to air [kg]	NMVOC (unspecified)	1.01E-04	2.63E-07	1.55E-05	9.47E-06	1.72E-04	2.99E-04
Heavy metals to air [kg]	Antimony	2.02E-10	5.93E-11	1.78E-10	8.53E-11	1.62E-10	6.88E-10
	Arsenic	3.39E-14	3.84E-16	1.50E-15	4.74E-16	3.24E-15	3.95E-14
	Arsenic (+V)	1.69E-09	6.79E-10	1.22E-09	9.23E-10	1.48E-09	6.00E-09
	Arsenic trioxide	6.87E-13	2.14E-15	3.58E-14	8.90E-15	1.03E-13	8.37E-13
	Cadmium	3.37E-10	3.76E-11	5.33E-10	7.04E-11	1.10E-10	1.09E-09
	Chromium	7.01E-09	1.26E-10	1.20E-09	2.09E-10	1.29E-09	9.83E-09
	Chromium (+III)	1.35E-10	6.49E-13	7.28E-12	1.94E-12	1.36E-11	1.59E-10
	Chromium (+VI)	1.42E-15	1.64E-17	8.37E-17	2.61E-17	2.26E-16	1.77E-15
	Cobalt	4.06E-10	6.26E-11	2.22E-10	5.50E-11	1.05E-10	8.51E-10
	Copper	8.22E-09	1.56E-10	1.48E-09	2.65E-10	1.63E-09	1.17E-08
	Hydrogen arsenic (arsine)	5.70E-11	1.78E-13	2.97E-12	7.38E-13	8.59E-12	6.95E-11
	Iron	1.68E-07	7.58E-10	1.14E-08	2.97E-09	2.52E-08	2.09E-07
	Lanthanum	1.12E-17	1.18E-17	1.76E-17	1.69E-17	8.23E-19	5.83E-17
	Lead	1.16E-07	9.79E-10	9.88E-09	2.20E-09	1.90E-08	1.49E-07
	Manganese	2.31E-07	1.39E-09	1.66E-08	3.88E-09	3.77E-08	2.91E-07
	Mercury	7.72E-10	1.10E-10	1.51E-08	1.16E-10	8.89E-10	1.70E-08
	Molybdenum	2.13E-10	5.32E-12	1.16E-10	1.52E-11	1.34E-11	3.63E-10
	Nickel	6.26E-09	2.24E-09	7.66E-09	4.01E-10	6.36E-10	1.72E-08
	Palladium	6.13E-18	6.52E-18	9.69E-18	9.30E-18	4.51E-19	3.21E-17
	Rhodium	5.92E-18	6.30E-18	9.36E-18	8.97E-18	4.36E-19	3.10E-17
	Scandium	5.69E-18	6.05E-18	9.01E-18	8.64E-18	4.22E-19	2.98E-17
	Selenium	2.37E-09	1.83E-09	2.89E-09	2.41E-09	3.39E-09	1.29E-08
	Silver	1.74E-11	6.12E-12	4.96E-12	8.39E-12	3.59E-12	4.04E-11
	Tellurium	1.27E-11	5.87E-14	5.97E-13	1.86E-13	1.07E-12	1.46E-11
	Thallium	8.65E-11	4.01E-13	5.18E-12	1.28E-12	1.12E-11	1.05E-10
	Tin	2.12E-09	5.88E-10	1.25E-09	9.25E-10	1.58E-09	6.47E-09
	Titanium	3.21E-09	1.47E-11	2.13E-10	4.77E-11	4.97E-10	3.98E-09
	Vanadium	2.46E-08	8.49E-09	1.08E-08	1.64E-09	2.05E-09	4.76E-08
	Zinc	1.85E-08	1.23E-09	1.55E-08	2.73E-09	5.26E-09	4.33E-08
Particles to air [kg]	Dust (> PM10)	2.16E-06	1.18E-06	2.31E-06	1.70E-06	2.94E-06	1.03E-05
	Dust (PM10)	4.76E-08	4.80E-10	6.27E-09	1.83E-06	7.52E-07	2.63E-06
	Dust (PM2.5 - PM10)	2.81E-05	7.54E-07	1.19E-05	4.68E-07	1.27E-05	5.39E-05
	Dust (PM2.5)	1.94E-05	3.41E-07	1.49E-06	4.17E-06	3.50E-06	2.89E-05
	Silicon dioxide (silica)	1.63E-12	5.76E-13	4.67E-13	7.90E-13	3.38E-13	3.80E-12
	Ammonia	1.09E-07	2.16E-08	3.67E-08	2.48E-08	4.79E-08	2.40E-07



