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Environmental life-cycle impacts of bitumen: Systematic review and new Canadian models

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ABSTRACT

Bitumen – or asphalt binder – is a major contributor to pavement environmental impacts. Nevertheless, the literature only counts scarce asphalt binder LCAs, with highly variable results. To better understand bitumen environmental impacts, we review LCAs published before 2024. Then, we build bitumen LCA models for different Canadian markets, using TRACI 2.1 and ecoinvent v3.6. The carbon footprint of Canadian asphalt binders ranges within [826–1098] $kgCO_2eq/t$ (potentially up to 2680 $kgCO_2eq/t$ when including fugitive emissions). Crude oil extraction is the main contributor to most life cycle environmental impact categories, but likely still underestimated. Transportation impacts can vary highly ([18–291] $kgCO_2eq/t$ in Canada). Models for these two hotspots must be tailored. Finally, we critically compare the carbon footprints of all published virgin asphalt binders LCAs: previous carbon footprints range within [143–637] $kgCO_2eq/t$ and are very likely underestimated. Previous pavement LCA results must be questioned, and higher-quality LCIs urgently developed to produce robust regionalized LCA-based recommendations on pavement green practices.

1. Introduction

In 2020, an estimated 143 million metric tons of bitumen were produced to build pavements and roofs (ADI Analytics, 2021), with most of the environmental and financial costs of these structures being associated with this material. Bitumen, also called asphalt binder, asphalt cement binder or asphalt cement, is a black viscous mixture of hydrocarbons mostly obtained as a residue from petroleum distillation. It is mainly used to ensure cohesion – thus resistance to loads – between aggregates of road, port and airport's pavement, to waterproof pavements and roofs, and to produce asphalt shingles covering various structures. It is difficult to estimate with certainty what proportion of the bitumen market is taken up by infrastructure, with road use representing between 50 and 91 % of the whole (ADI Analytics, 2021; Asphalt Institute and Eurobitume, 2011; OG Analysis, 2019).

According to ADI Analytics, in 2020, 88 % of global bitumen production was dedicated to road pavements, making roads by far the leading beneficiary of bitumen use (ADI Analytics, 2021). Based on the carbon footprint considered, which varied between 205 kg of carbon dioxide equivalent per ton ($kgCO_2eq/t$) (Eurobitume, 2020) and 637 $kgCO_2eq/t$ (Thinkstep, 2019), road bitumen production is estimated to have emitted between 26 and 80 million tons of carbon dioxide equivalent (tCO_2eq) in 2020, *i.e.*, between 0.05 and 0.15 % of global greenhouse gas emissions (GHG) (Ritchie et al., 2020). Today, bitumen is recognized as the biggest contributor to the

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environmental impact of asphalt pavements construction (de Bortoli, 2020), and a series of innovations are being developed to reduce this impact: expansion processes (Liliana Abreu et al., 2017), multi-recycling (Abdalla et al., 2022), introduction of bio-sourced materials such as lignine (Wu et al., 2021), sugarcane waste molasses (Van Phuc Le, 2021), or food waste bio-products (Mahssin et al., 2021). Nevertheless, although several dozen types of non-modified bitumen are produced worldwide, our understanding of their true environmental impacts is extremely limited, because over the last two decades, only a half-dozen life cycle assessments (LCA) have been performed to study this product, as will be seen in the literature review section. Furthermore, the impacts shown in published LCA studies are hardly consistent, with uncertainties often being unknown and the quantification models produced being very heterogeneous. This lack of a consistent understanding of the environmental footprint of asphalt binder worldwide obviously hinders the environmental optimization of asphalt roads. Indeed, until uncertainties are robustly quantified within assessment models, it cannot be determined whether or not recommendations based on LCA or other quantitative environmental assessments are robust.

This article aims mainly at providing a better understanding of the environmental footprint of asphalt binders and of their variability and uncertainties. We will begin with a review of the literature and perform a critical analysis of bitumen LCA models published up to 2024. Next, we will build bitumen LCA models for different Canadian markets, with a particular focus on Quebec, where no related study has been published to date. Following that, we will compare the robustness of our Quebec model with that of the only model having a Canadian geographic representation that has thus far been published, in the context of Quebec in 2019, by propagating uncertainties using the Pedigree Matrix approach and a 10000-run Monte-Carlo simulation. Finally, we will critically compare the average carbon footprint values from all bitumen LCA models published before 2024 and our new models, and discuss these results, especially questioning the consequence of modeling better oil extraction, and especially of accounting for hard-to-assess fugitive emissions.