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
Inorganic emissions to freshwater [kg]	Ammonium	1.73E-07	1.23E-08	4.22E-06	1.87E-08	1.88E-06	6.31E-06
	Nitrate	4.51E-06	5.28E-07	7.74E-06	7.41E-07	4.23E-06	1.78E-05
	Nitrogen organic bound	1.74E-06	5.55E-08	2.59E-05	1.29E-07	5.20E-07	2.84E-05
	Phosphate	3.72E-07	1.35E-08	1.41E-06	2.80E-08	4.31E-08	1.87E-06
	Phosphorus	2.23E-08	9.06E-10	2.17E-06	1.26E-09	1.02E-06	3.22E-06
Heavy metals to fresh water [kg]	Antimony	3.43E-12	3.35E-12	1.74E-10	5.35E-12	7.10E-12	1.94E-10
	Arsenic	7.19E-14	5.73E-16	3.08E-15	6.70E-16	6.82E-15	8.30E-14
	Arsenic (+V)	2.49E-06	7.16E-10	1.10E-06	2.39E-08	1.33E-08	3.63E-06
	Cadmium	1.09E-06	4.83E-10	2.52E-08	1.05E-08	1.89E-08	1.15E-06
	Chromium	1.20E-05	9.19E-08	1.35E-06	1.78E-07	4.36E-06	1.80E-05
	Chromium (+III)	9.34E-10	1.66E-10	2.68E-10	1.86E-10	3.18E-10	1.87E-09
	Chromium (+VI)	9.60E-11	2.28E-12	4.13E-09	3.37E-12	1.92E-09	6.15E-09
	Cobalt	6.94E-12	1.59E-13	4.53E-10	2.35E-13	1.31E-10	5.91E-10
	Copper	1.21E-06	1.08E-09	3.57E-08	1.36E-08	4.38E-08	1.31E-06
	Iron	2.84E-05	1.68E-05	2.74E-05	9.14E-06	6.75E-05	1.49E-04
	Lead	9.00E-07	2.29E-09	2.88E-08	1.07E-08	5.59E-08	9.98E-07
	Manganese	7.92E-09	4.68E-09	2.60E-08	6.25E-09	1.71E-08	6.19E-08
	Mercury	8.10E-09	2.00E-11	3.64E-10	1.10E-10	3.52E-10	8.94E-09
	Molybdenum	3.18E-09	2.10E-09	2.63E-09	2.01E-09	3.33E-09	1.33E-08
	Nickel	1.48E-06	1.05E-09	4.68E-08	1.52E-08	2.45E-08	1.57E-06
	Selenium	5.28E-10	2.65E-10	6.80E-08	3.00E-10	4.48E-10	6.96E-08
	Silver	1.40E-11	1.39E-12	5.53E-10	1.98E-12	2.58E-10	8.28E-10
	Tantalum	3.34E-17	2.20E-17	5.29E-17	2.65E-17	1.05E-16	2.40E-16
	Thallium	2.41E-11	7.51E-14	1.26E-12	3.12E-13	3.63E-12	2.94E-11
	Tin	8.81E-16	3.80E-16	4.05E-17	1.62E-17	2.37E-16	1.55E-15
	Titanium	7.15E-10	2.97E-10	4.04E-10	2.89E-10	4.90E-10	2.20E-09
	Tungsten	1.35E-12	4.40E-13	1.05E-12	5.63E-13	1.90E-12	5.30E-12
	Vanadium	1.38E-09	3.78E-10	4.74E-08	4.30E-10	6.22E-10	5.02E-08
	Zinc	1.06E-07	8.53E-10	5.15E-08	2.39E-09	2.15E-08	1.82E-07
Water quality metrics [kg]	Adsorbable organic halogen compounds (AOX)	9.05E-09	3.34E-09	3.42E-07	4.74E-09	9.24E-08	4.52E-07
	Biological oxygen demand (BOD)	9.27E-06	1.53E-08	4.69E-05	1.30E-07	3.27E-06	5.95E-05
	Chemical oxygen demand (COD)	2.13E-04	1.09E-05	2.38E-04	1.42E-05	3.25E-05	5.08E-04
	Nitrogenous Matter	2.01E-07	9.36E-10	1.48E-08	2.97E-09	3.14E-08	2.52E-07
	Solids (dissolved)	2.74E-08	2.27E-08	4.21E-08	3.27E-08	4.28E-08	1.68E-07
	Total dissolved organic bound carbon (TOC)	4.16E-12	1.85E-12	3.92E-13	1.91E-13	1.89E-12	8.48E-12
	Total organic bound carbon (TOC)	9.15E-06	1.31E-08	4.42E-05	1.20E-07	6.10E-07	5.41E-05
Other emissions to	Collected rainwater to river	4.96E-04	3.14E-05	4.82E-03	4.13E-05	5.03E-03	1.04E-02



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
fresh water [kg]	Cooling water to river	1.52E+01	6.73E-01	1.34E+00	5.32E-01	1.10E+00	1.89E+01
	Processed water to groundwater	2.31E-03	1.02E-04	1.69E+00	1.60E-04	1.58E-03	1.70E+00
	Processed water to river	1.88E-01	5.60E-03	6.37E-01	1.52E-02	3.19E-01	1.16E+00
	Turbined water to river	5.03E+01	2.57E+01	7.43E+00	7.62E+00	5.84E+00	9.69E+01
Water releases to sea water [kg]	Cooling water to sea	1.22E+00	1.87E-01	4.72E-01	2.22E-01	4.17E-01	2.52E+00
	Processed water to sea	8.70E-03	2.87E-06	8.06E-05	3.78E-05	1.07E-04	8.93E-03

Table B-2: LCI Asphalt binder PPA

Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
Inputs							
Non-renewable energy resources [MJ]	Crude oil (resource) ¹³	4.21E+01	1.50E-01	3.19E-01	2.74E-01	3.09E-01	4.32E+01
	Hard coal (resource)	1.02E-01	5.34E-02	1.04E-01	8.34E-02	1.35E-01	4.78E-01
	Lignite (resource)	2.21E-02	9.94E-03	1.61E-02	5.34E-03	3.97E-02	9.33E-02
	Natural gas (resource)	7.11E+00	5.68E-02	6.46E-01	7.88E-02	1.63E+00	9.52E+00
	Peat (resource)	3.44E-05	2.51E-06	1.78E-06	5.98E-07	4.24E-06	4.36E-05
	Uranium (resource)	5.10E-02	3.81E-02	5.39E-02	4.15E-02	7.06E-02	2.55E-01
Renewable energy resources [MJ]	Primary energy from geothermics	9.86E-04	1.05E-03	1.56E-03	1.50E-03	4.99E-04	5.60E-03
	Primary energy from hydro power	4.60E-02	2.48E-02	6.80E-03	7.30E-03	7.24E-03	9.21E-02
	Primary energy from solar energy	1.86E-02	4.69E-03	7.78E-03	5.98E-03	8.55E-03	4.55E-02
	Primary energy from waves	4.26E-15	6.36E-16	9.85E-16	8.97E-16	2.96E-15	9.74E-15
	Primary energy from wind power	8.33E-03	6.18E-03	1.50E-02	7.72E-03	3.08E-02	6.80E-02
Non-renewable elements [kg]	Antimony	3.69E-10	1.17E-11	2.63E-11	1.53E-11	4.06E-11	4.63E-10
	Chromium	2.07E-07	1.06E-07	5.42E-08	4.32E-08	8.17E-08	4.92E-07
	Lead	4.57E-05	1.49E-07	2.39E-06	6.00E-07	6.02E-06	5.49E-05
	Silver	4.86E-08	2.00E-10	2.57E-09	6.87E-10	6.47E-09	5.86E-08
	Zinc	2.96E-05	1.22E-07	1.56E-06	4.19E-07	3.93E-06	3.57E-05
	Colemanite ore	2.89E-05	1.20E-08	5.06E-08	3.05E-08	7.18E-08	2.91E-05

¹³ Crude oil (resource) includes crude used as a feedstock and as an energy resource. The split between the two can be found in Table 4-5



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
Non-renewable resources [kg]	Sodium chloride (rock salt)	5.85E-04	3.84E-06	8.46E-05	2.22E-06	2.74E-04	9.49E-04
Water resources [kg]	Ground water	9.94E-02	7.45E-03	1.65E+00	8.12E-03	1.80E-01	1.95E+00
	Lake water	5.55E-02	2.52E-04	5.18E-03	4.07E-03	7.04E-03	7.21E-02
	Lake water to turbine	1.22E+01	6.62E+00	1.71E+00	1.86E+00	1.82E+00	2.42E+01
	Rain water	2.74E-01	2.15E-02	4.54E-02	2.77E-02	3.87E-01	7.56E-01
	River water	1.75E+01	7.65E-01	2.56E+00	6.47E-01	1.48E+00	2.30E+01
	River water to turbine	4.15E+01	2.16E+01	6.31E+00	6.39E+00	7.76E+00	8.36E+01
	Sea water	1.34E+00	2.05E-01	5.13E-01	2.42E-01	4.89E-01	2.79E+00
Renewable resources [kg]	Carbon dioxide	1.73E-03	3.83E-04	7.42E-04	4.95E-04	7.30E-04	4.08E-03
	Nitrogen	6.23E-14	9.79E-15	1.59E-14	1.45E-14	4.27E-14	1.45E-13
	Oxygen	2.25E-04	6.85E-06	5.03E-05	6.59E-03	1.67E-04	7.04E-03
Outputs							
Deposited goods [kg]	Hazardous waste (deposited)	1.08E-08	6.08E-11	2.39E-09	1.86E-10	9.08E-10	1.43E-08
	Overburden (deposited)	5.95E-02	1.81E-02	3.70E-02	1.96E-02	1.02E-01	2.36E-01
	Slag (deposited)	5.17E-14	1.82E-14	1.45E-14	2.45E-14	3.29E-14	1.42E-13
	Spoil (deposited)	1.90E-02	4.09E-04	2.35E-03	4.10E-04	6.71E-03	2.88E-02
	Tailings (deposited)	4.18E-01	8.85E-05	1.93E-03	1.82E-03	2.14E-03	4.24E-01
	Waste (deposited)	7.40E-04	4.75E-05	2.88E-03	6.27E-05	6.49E-02	6.86E-02
Inorganic emissions to air	Aluminium	1.88E-11	6.62E-12	5.37E-12	9.07E-12	1.22E-11	5.20E-11
	Ammonia	1.45E-06	8.14E-08	1.48E-06	4.79E-07	1.36E-06	4.84E-06
	Carbon dioxide	3.57E-01	9.36E-03	7.10E-02	3.15E-02	1.11E-01	5.80E-01
	Carbon dioxide (aviation)	4.29E-08	2.19E-08	4.11E-08	2.76E-08	8.52E-08	2.19E-07
	Carbon dioxide (biotic)	1.06E-03	3.82E-04	2.32E-03	1.13E-03	1.50E-03	6.40E-03
	Carbon dioxide (land use change)	2.13E-04	3.11E-06	1.03E-05	6.07E-06	2.05E-05	2.53E-04
	Carbon dioxide (peat oxidation)	1.65E-10	4.15E-11	1.04E-06	5.53E-11	1.03E-10	1.04E-06
	Carbon monoxide	3.53E-04	4.20E-06	5.44E-05	4.42E-05	6.98E-05	5.26E-04
	Chlorine	5.97E-09	6.77E-11	1.22E-07	1.04E-10	6.79E-08	1.96E-07
	Hydrogen chloride	8.81E-07	5.16E-07	6.87E-07	4.19E-07	6.03E-07	3.11E-06
	Hydrogen sulphide	2.65E-06	4.41E-07	1.38E-06	6.39E-07	6.23E-07	5.73E-06
	Nitrogen dioxide	6.62E-08	2.74E-09	8.13E-09	2.60E-08	2.67E-08	1.30E-07
	Nitrogen monoxide	6.51E-07	1.61E-08	1.48E-07	3.24E-07	1.68E-07	1.31E-06
	Nitrogen oxides	1.00E-03	1.72E-05	6.79E-05	1.92E-04	1.47E-04	1.43E-03
	Nitrogen, total	7.22E-14	9.27E-14	2.55E-09	1.15E-13	1.57E-13	2.55E-09
	Nitrogen trifluoride	9.12E-14	5.08E-14	1.07E-13	6.29E-14	2.20E-13	5.31E-13