2. Literature review

2.1. Overview of asphalt binder LCAs

The literature, both scientific and gray, covers a dozen bitumen LCA models, with hardly any being exhaustive. The first models were developed in Europe in the 90s. First, Häkkinen and Mäkelä (Häkkinen and Mäkelä, 1996) produced the Life Cycle Inventories (LCI) of the ecoinvent database (Dones et al., 2007; Jungbluth, 2007). Then, Eurobitume, the union of European bitumen producers, is believed to have developed its first inventory in 1999. The document was not found online, but is titled "Partial life cycle inventory or "Eco-profile" for paving grade bitumen, Report 99/007" in several articles (e.g., Blomberg et al., 2012a, 2012b; Blomberg and Lyall, 2000). In the early 2000s, new LCAs were published, starting with Stripple's study from the Swedish Environmental Research Stripple, 2001), who contributed to regional inventory development using data specific to Sweden, then, by the Athena Sustainable Materials Institute, a construction sector LCA research organization which produced a road asphalt LCI for North America (Athena Institute, 2001). These models were analyzed by Yang (2014), and it can safely be assumed that these LCIs are today obsolete, especially given that LCA practices have since improved considerably, as have the production technologies in the bitumen supply chain, and thanks to changes in asphaltic crude oil supply. In Europe, Eurobitume pursued its work with the publication of a second LCI version in 2011 (Blomberg et al., 2011), then a third in 2020 (Eurobitume, 2020). At about the same time, the Asphalt Institute (AI) published LCIs for both modified and non-modified asphalt binders for North America (Thinkstep, 2019). Other LCIs ensuing from academic research were published for the American (Yang, 2014) and French (de Bortoli, 2018a) markets, as well as for South African production, which was not based on a consistent LCI background database thus not included in this review (Blaauw et al., 2020). Recent models derived from the USLCI model (USLCI 2012) have also been produced, such as a Californian model by Saboori et al. (2022) and an LCI that they refer to, from the EarthShare LCI database but that is not retraceable and thus not included in our review. Also, the bitumen LCI used by Moretti et al. (2022) comes from a report written in Dutch, and we were thus not able to include it in our review, while knowing it uses thermodynamic allocation and ecoinvent v3.5 background database.

2.2. Methodological comparison

The methodology choices for these LCA models are summarized in Table 1. The models vary in terms of system boundaries, background data, refining impacts allocation between co-products, and data collection period, among others. The system boundaries considered mostly range from the extraction of crude oil to the production of bitumen at the refinery outlet (*cradle-to-refinery gate*). Some studies include the infrastructure amortization. Infrastructure can include all the built infrastructure required to produce, transport, and refine crude oil, such as wells, pipelines, and refinery complex. But the impact of capital goods' amortization is not considered systematically, and the post-refinery stages (e.g. bitumen storage after production) are only modeled in the AI study (Thinkstep, 2019). Furthermore, some LCAs model the extraction of a mix of crude oils specific to bitumen production – called asphaltic or bitumen crude slate –, while other less fine-tuned models consider generic crudes. This last approach is not recommended, as only heavy crude oils can produce significant quantities of high-quality bitumen adapted to road use. The studies also consider different refinery impact allocation methods: mass, economic, or thermodynamic allocation.

Background LCIs used to model bitumen production impacts also vary, including the GaBi database, GREET, USLCI, US-EI 2.2 and Franklin Associate databases, as well as several ecoinvent (EI) versions. The life cycle impact assessment (LCIA) methods) selected, also called characterization methods, vary as well. Finally, the studies cover various bitumen production or consumption markets, and the data represent different periods. These methodological variations influence all the bitumen-related environmental impact results obtained from LCAs as well as their accuracy. Moreover, these variations make it difficult to carry out any direct meaningful

Table 1
Main features of published LCA models of asphalt binders.

	System boundaries				Crude slate		Refinery model		Data & LCIA method		
Reference	Cradle-to-refinery's gate	Hot storage	Transport to terminal + blending	Infra-struc-ture	Specific to bitumen	Repre-sentati-veness	Bitumen yield	Multi-function-ality allocation rules	Background database	LCIA method	Data from
Saboori et al., 2022	X	–	–	–	No	Cali-fornia	–	Massic	GaBi, USLCI database	TRACI 2.1	Mixed
Eurobitume 2020	X	X	–	(X)	Yes	Europe	28.5 %	Thermo-dynamic	ecoinvent V3.5	Various	2013–2017
Thinkstep, 2019	X	X	X	–	Yes	North America	20.1 %	Thermo-dynamic	GaBi 2017	TRACI 2.1, CML 4.7	2015–2016
de Bortoli, 2018a	X	X	–	X	Yes	France	22.3 %	Economic	ecoinvent V3.2	IW+ v1.30/ 1.48	2005–2017
Yang 2014	X	X	X	–	No	USA	3.4 %	Economic	GREET, US-EI 2.2	TRACI 2.1	2005–2013
Blomberg et al., 2012a	X	X	–	(X)	Yes	Europe	22.3 %	Economic	ecoinvent V2.2	None	2005–2010
USLCI 2012	X	–	–	–	No	USA	–	Massic, Economic	USLCI & Franklin Associates	None	<2004
ATHENA INSTITUTE 2001	X	–	–	–	No	USA Canada	–	Massic	Franklin Associates	None	<1998

(X) = optional.

comparisons between these different asphalt binders, since the inconsistent results are due to both epistemological uncertainties (=errors and lack of knowledge) and stochastic variabilities (=natural variability) (Pannier, 2017).