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
	Nitrous oxide	7.32E-06	1.75E-07	1.91E-07	3.72E-07	6.29E-07	8.68E-06
	Sulphur dioxide	4.99E-04	4.17E-05	1.05E-04	6.56E-05	2.07E-04	9.18E-04
	Sulphur hexafluoride	1.29E-14	1.37E-14	2.04E-14	1.95E-14	6.50E-15	7.30E-14
	Sulphur trioxide	1.50E-09	2.38E-10	7.69E-10	3.16E-10	6.37E-10	3.46E-09
	Sulphuric acid	3.33E-09	1.12E-11	1.75E-10	4.38E-11	4.41E-10	4.01E-09
Organic emissions to air [kg]	Methane	1.82E-03	1.62E-05	1.56E-04	3.92E-05	3.21E-04	2.35E-03
	Methane (biotic)	9.15E-07	9.47E-08	2.60E-05	1.06E-07	8.35E-06	3.55E-05
Halogenated organic emissions to air [kg]	Chloromethane (methyl chloride)	3.80E-15	7.84E-16	1.99E-11	1.07E-15	2.42E-15	1.99E-11
	R 114 (dichlorotetrafluoroethane)	4.77E-12	4.09E-12	6.34E-12	4.94E-12	7.88E-12	2.80E-11
	R 22 (chlorodifluoromethane)	3.55E-13	2.26E-13	2.67E-13	2.02E-13	3.85E-13	1.44E-12
NMVOC (organic) emissions to air [kg]	NMVOC (unspecified)	1.09E-04	2.84E-07	1.68E-05	1.02E-05	1.72E-04	3.08E-04
Heavy metals to air [kg]	Antimony	2.19E-10	6.42E-11	1.93E-10	9.22E-11	1.91E-10	7.59E-10
	Arsenic	3.67E-14	4.15E-16	1.62E-15	5.13E-16	2.98E-15	4.22E-14
	Arsenic (+V)	1.83E-09	7.34E-10	1.32E-09	9.99E-10	1.78E-09	6.67E-09
	Arsenic trioxide	7.43E-13	2.32E-15	3.88E-14	9.62E-15	9.76E-14	8.91E-13
	Cadmium	3.65E-10	4.07E-11	5.76E-10	7.62E-11	2.25E-10	1.28E-09
	Chromium	7.58E-09	1.36E-10	1.29E-09	2.26E-10	1.33E-09	1.06E-08
	Chromium (+III)	1.46E-10	7.02E-13	7.87E-12	2.10E-12	1.38E-11	1.71E-10
	Chromium (+VI)	1.54E-15	1.78E-17	9.05E-17	2.83E-17	2.19E-16	1.89E-15
	Cobalt	4.39E-10	6.78E-11	2.40E-10	5.95E-11	1.56E-10	9.63E-10
	Copper	8.88E-09	1.68E-10	1.60E-09	2.86E-10	1.69E-09	1.26E-08
	Hydrogen arsenic (arsine)	6.16E-11	1.92E-13	3.22E-12	7.99E-13	8.10E-12	7.39E-11
	Iron	1.82E-07	8.19E-10	1.24E-08	3.21E-09	2.68E-08	2.25E-07
	Lanthanum	1.21E-17	1.28E-17	1.90E-17	1.83E-17	6.10E-18	6.82E-17
	Lead	1.26E-07	1.06E-09	1.07E-08	2.37E-09	1.87E-08	1.59E-07
	Manganese	2.50E-07	1.50E-09	1.79E-08	4.19E-09	3.67E-08	3.10E-07
	Mercury	8.35E-10	1.19E-10	1.63E-08	1.25E-10	1.80E-09	1.92E-08
	Molybdenum	2.30E-10	5.75E-12	1.26E-10	1.64E-11	6.77E-11	4.46E-10
	Nickel	6.77E-09	2.42E-09	8.28E-09	4.34E-10	1.15E-09	1.91E-08
	Palladium	6.63E-18	7.06E-18	1.05E-17	1.01E-17	3.35E-18	3.76E-17
	Rhodium	6.40E-18	6.81E-18	1.01E-17	9.70E-18	3.23E-18	3.63E-17
	Scandium	6.16E-18	6.54E-18	9.75E-18	9.35E-18	3.12E-18	3.49E-17
	Selenium	2.56E-09	1.97E-09	3.12E-09	2.61E-09	4.20E-09	1.45E-08
	Silver	1.88E-11	6.62E-12	5.37E-12	9.07E-12	1.22E-11	5.20E-11
	Tellurium	1.37E-11	6.35E-14	6.45E-13	2.01E-13	1.11E-12	1.57E-11
	Thallium	9.36E-11	4.34E-13	5.60E-12	1.39E-12	1.10E-11	1.12E-10
	Tin	2.30E-09	6.36E-10	1.36E-09	1.00E-09	1.88E-09	7.17E-09
	Titanium	3.47E-09	1.59E-11	2.31E-10	5.15E-11	4.80E-10	4.25E-09
	Vanadium	2.66E-08	9.18E-09	1.17E-08	1.77E-09	4.92E-09	5.42E-08
	Zinc	2.00E-08	1.33E-09	1.68E-08	2.95E-09	1.11E-08	5.23E-08
Particles to air [kg]	Dust (> PM10)	2.33E-06	1.27E-06	2.50E-06	1.84E-06	3.55E-06	1.15E-05
	Dust (PM10)	5.14E-08	5.19E-10	6.78E-09	1.97E-06	1.08E-07	2.14E-06