Finally, unions' LCAs lack transparency. The last Eurobitume LCA report (Eurobitume, 2020) does not provide complete LCIs, while the LCA model provided from the Union is made confidential by containing the list of elementary flows rather than the intermediary and elementary flows that could help fully understand and adapt the model. The AI model lacks transparency on two fronts. Firstly, it is based on GaBi LCIs, which are aggregated to ensure confidentiality of industrial data, and thus not fully transparent. Indeed, access to intermediary flow exchanges is not provided in GaBi LCIs. Next, foreground data (including inventory data and choice of processes) and allocation factors are not accessible, and consequently, the model is not reproducible. Furthermore, even though it is stated that the LCA has been reviewed by three external experts forming a review committee, the critical review is incomplete with regards to the requirements indicated in section 6.2 of the ISO 14044, as reviewers' report (comments and answers) are not included in the LCA report (International Organization for Standardization, 2006a) (though reviewer reports are said to be accessible upon request). In the end, we believe that these elements may constitute a breach with regards to the ISO principle of transparency (International Organization for Standardization, 2006a, 2006b).

2.3. Focus on Canadian models

In the Canadian region, an LCI was developed in 2008 by the Polytechnique Montreal's CIRAIG research centre on request of the Ministry of Transportation of Quebec (MTQ) (Kicak and Ménard, 2009). But the inventories were never published and remain the property of the MTQ. Moreover, the AI LCAs, which are supposed to represent North America, are more representative of the United States (US) than of Canada. Among the sites assessed, 9 refining sites of 6 companies are situated in the US, versus 3 sites of 2 companies in Canada (Thinkstep, 2019). The models consider a 53 % bitumen crude supply from Canada and 26 % from the US, with the balance coming from the Gulf countries and the rest of America. In the model, 44 % of the crude comes from the Alberta oil sands, and 80 % of this supply gets to the refinery in the form of dilbit, 16 % as synthetic oil, and 3 % as synbit. This crude slate does not align with the information found in the literature in the case of Canada, as no asphalt binder would be produced from oil sands for the Canadian market (as of 2020), despite it is technically possible (Lill et al., 2020). In all cases, and as already said, the AI model is not reproducible. It does not provide foreground data, and the background data used is drawn from the GaBi 2017 database, which is proprietary and non-transparent. LCIs can be imported in ILCD (International Reference Life Cycle Data System) format. However, import into OpenLCA provides carbon footprints that are lower than the impacts presented in the related report using the same characterization method versions. Furthermore, importing the model to the LCA software SimaPro failed. To conclude, no recent, open-source and transparent LCI model that is representative of the asphalt binders in the Quebec and Canadian markets is available.

2.4. Variabilities, uncertainties, and LCI quality

Environmental impact results comprise some variability and uncertainties (AzariJafari et al., 2018; Huijbregts, 2001), which are often not well characterized in LCAs due to the additional effort required to gather field data and perform calculations. However, the validity of the solutions ranking being prioritized based on their environmental performance depends on the reliability of the LCA results (Gregory et al., 2016). High quality life cycle inventory (LCI) data allow to reduce the uncertainty of LCA results (Weidema, 1998), and consequently, to provide reliable and adequate environmental decision-making. The Pedigree Matrix approach, which is arguably the most broadly used LCI data quality characterization system, was conceptualized for LCA in 1996 by Weidema and Wesnæs (Weidema and Wesnæs, 1996): the quality of each LCI can be described by a 5-dimensional vector which describes the reliability of data, their completeness, the temporal correlation of LCI data with the modeled system, their geographical correlation, and any other technological correlations. The vector provides a data quality score from 1 to 5 for each of the five dimensions, with 1 being the best quality and 5, the worst.

A reliable LCA environmental assessment thus calls for LCI models that accurately represent the system being assessed. But very little information is available on the robustness of environmental assessments of asphalt binders or on the specific quality of a bitumen LCI used in a road LCA. Only the 2020 Eurobitume study analyzes these uncertainties, using uncertainty factors generated through the Pedigree Matrix to carry out Monte Carlo simulations (MCS) (Eurobitume, 2020), which constitute the most popular stochastic method to assess uncertainties of LCA results (Lloyd and Ries, 2007). However, every road LCA is conducted within the confines of a specific time and place, as well as in a specific technological reality that often does not correspond to the LCI of the bitumen used. Finally, these uncertainties could sometimes lead to faulty recommendations based on road-related LCAs having results that are too uncertain. Such uncertainties could have the effect of compromising the very justification for using road LCA results, i.e., a reduction of the environmental impact of road infrastructure.

3. Background information on crude oil production and asphaltic crudes

As the type of oil refined to produce asphalt binder has a primary influence on its environmental impact (e.g., Thinkstep, 2019), it is essential to understand oil production and asphaltic crude slates (as described in section 2) from a technical point of view, to develop a sound method to conduct an LCA on Canadian asphalt binders. We explain here the different types of crudes and production pathways, and explore asphaltic crude slates, specifically for the case of Canadian crudes.