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
	Dust (PM2.5 - PM10)	3.04E-05	8.16E-07	1.28E-05	5.06E-07	2.85E-05	7.31E-05
	Dust (PM2.5)	2.10E-05	3.69E-07	1.61E-06	4.51E-06	3.07E-06	3.05E-05
	Silicon dioxide (silica)	1.77E-12	6.23E-13	5.05E-13	8.54E-13	1.15E-12	4.90E-12
Inorganic emissions to freshwater [kg]	Ammonia	1.17E-07	2.34E-08	3.97E-08	2.68E-08	5.59E-08	2.63E-07
	Ammonium	1.87E-07	1.33E-08	4.57E-06	2.02E-08	2.09E-06	6.88E-06
	Nitrate	4.88E-06	5.71E-07	8.37E-06	8.01E-07	5.52E-06	2.01E-05
	Nitrogen organic bound	1.88E-06	6.00E-08	2.80E-05	1.39E-07	9.15E-07	3.10E-05
	Phosphate	4.02E-07	1.46E-08	1.53E-06	3.03E-08	1.01E-07	2.07E-06
	Phosphorus	2.41E-08	9.80E-10	2.35E-06	1.36E-09	1.13E-06	3.51E-06
	Antimony	3.71E-12	3.62E-12	1.88E-10	5.78E-12	9.01E-12	2.11E-10
Heavy metals to fresh water [kg]	Arsenic	7.77E-14	6.20E-16	3.33E-15	7.25E-16	6.27E-15	8.87E-14
	Arsenic (+V)	2.69E-06	7.75E-10	1.19E-06	2.59E-08	3.10E-08	3.94E-06
	Cadmium	1.18E-06	5.22E-10	2.73E-08	1.14E-08	2.51E-08	1.24E-06
	Chromium	1.30E-05	9.94E-08	1.46E-06	1.92E-07	3.95E-06	1.87E-05
	Chromium (+III)	1.01E-09	1.79E-10	2.89E-10	2.02E-10	4.06E-10	2.09E-09
	Chromium (+VI)	1.04E-10	2.46E-12	4.47E-09	3.64E-12	2.48E-09	7.06E-09
	Cobalt	7.51E-12	1.72E-13	4.90E-10	2.54E-13	1.68E-10	6.66E-10
	Copper	1.31E-06	1.17E-09	3.86E-08	1.47E-08	5.02E-08	1.42E-06
	Iron	3.07E-05	1.82E-05	2.96E-05	9.89E-06	1.03E-04	1.91E-04
	Lead	9.74E-07	2.48E-09	3.11E-08	1.15E-08	5.76E-08	1.08E-06
	Manganese	8.57E-09	5.07E-09	2.81E-08	6.76E-09	2.15E-08	7.00E-08
	Mercury	8.76E-09	2.17E-11	3.94E-10	1.19E-10	4.23E-10	9.71E-09
	Molybdenum	3.44E-09	2.27E-09	2.85E-09	2.17E-09	4.08E-09	1.48E-08
	Nickel	1.60E-06	1.14E-09	5.06E-08	1.65E-08	3.46E-08	1.71E-06
	Selenium	5.71E-10	2.87E-10	7.36E-08	3.24E-10	5.96E-10	7.54E-08
	Silver	1.51E-11	1.50E-12	5.99E-10	2.15E-12	3.33E-10	9.50E-10
	Tantalum	3.62E-17	2.38E-17	5.72E-17	2.87E-17	1.17E-16	2.63E-16
	Thallium	2.61E-11	8.13E-14	1.36E-12	3.38E-13	3.43E-12	3.13E-11
	Tin	9.53E-16	4.11E-16	4.38E-17	1.75E-17	2.63E-16	1.69E-15
	Titanium	7.74E-10	3.22E-10	4.37E-10	3.13E-10	5.92E-10	2.44E-09
	Tungsten	1.46E-12	4.76E-13	1.13E-12	6.09E-13	2.54E-12	6.22E-12
	Vanadium	1.49E-09	4.09E-10	5.13E-08	4.65E-10	1.03E-09	5.47E-08
	Zinc	1.14E-07	9.22E-10	5.57E-08	2.58E-09	2.52E-08	1.99E-07
Water quality metrics [kg]	Adsorbable organic halogen compounds (AOX)	9.78E-09	3.61E-09	3.70E-07	5.13E-09	1.16E-07	5.04E-07
	Biological oxygen demand (BOD)	1.00E-05	1.66E-08	5.07E-05	1.40E-07	4.06E-06	6.49E-05
	Chemical oxygen demand (COD)	2.30E-04	1.18E-05	2.57E-04	1.54E-05	3.96E-05	5.54E-04
	Nitrogenous Matter	2.18E-07	1.01E-09	1.60E-08	3.21E-09	3.11E-08	2.69E-07
	Solids (dissolved)	2.97E-08	2.45E-08	4.56E-08	3.54E-08	5.40E-08	1.89E-07
	Total dissolved organic bound carbon (TOC)	4.50E-12	2.00E-12	4.24E-13	2.07E-13	2.13E-12	9.26E-12



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
	Total organic bound carbon (TOC)	9.90E-06	1.41E-08	4.78E-05	1.30E-07	6.32E-07	5.85E-05
Other emissions to fresh water [kg]	Collected rainwater to river	5.37E-04	3.40E-05	5.22E-03	4.46E-05	5.11E-02	5.69E-02
	Cooling water to river	1.65E+01	7.28E-01	1.45E+00	5.75E-01	1.30E+00	2.05E+01
	Processed water to groundwater	2.50E-03	1.11E-04	1.83E+00	1.73E-04	1.49E-03	1.83E+00
	Processed water to river	2.03E-01	6.06E-03	6.88E-01	1.64E-02	4.43E-01	1.36E+00
	Turbined water to river	5.44E+01	2.78E+01	8.03E+00	8.24E+00	9.61E+00	1.08E+02
Water releases to sea water [kg]	Cooling water to sea	1.32E+00	2.02E-01	5.10E-01	2.40E-01	4.86E-01	2.76E+00
	Processed water to sea	9.41E-03	3.10E-06	8.72E-05	4.09E-05	1.64E-04	9.70E-03

Table B-3: LCI Asphalt binder SBS

Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
Inputs							
Non-renewable energy resources [MJ]	Crude oil (resource) ¹⁴	4.08E+01	1.46E-01	3.10E-01	2.65E-01	1.06E+00	4.26E+01
	Hard coal (resource)	9.93E-02	5.18E-02	1.01E-01	8.09E-02	2.29E-01	5.62E-01
	Lignite (resource)	2.15E-02	9.64E-03	1.56E-02	5.18E-03	4.89E-02	1.01E-01
	Natural gas (resource)	6.90E+00	5.51E-02	6.26E-01	7.64E-02	3.95E+00	1.16E+01
	Peat (resource)	3.34E-05	2.44E-06	1.73E-06	5.80E-07	1.18E-05	5.00E-05
	Uranium (resource)	4.94E-02	3.69E-02	5.23E-02	4.02E-02	1.09E-01	2.88E-01
Renewable energy resources [MJ]	Primary energy from geothermics	9.56E-04	1.02E-03	1.52E-03	1.45E-03	1.75E-03	6.70E-03
	Primary energy from hydro power	4.46E-02	2.40E-02	6.60E-03	7.08E-03	1.44E-02	9.67E-02
	Primary energy from solar energy	1.80E-02	4.55E-03	7.54E-03	5.80E-03	2.61E-02	6.20E-02
	Primary energy from waves	4.13E-15	6.17E-16	9.55E-16	8.70E-16	8.81E-15	1.54E-14
	Primary energy from wind power	8.08E-03	5.99E-03	1.45E-02	7.49E-03	3.86E-02	7.47E-02
	Antimony	3.58E-10	1.13E-11	2.55E-11	1.49E-11	5.37E-11	4.64E-10
	Chromium	2.00E-07	1.03E-07	5.25E-08	4.19E-08	1.28E-07	5.26E-07

¹⁴ Crude oil (resource) includes crude used as a feedstock and as an energy resource. The split between the two can be found in Table 4-5



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
Non-renewable elements [kg]	Lead	4.44E-05	1.44E-07	2.32E-06	5.82E-07	1.49E-05	6.23E-05
	Silver	4.72E-08	1.94E-10	2.50E-09	6.67E-10	1.60E-08	6.65E-08
	Zinc	2.87E-05	1.18E-07	1.52E-06	4.07E-07	9.76E-06	4.05E-05
Non-renewable resources [kg]	Colemanite ore	2.81E-05	1.16E-08	4.91E-08	2.96E-08	1.29E-07	2.83E-05
	Sodium chloride (rock salt)	5.68E-04	3.73E-06	8.21E-05	2.15E-06	1.03E-03	1.68E-03
Water resources [kg]	Ground water	9.64E-02	7.22E-03	1.60E+00	7.87E-03	5.24E-01	2.24E+00
	Lake water	5.39E-02	2.44E-04	5.02E-03	3.95E-03	4.89E-02	1.12E-01
	Lake water to turbine	1.19E+01	6.42E+00	1.66E+00	1.80E+00	3.53E+00	2.53E+01
	Rain water	2.66E-01	2.08E-02	4.41E-02	2.69E-02	6.17E-01	9.75E-01
	River water	1.70E+01	7.42E-01	2.48E+00	6.28E-01	2.60E+00	2.34E+01
	River water to turbine	4.03E+01	2.10E+01	6.12E+00	6.19E+00	1.59E+01	8.95E+01
	Sea water	1.30E+00	1.99E-01	4.98E-01	2.35E-01	7.12E-01	2.94E+00
Renewable resources [kg]	Carbon dioxide	1.68E-03	3.72E-04	7.20E-04	4.80E-04	1.88E-03	5.13E-03
	Nitrogen	6.04E-14	9.50E-15	1.54E-14	1.41E-14	1.28E-13	2.27E-13
	Oxygen	2.18E-04	6.64E-06	4.88E-05	6.39E-03	5.30E-04	7.20E-03
Outputs							
Deposited goods [kg]	Hazardous waste (deposited)	1.05E-08	5.90E-11	2.32E-09	1.80E-10	1.72E-09	1.47E-08
	Overburden (deposited)	5.77E-02	1.75E-02	3.59E-02	1.90E-02	9.08E-02	2.21E-01
	Slag (deposited)	5.02E-14	1.77E-14	1.40E-14	2.37E-14	9.37E-14	1.99E-13
	Spoil (deposited)	1.84E-02	3.97E-04	2.28E-03	3.97E-04	1.47E-02	3.62E-02
	Tailings (deposited)	4.06E-01	8.58E-05	1.87E-03	1.77E-03	6.92E-03	4.16E-01
	Waste (deposited)	7.18E-04	4.61E-05	2.80E-03	6.09E-05	3.83E-03	7.45E-03
Inorganic emissions to air	Aluminium	1.82E-11	6.42E-12	5.20E-12	8.80E-12	3.48E-11	7.34E-11
	Ammonia	1.41E-06	7.90E-08	1.43E-06	4.65E-07	3.96E-06	7.34E-06
	Carbon dioxide	3.46E-01	9.07E-03	6.89E-02	3.06E-02	2.25E-01	6.79E-01
	Carbon dioxide (aviation)	4.16E-08	2.13E-08	3.99E-08	2.68E-08	1.30E-07	2.60E-07
	Carbon dioxide (biotic)	1.03E-03	3.70E-04	2.25E-03	1.09E-03	2.08E-03	6.83E-03
	Carbon dioxide (land use change)	2.07E-04	3.01E-06	9.99E-06	5.89E-06	7.34E-05	2.99E-04
	Carbon dioxide (peat oxidation)	1.60E-10	4.03E-11	1.01E-06	5.37E-11	1.83E-10	1.01E-06
	Carbon monoxide	3.42E-04	4.07E-06	5.27E-05	4.29E-05	1.47E-04	5.90E-04
	Chlorine	5.79E-09	6.56E-11	1.18E-07	1.01E-10	6.23E-08	1.87E-07
	Hydrogen chloride	8.54E-07	5.01E-07	6.67E-07	4.07E-07	1.06E-06	3.49E-06
	Hydrogen sulphide	2.57E-06	4.27E-07	1.34E-06	6.20E-07	1.38E-06	6.34E-06
	Nitrogen dioxide	6.42E-08	2.65E-09	7.88E-09	2.52E-08	1.09E-07	2.09E-07
	Nitrogen monoxide	6.31E-07	1.57E-08	1.44E-07	3.14E-07	3.00E-07	1.40E-06