3.1. Types of crudes and production pathways

Petroleum geologists classify crude oils based on their density, quantified using the American Petroleum Institute (API) gravity index, under the categories of light, medium, heavy, or extra-heavy oils. Light and medium crudes are extracted by conventional means called "primary" and "secondary" recoveries, where wells are vertically drilled, and petroleum easily flows to the surface. After these extractions, 50 to 80 % of conventional heavy crude is still in the well, and can be extracted with different means – thermal, gas injection, chemical or other recoveries (Kokal and Al-Kaabi, 2010): this is called tertiary recovery, sometimes characterized under "non-conventional extraction" of conventional heavy oil. Finally, non-conventional oil can be produced either by mechanical scraping of superficial natural bitumen (open-pit surface mining) or injection of hot steam for deeper bitumen (in situ production) (CAPP, 2023). Some confusion can occur when talking about heavy oil: while it should refer to tertiary-recovered conventional oil, it is also often used to talk about oil sands that are in fact extra-heavy oil. Oil sands can also be called tar sands or non-conventional oils. In the same way, tertiary-recovered conventional oil is sometimes called non-conventional oil, while only the recovery pathways are non-conventional. Likewise, bitumen can be used to talk about asphalt binders (UK vs US term), or natural bitumen contained in the oil sands. In this article, "bitumen" refers to asphalt binder, and natural bitumen refers to oil sands. These confusions and polysemous words can complexify the understanding of oil and asphalt binder markets, and a specific effort will be brought to be as rigorous as possible in the use of the different terms in this article.

3.2. Bitumen production and asphaltic crude slate

Not all crude oils can produce thick viscous residue at distillation, called bitumen (UK) or asphalt (US), and then used as a base for asphalt binders. In average in the US, 2 to 5 % of crude distillation ends up as asphalt (U.S. Energy Information Administration (EIA), 2023), while oil distillation oriented towards bitumen production typically yield 10 to 50 % or more asphalt (IARC Working Group on the Evaluation of Carcinogenic Risks to humans, 2013). Lighter crudes produce less asphalt, and down to 0 %, while the heaviest crude oils produce the most bitumen as they have higher percentage of compounds with over sixty carbon atoms, thus a high molecular weight and high boiling point (Dusseault, 2001; Manke, 2010). Heavy crude oil residue rate (=asphalt yield) from simple distillation would represent more than 60–70 % of the Canadian heavy crudes (Sanchez Lemus, 2015). Nevertheless, some refineries are now able to break the long hydrocarbon chains contained in this lower value residue to transform it in lighter and higher value petroleum products such as combustion fuels, but at a higher cost (Manke, 2010; U.S. Energy Information Administration (EIA), 2023). On the other hand, some "asphalt refineries" are dedicated to producing asphalt (MacLeod, 2009) and specifically process heavy oil to produce road asphalt binders of excellent quality (Cenovus, xxxx). The asphaltic crude slate of a given market is thus driven by economic and technical aspects, and thus changes overtime. Indeed, the objective of a refinery is to set its distillation parameter and activities to maximize profit. From a given type of crude oil, depending on the respective market prices at that time, the demand, and the cost to produce different shares of co-products, the refinery will thus try to optimize its added value. But the quality of the co-products is also part of the equation. Indeed, the best asphalt binders have a high fraction of asphaltenes and low fraction of wax (Lill et al., 2020). Asphaltenes are molecules that give a good resistance to high temperature ranges (Hesp, 2022) and limit the occurrence of cracks in the future asphalt pavement (Ma et al., 2022). Similarly, a low fraction of wax (i.e., in non-paraffinic crudes), allows the pavement not to get stiff at low temperature to reduce cracking too, and to better recycle reclaimed asphalt pavement (RAP) (Hesp, 2022; Kriz et al., 2017; MacLeod, 2009). In regions where temperatures go low, it is thus even more important to prioritize high-asphaltene and low-wax asphalt binders to ensure long-lasting and recyclable road infrastructure. Also, as the physical properties of good asphalts deteriorate when heated at high temperature (as volatile components are distilled), the temperature of crude oil distillation to produce good quality asphalt needs to stay under 400 °C (644°F) (IARC Working Group on the Evaluation of Carcinogenic Risks to humans, 2013).

3.3. The case of Canadian asphaltic crudes

In Canada, winters can be quite rigorous while summers very hot: this requires an excellent susceptibility of bitumen to stand these high temperature ranges. Thus, the best crudes for asphalt pavements are said to be the heavy naphthenic crudes (MacLeod, 2009). In general, oil is heavier in the northeast of Canada, while closer to the Rockies, the crude is lighter (MacLeod, 2009). In particular, southeastern Saskatchewan mainly produces light oil (Manke, 2010) while heavy oil deposits are located in Alberta and Saskatchewan, specifically in the Cold Lake and Lloydminster areas (Canada's Oil and Natural Gas Producers, xxxx; Manke, 2010). The Lloydminster area, nicknamed "the Heavy oil Capital of the World" (City of Lloydminster, 2023), is also known for producing the best quality asphalt binders (Cenovus, n.d.). With Cold Lake, it produces a large part of Canada's heavy oil from "recompleted wells". These are former primary and secondary recovery wells that were first economically abandoned as the remaining petroleum was too thick to flow well (Canada's Oil and Natural Gas Producers, n.d.; Manke, 2010). In Lloydminster, heavy oil is produced by both cold (=gas injection and other cold recoveries) and thermal recoveries, while in Cold Lake, it can only be recovered by thermal stimulation (MacLeod, 2009).