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
	Nitrogen oxides	9.74E-04	1.67E-05	6.58E-05	1.86E-04	4.30E-04	1.67E-03
	Nitrogen, total	7.01E-14	8.99E-14	2.47E-09	1.12E-13	1.98E-13	2.47E-09
	Nitrogen trifluoride	8.84E-14	4.93E-14	1.03E-13	6.10E-14	3.11E-13	6.13E-13
	Nitrous oxide	7.10E-06	1.70E-07	1.85E-07	3.61E-07	2.07E-06	9.88E-06
	Sulphur dioxide	4.84E-04	4.05E-05	1.02E-04	6.36E-05	2.11E-04	9.01E-04
	Sulphur hexafluoride	1.25E-14	1.33E-14	1.97E-14	1.89E-14	2.28E-14	8.73E-14
	Sulphur trioxide	1.45E-09	2.31E-10	7.46E-10	3.06E-10	5.83E-09	8.57E-09
	Sulphuric acid	3.23E-09	1.08E-11	1.70E-10	4.25E-11	1.09E-09	4.54E-09
Organic emissions to air [kg]	Methane	1.77E-03	1.57E-05	1.52E-04	3.80E-05	7.68E-04	2.74E-03
	Methane (biotic)	8.88E-07	9.18E-08	2.52E-05	1.02E-07	8.82E-06	3.51E-05
Halogenated organic emissions to air [kg]	Chloromethane (methyl chloride)	3.69E-15	7.61E-16	1.93E-11	1.04E-15	4.94E-15	1.93E-11
	R 114 (dichlorotetrafluoroethane)	4.63E-12	3.96E-12	6.15E-12	4.79E-12	1.20E-11	3.15E-11
	R 22 (chlorodifluoromethane)	3.45E-13	2.20E-13	2.59E-13	1.96E-13	5.86E-13	1.60E-12
NM VOC (organic) emissions to air [kg]	NM VOC (unspecified)	1.06E-04	2.76E-07	1.63E-05	9.93E-06	1.95E-04	3.28E-04
Heavy metals to air [kg]	Antimony	2.12E-10	6.22E-11	1.87E-10	8.94E-11	2.99E-10	8.50E-10
	Arsenic	3.56E-14	4.02E-16	1.57E-15	4.97E-16	5.52E-15	4.36E-14
	Arsenic (+V)	1.78E-09	7.12E-10	1.28E-09	9.69E-10	2.94E-09	7.68E-09
	Arsenic trioxide	7.20E-13	2.25E-15	3.76E-14	9.33E-15	2.42E-13	1.01E-12
	Cadmium	3.54E-10	3.95E-11	5.59E-10	7.39E-11	9.92E-10	2.02E-09
	Chromium	7.35E-09	1.32E-10	1.25E-09	2.19E-10	3.05E-09	1.20E-08
	Chromium (+III)	1.42E-10	6.81E-13	7.63E-12	2.03E-12	3.38E-11	1.86E-10
	Chromium (+VI)	1.49E-15	1.72E-17	8.78E-17	2.74E-17	5.33E-16	2.16E-15
	Cobalt	4.26E-10	6.57E-11	2.33E-10	5.77E-11	3.05E-10	1.09E-09
	Copper	8.62E-09	1.63E-10	1.55E-09	2.78E-10	4.00E-09	1.46E-08
	Hydrogen arsenic (arsine)	5.98E-11	1.86E-13	3.12E-12	7.75E-13	2.01E-11	8.40E-11
	Iron	1.77E-07	7.95E-10	1.20E-08	3.11E-09	6.34E-08	2.56E-07
	Lanthanum	1.17E-17	1.24E-17	1.85E-17	1.77E-17	2.14E-17	8.17E-17
	Lead	1.22E-07	1.03E-09	1.04E-08	2.30E-09	4.56E-08	1.81E-07
	Manganese	2.43E-07	1.45E-09	1.74E-08	4.06E-09	8.85E-08	3.54E-07
	Mercury	8.09E-10	1.15E-10	1.58E-08	1.22E-10	3.54E-08	5.23E-08
	Molybdenum	2.23E-10	5.58E-12	1.22E-10	1.59E-11	1.33E-10	5.00E-10
	Nickel	6.57E-09	2.35E-09	8.03E-09	4.21E-10	2.40E-09	1.98E-08
	Palladium	6.43E-18	6.84E-18	1.02E-17	9.75E-18	1.18E-17	4.49E-17
	Rhodium	6.21E-18	6.61E-18	9.81E-18	9.41E-18	1.13E-17	4.34E-17
	Scandium	5.97E-18	6.34E-18	9.45E-18	9.07E-18	1.10E-17	4.18E-17
	Selenium	2.48E-09	1.91E-09	3.03E-09	2.53E-09	6.62E-09	1.66E-08
	Silver	1.82E-11	6.42E-12	5.20E-12	8.80E-12	3.48E-11	7.34E-11
	Tellurium	1.33E-11	6.16E-14	6.26E-13	1.95E-13	2.79E-12	1.69E-11
	Thallium	9.08E-11	4.21E-13	5.43E-12	1.35E-12	2.74E-11	1.25E-10
	Tin	2.23E-09	6.17E-10	1.32E-09	9.70E-10	3.11E-09	8.24E-09
	Titanium	3.37E-09	1.54E-11	2.24E-10	5.00E-11	1.19E-09	4.85E-09