4. Method

The present study aims at carrying out an LCA of bitumen consumed in various markets in Canada in accordance with ISO 14040 and 14044 (International Organization for Standardization, 2006c, 2006d). Specifically, we will be producing an LCI for bitumen consumed in Quebec, after which we will assess its environmental impacts, and then analyze scenarios covering different Canadian crude oil transportation in order to assess the impacts of bitumen for other market archetypes in Canada. Indeed, the crude slate to produce bitumen seems to be stable within Canada, as well as the refining step, that does not rely on very regional processes such as the use of electricity. Next, we will calculate the probability density of the carbon footprints of our Quebec model and of the AI model used in the Quebec context in 2019, by combining uncertainty factors derived from the Pedigree Matrix data quality scores and an MCS (Muller, 2015; Muller et al., 2016), in a bid to compare the robustness of the results of the two models.

4.1. Goal and scope

The baseline functional unit (FU) considered consists in "providing one metric ton (1000 kg) of non-modified road bitumen at the refinery gates for the Quebec market in 2019". The system boundaries thus cover the so-called "*cradle-to-gate*" perimeter, considering three stages of the product life cycle: extraction of asphaltic crude oil, its transportation to the refinery, and its refining (Fig. 1). The product system is modeled on the SimaPro 9.2.0.2 LCA software, and the potential impact calculations are performed using the Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI) 2.1 v1.05 impact assessment method. The TRACI method (Bare, 2011) is selected according to ISO 21930 recommendations for LCAs in the construction sector in North America (ISO, 2017). But this method is relatively obsolete. For example, to calculate climate change indicator result, it uses the 2007 IPCC GWP100a factors, whereas the latest factors date back to 2021 (Pier et al., 2021). Nevertheless, proceeding with this choice will allow more consistent comparisons with the impact values available in the literature, especially for North America. To understand the consequence of selecting this impact method, we will also use the IMPACT World+ (IW+) v1.28 method, which from a scientific perspective, is the most up-to-date characterization method (Bulle et al., 2019). The computational structure of LCA is detailed in a seminal paper by Heijungs and Suh (Heijungs and Suh, 2002).

The background data come from the ecoinvent v3.6 database and describe exchanges between the ecosphere (=nature) and the technosphere (=total economic production) occurring during a product life cycle. Moreover, we will use the most common "cut-off" system model (Allacker et al., 2017), again for consistency-to-the-literature reasons.

Our baseline model, tailored for Quebec, assumes that crude bitumen comes from conventional Western Canadian oil production sites, after which it is transported mainly through pipelines from Cold Lake, Alberta, to Quebec, where it is refined at the Montreal-East refinery in Montreal, Quebec. The scenario analysis, looking at different Canadian markets, models alternative crude transportation modes as described in greater detail later.

4.2. Data collection and inventory development

4.2.1. Conventional oil extraction

4.2.1.1. Method overview. The foreground data needed to develop the asphalt crude extraction LCI cover the average bitumen crude oil supply feeding refineries in Quebec. Given the inter-seasonal temperature differences to which it is subjected, Quebec bitumen must behave very well at both high and low temperatures. As said in the background section (section 3), heavy crudes from Lloydminster and Cold Lake areas are optimal to produce high quality asphalts adapted to the climate conditions of Canada, and no oil sands crude is transformed in asphalt binder for the Canadian market to date. We thus assume that the asphaltic crude slate comes 100 % from conventional oil produced through tertiary recovery in Lloydminster and Cold Lake areas. Thermal stimulation also seems to be the most spread recovery technique for that type of oil, and is thus modeled. We also assume an asphalt yield of around 60 % from these specific crudes (Sanchez Lemus 2015).

Relatively few crude oil extraction LCIs exist. Ecoinvent v3.6 includes a process for oil produced in Alberta named "*Petroleum and gas production, on shore CA-AB*". According to ecoinvent metadata, this model was not built on Alberta-specific data inventory, but rather, extrapoled from an LCI relating to the exploitation of oil in the Niger Delta in 1999 and 2000. This lack of geographic, temporal and technological representativeness leads us to develop an LCI specific to conventional heavy crude oils from Alberta, with the impact of oil extraction known to be the major contributor to the impact of bitumen for most environmental indicators (Eurobitume, 2020;