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
Particles to air [kg]	Vanadium	2.58E-08	8.91E-09	1.13E-08	1.72E-09	1.04E-08	5.82E-08
	Zinc	1.94E-08	1.29E-09	1.63E-08	2.86E-09	1.39E-08	5.38E-08
	Dust (> PM10)	2.26E-06	1.24E-06	2.43E-06	1.79E-06	5.78E-06	1.35E-05
	Dust (PM10)	4.99E-08	5.03E-10	6.58E-09	1.91E-06	1.55E-07	2.13E-06
	Dust (PM2.5 - PM10)	2.95E-05	7.91E-07	1.24E-05	4.91E-07	1.54E-05	5.87E-05
	Dust (PM2.5)	2.03E-05	3.58E-07	1.56E-06	4.37E-06	9.51E-06	3.61E-05
	Silicon dioxide (silica)	1.71E-12	6.04E-13	4.90E-13	8.28E-13	3.27E-12	6.91E-12
Inorganic emissions to freshwater [kg]	Ammonia	1.14E-07	2.27E-08	3.85E-08	2.60E-08	1.56E-07	3.57E-07
	Ammonium	1.82E-07	1.29E-08	4.43E-06	1.96E-08	2.19E-06	6.83E-06
	Nitrate	4.73E-06	5.54E-07	8.12E-06	7.77E-07	1.29E-05	2.71E-05
	Nitrogen organic bound	1.83E-06	5.82E-08	2.72E-05	1.35E-07	2.03E-06	3.12E-05
	Phosphate	3.90E-07	1.42E-08	1.48E-06	2.94E-08	3.79E-07	2.29E-06
	Phosphorus	2.33E-08	9.50E-10	2.28E-06	1.32E-09	1.09E-06	3.40E-06
Heavy metals to fresh water [kg]	Antimony	3.60E-12	3.51E-12	1.83E-10	5.61E-12	1.44E-11	2.10E-10
	Arsenic	7.54E-14	6.01E-16	3.23E-15	7.03E-16	1.17E-14	9.16E-14
	Arsenic (+V)	2.61E-06	7.51E-10	1.15E-06	2.51E-08	1.00E-07	3.89E-06
	Cadmium	1.14E-06	5.06E-10	2.65E-08	1.10E-08	7.19E-08	1.25E-06
	Chromium	1.26E-05	9.64E-08	1.41E-06	1.86E-07	9.58E-06	2.39E-05
	Chromium (+III)	9.80E-10	1.74E-10	2.81E-10	1.96E-10	1.38E-09	3.01E-09
	Chromium (+VI)	1.01E-10	2.39E-12	4.33E-09	3.53E-12	2.24E-09	6.68E-09
	Cobalt	7.28E-12	1.67E-13	4.75E-10	2.47E-13	1.52E-10	6.35E-10
	Copper	1.27E-06	1.13E-09	3.74E-08	1.42E-08	1.30E-07	1.46E-06
	Iron	2.98E-05	1.77E-05	2.87E-05	9.59E-06	7.99E-05	1.66E-04
	Lead	9.44E-07	2.40E-09	3.02E-08	1.12E-08	1.47E-07	1.14E-06
	Manganese	8.31E-09	4.91E-09	2.73E-08	6.56E-09	2.75E-08	7.45E-08
	Mercury	8.49E-09	2.10E-11	3.82E-10	1.15E-10	9.23E-10	9.93E-09
	Molybdenum	3.33E-09	2.20E-09	2.76E-09	2.11E-09	6.15E-09	1.66E-08
	Nickel	1.56E-06	1.10E-09	4.91E-08	1.60E-08	9.69E-08	1.72E-06
	Selenium	5.54E-10	2.78E-10	7.14E-08	3.15E-10	9.45E-10	7.35E-08
	Silver	1.47E-11	1.46E-12	5.80E-10	2.08E-12	3.02E-10	9.01E-10
	Tantalum	3.51E-17	2.30E-17	5.55E-17	2.78E-17	1.49E-16	2.91E-16
	Thallium	2.53E-11	7.88E-14	1.32E-12	3.27E-13	8.49E-12	3.55E-11
	Tin	9.24E-16	3.98E-16	4.24E-17	1.70E-17	3.43E-16	1.73E-15
	Titanium	7.50E-10	3.12E-10	4.23E-10	3.03E-10	9.12E-10	2.70E-09
	Tungsten	1.42E-12	4.61E-13	1.10E-12	5.90E-13	4.28E-12	7.85E-12
	Vanadium	1.44E-09	3.97E-10	4.98E-08	4.51E-10	1.61E-09	5.37E-08
	Zinc	1.11E-07	8.94E-10	5.40E-08	2.51E-09	3.89E-08	2.07E-07
Water quality metrics [kg]	Adsorbable organic halogen compounds (AOX)	9.49E-09	3.50E-09	3.59E-07	4.97E-09	1.66E-07	5.43E-07
	Biological oxygen demand (BOD)	9.72E-06	1.61E-08	4.91E-05	1.36E-07	4.75E-06	6.38E-05
	Chemical oxygen demand (COD)	2.23E-04	1.14E-05	2.49E-04	1.49E-05	6.56E-05	5.64E-04
	Nitrogenous Matter	2.11E-07	9.81E-10	1.55E-08	3.12E-09	1.92E-07	4.23E-07



Type	Flow	Asphalt binder, Crude oil	Asphalt binder, Transport to refinery	Asphalt binder, Refinery	Asphalt binder, Transport to terminal	Asphalt binder, Terminal	Total
	Solids (dissolved)	2.88E-08	2.38E-08	4.42E-08	3.43E-08	8.67E-08	2.18E-07
	Total dissolved organic bound carbon (TOC)	4.36E-12	1.94E-12	4.11E-13	2.01E-13	2.85E-12	9.76E-12
	Total organic bound carbon (TOC)	9.60E-06	1.37E-08	4.64E-05	1.26E-07	2.23E-06	5.84E-05
Other emissions to fresh water [kg]	Collected rainwater to river	5.21E-04	3.29E-05	5.06E-03	4.33E-05	5.75E-03	1.14E-02
	Cooling water to river	1.60E+01	7.06E-01	1.41E+00	5.58E-01	2.04E+00	2.07E+01
	Processed water to groundwater	2.42E-03	1.07E-04	1.77E+00	1.68E-04	3.38E-03	1.78E+00
	Processed water to river	1.97E-01	5.88E-03	6.68E-01	1.59E-02	4.56E-01	1.34E+00
	Turbined water to river	5.28E+01	2.69E+01	7.79E+00	7.99E+00	1.98E+01	1.15E+02
Water releases to sea water [kg]	Cooling water to sea	1.28E+00	1.96E-01	4.95E-01	2.33E-01	7.06E-01	2.91E+00
	Processed water to sea	9.12E-03	3.01E-06	8.45E-05	3.97E-05	5.04E-04	9.76E-03