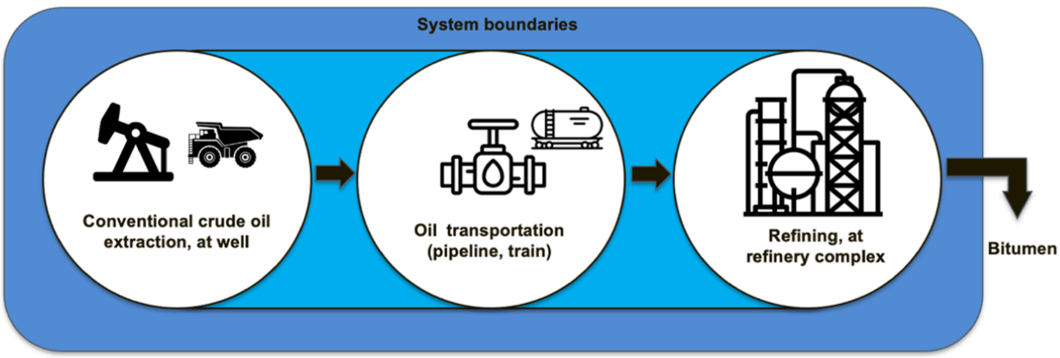

Fig. 1. System boundaries for the bitumen LCI (*cradle-to-refinery gate*).

Thinkstep, 2019). To build our model, we modify the Alberta ecoinvent model by using the technological information presented in the ecoinvent-related crude oil LCI report (Meili et al., 2018) that we consider matching our functional unit (2019) as well as data garnered from environmental disclosures relating to oil extraction companies in West Canada (see hereinafter).

4.2.1.2. LCI development. **Scopes 1 & 2: direct emissions and electricity flows**: The new Alberta asphaltic conventional oil extraction LCI is based primarily on a major company's voluntary disclosure provided through the Carbon Disclosure Project (CDP), as this company produces the type of oil that is used to produce Canada's asphalt binder, i.e., heavy conventional oil from thermal stimulation. We use the data from the disclosure reports relating to *Climate change* and *Water security* (Husky Energy Inc., 2020a, 2020b), which provide information on how these types of recoveries impact climate change and water consumption. We supplement these data with the flows of pollutants emitted by each operating site considered. To that end, we use the data reported by the producer in the 2019 National Pollutant Release Inventory (NPRI) (Gouvernement du Canada, 2020). The NPRI is a Canadian self-reporting registry of pollutant emissions inventories completed by companies subject to the *Canadian Environmental Protect Act, 1999* (Government of Canada, 2021). The company's disclosures include conventional crude production sites, which fall under the so-called "*thermal plant*" listing. The flows or resources and substances emitted are recalculated per kilogram (kg) of crude extracted and scaled to match the final FU.

Using data from the CDP *Climate change* report, we isolate GHG emissions (in tCO_2eq) from scopes 1 and 2, for the 8 thermal plants found. These thermal plants are associated with the thermal production of Western Canadian conventional heavy crude oil in Athabasca and Cold Lake. For each extraction site i, the crude oil production per site $\text{heavy\_oil\_production}_i$ (in m^3) is then calculated by dividing the scope 1 GHG emissions values $\text{scope1\_GHG\_emissions}_i$ (in tCO_2eq) by those of the extraction activity intensity $\text{extraction\_activity\_intensity}_i$ (in tCO_2eq/m^3 of crude) of each site i, according to Eq. (1).

$$\text{heavy\_oil\_production}_i = \frac{\text{scope1\_GHG\_emissions}_i}{\text{extraction\_activity\_intensity}_i} \tag{1}$$

Based on the CDP Water report data, oil_extraction_water_consumption, the quantity of water consumed on average per cubic meter of extracted oil, is the annual weighted average of consumed_water_i, the water consumption reported per unit of crude production activity (m^3 of water/ m^3 of crude) at each of the eight sites i, considering $\text{heavy\_oil\_production}_i$, the annual oil production of each site, and calculated according to Eq. (2).

$$\text{oil\_extraction\_water\_consumption} = \frac{\sum_{i=1}^{8} \text{consumed\_water}_i \times \text{heavy\_oil\_production}_i}{\sum_{i=1}^{8} \text{heavy\_oil\_production}_i} \tag{2}$$

Based on the NPRI database data, pollutant emissions (for p types of pollutants with $p = 1 \ldots n$) per cubic meter of crude oil extracted are calculated for each of the substances respectively emitted to the air, to water, and to the soil, based on Eq. (3).

$$\text{emission\_intensity}_{\text{pollutant } p} = \frac{\sum_{i=1}^{8} \text{NPRI\_pollutant\_quantity}_{p,i}}{\sum_{i=1}^{8} \text{heavy\_oil\_production}_i} \tag{3}$$

The results are then recalculated for 1 kg of crude extracted by using an average density of 926.8 kg/m^3 calculated from Canadian heavy conventional crude oil data for the period of 2011 to 2021 (Crude Quality Inc., 2021).

Scope 3 inventory

All other flows related to known technosphere inputs in the existing Alberta crude life cycle inventory from ecoinvent were retained to consider scope 3 emissions for which we had no data. These were related to the capital goods amortization as well as to organic and inorganic chemicals consumption. To avoid double-counting, two ecoinvent intermediary flows were withdrawn from the existing ecoinvent inventory: "*natural* gas, *vented*" and "*sweet gas, burned in gas turbine*". Indeed, the data gathered in the CDP and NPRI databases should already include the direct emissions associated with these processes.

To our knowledge, this inventory reconstruction method, based on CDP and NPRI disclosures, is innovative. One limitation of this approach is that the quality of this inventory depends on the integrity and quality of companies' voluntary disclosures, as well as on the rules to declare the emissions in the NPRI.

Table 2
Scenarios for the transportation of crude oil.

Scenarios	Mode of transportation	Route	Estimated distance (km)
Scenario 1	Pipeline	Cold-Lake (AB) to Montreal (QC)	4143
Scenario 2	Pipeline	Cold-Lake (AB) to Edmonton (AB)	495
Scenario 3	Pipeline + Train	Cold-Lake (AB) to Montreal (QC), pipeline	4143
		Montreal (QC) to Saint-John (NB), train	1240
Scenario 4	Train	Cold-Lake (AB) to Saint-John (NB)	4945

4.2.2. Oil transportation

4.2.2.1. Model overview. To model crude transportation from Alberta extraction sites all the way to the refining sites, four scenarios are proposed to cover all possible alternatives, and to thus illustrate how distance and the mode of transportation (pipeline or rail) influence the ultimate impacts of asphalt binder. Supplies by pipeline, rail, or using pipeline-rail combinations, were modeled. The modes of transportation in the scenarios were chosen according to current practices, based on Canadian oil logistics data (Government of Canada, 2023a). To illustrate the range of impacts related to the transportation of crude extracted in Alberta and delivered to Canadian refineries, the scenarios cover the cases of a minimal transportation to a refinery in Alberta and longer transportation to the Eastern Canadian provinces (Quebec and Maritimes). Additional transportation is not considered as pipeline and rail reach the refinery. These scenarios are presented in Table 2.

Specifically, the base case scenario (Scenario 1) considers pipeline transport from Cold Lake, Alberta (AB), to Montreal, Quebec (QC), using the main pipelines to deliver to the Montreal-East refinery in Quebec. Pipeline transportation distances are estimated using the measuring tool proposed by Google Maps for routes represented on the map of the main North America pipelines (Canadian Association of Petroleum Producers, 2021). Scenario 2 considers a short pipeline transportation between the Cold Lake extraction site and Suncor's refinery in Edmonton, Alberta. Scenario 3 combines pipeline transportation between Cold Lake and Montreal and rail transportation to Irving Oil's refinery in Saint John, New Brunswick (NB). Rail transportation distances are also estimated using the Google Maps measurement tool, based on a virtual line drawn as close as possible to the railway used by the rail operator VIA RAIL between Montreal and Saint John. Finally, Scenario 4 is developed to illustrate the increase in rail transportation of crude oil from the West Canadian producing regions to the Maritimes. Indeed, recent data on crude oil transportation by rail in Canada, particularly to the Maritime provinces (New Brunswick, Newfoundland and Labrador, Nova Scotia, Prince Edward Island), show an increase in this mode of transportation. Canadian oil and natural gas producers indicate that in 2019, 237000 barrels of oil were transported by rail daily, as against 156000 in 2017 (CAPP, 2022). This scenario also considers rail transportation between Cold Lake and Saint John. However, the limited number of tank cars, the cost of diesel, and, ultimately, of rail freight as compared to pipeline transportation, associated with the risk of accidents, are factors that currently limit the development of this mode of oil transportation. Additional tanker truck transportation can be required when refineries are not directly connected to pipelines or railways, what is not the case in our modeled systems.

4.2.2.2. LCI of pipeline transportation. The FU of this basecase sub-model is to transport 1 ton of conventional heavy crude by pipeline over one kilometer between Cold Lake and Montreal. Pipeline transportation requires a specific infrastructure and electric power supply. Ecoinvent provides generic pipeline oil transportation LCIs. Nevertheless, our transportation scenarios use specific pipelines with specific characteristics, particularly with respect to electricity consumption, which depends on the viscosity of the crude oil, the diameter of the pipeline and the topography of the sites (Choquette-Levy et al., 2018).

Using the data and equations from the COPTEM model (Choquette-Levy et al., 2018), we recalculate the total electric power required per ton-kilometer (tkm) to transport a specific heavy crude on each pipeline through which the crude transits in our model. We adjust the diameter and the density of the asphaltic Canadian heavy crude (926.8 kg/m^3) in the pipeline electric power consumption formula proposed by Choquette-Levy et al. (Choquette-Levy et al., 2018), as the default equation considers an average oil density of 940 kg/m^3. Table 3 presents the electric consumption calculated for the pipelines used in our model as well as the distance of transportation in each case. It should be noted that lines 3 and 4 can be used interchangeably.

Next, for each pipeline, our inventories consider the use of specific electricity mixes for the provinces and states crossed between the well and the refinery, including Winconsin (WI, MRO), Michigan (MI, RFC) and Ontario (ON) (Table 4).

The pipeline infrastructure amortization-related input flows and oil loss (ground leak) output flows were copied from the ecoinvent v3.6 process, "*Transport, pipeline, onshore, petroleum {RoW}*", the default pipeline transportation LCI for the rest of the world (i.e., Australia, New Zealand, Africa, Asia, Latin America and Northern America). Finally, Table 5 presents the final average LCI for pipeline oil transportation from Cold Lake to Montreal. Note that methane leaks have not been accounted for, which underestimates the contribution to climate change from oil transportation. This will be addressed in a sensitivity analysis in the discussion section.

4.2.2.3. LCI of oil transportation by rail. Developing the LCI for crude oil transportation by rail in Canada would at the very least require data related to the following key parameters: average mass of goods transported (tank cars + crude oil), and train energy consumption for this load – mostly diesel for locomotives belonging to Canadian National and Canadian Pacific, the two leading freight rail companies in Canada (CBC NEWS, 2022; Gouvernement du Canada, 2022; Transport Canada, 2022). Although Vaezi and

Table 3
Characteristics of the pipelines to transport West Canadian crude oil to Montreal, Quebec.

Pipeline	Origin	Destination	Distance	Literature energy consumption	Adjusted energy consumption	
			km	Wh/bbl.km	Wh/bbl.km	Wh/tkm
Cold Lake	Cold Lake, AB	Edmonton, AB	495	5.07	5.00	33.92
Main Line 3	Edmonton, AB	Superior, WI	1768	1.04	1.16	7.90
Or Main Line 4	*Edmonton, AB*	*Superior, WI*	*1768*	*1.75*	*1.83*	*12.40*
Main Line 5	Superior, WI	Sarnia, ON	1038	1.82	2.37	16.08
Main Line 9	Sarnia, ON	Montreal, QC	842	0.53	0.64	4.34

Table 4
Pipeline's use stage model to transport crude oil from Alberta to Quebec, by ton-kilometer.

Pipeline	Energy grid	Total energy intensity relative main lines operation	Ratio on each route section	Adjusted energy consumption
		Wh/tons.km	%	kWh/tons.km
Cold Lake	Electricity mix, AB	33.92	100	3.39E-02
Main Line 3 or 4	Electricity mix, AB	10.15	15	1.52E-03
	Electricity mix, SK		40	4.06E-03
	Electricity mix, MB		15	1.52E-03
	Electricity mix, MN (MRO)		30	3.04E-03
Main Line 9	Electricity mix, QC	4.34	10	4.34E-04
	Electricity mix, ON		90	3.91E-03
Main Line 5	Electricity mix, WI (MRO)	16.08	60	9.65E-03
	Electricity mix, MI (RFC)		40	6.43E-03

Table 5
LCI to transport one ton of crude oil by pipeline from Alberta to Montreal over one kilometer.

Type	Flows	Quantity	unit
Inputs			
Pipeline amortization	Pipeline, petroleum {GLO}	9.46E-09	km
Electricity of Quebec	Electricity, medium voltage {CA-QC}	4.34E-04	kWh
Electricity of Ontario	Electricity, medium voltage {CA-ON}	3.91E-03	kWh
Electricity of Michigan	Electricity, medium voltage {RFC}	6.43E-03	kWh
Electricity of Wisconsin	Electricity, medium voltage {MRO, US only}	9.65E-03	kWh
Electricity of Minnesota	Electricity, medium voltage {MRO, US only}	3.04E-03	kWh
Electricity of Manitoba	Electricity, medium voltage {CA-MB}	1.52E-03	kWh
Electricity of Saskatchewan	Electricity, medium voltage {CA-SK}	4.06E-03	kWh
Electricity of Alberta	Electricity, medium voltage {CA-AB}	3.55E-02	kWh
Outputs			
Oils to soil	Oils, unspecified	1.07E-05	kg

Verma (2018) propose a modeling approach for the long-term development of rail transportation of crude oil in Canada, their model, however, does not allow isolating locomotives in order to recreate an LCI of rail crude oil transportation in Canada. Incidentally, very few recent rail transportation LCI models are identified (Messmer and Frischknecht, 2016; Stripple and Uppenberg, 2010; Horvath, 2006; Spielmann and Scholz, 2005), and even among these, none is specific to Canada.

Given the lack of minimum data specifying an LCI for crude oil transportation by rail in Canada, we will default to using the ecoinvent v3.6 rail freight US model "*Transport, freight train {US}| diesel*", mainly based on European statistical data from 1998, and which has a carbon footprint equal to 56 gCO_2eq/tkm.

4.2.3. Oil refining

4.2.3.1. Technological representation: Setting of PRELIM. We intend to model the oil refining stage which allows to obtain bitumen at the bottom of the distillation column. Oil refining consumption and emissions are functions of the crude being processed, the refining technology used, and the adjustment allowing to vary proportions of the different co-products obtained, according to the optimization goals of the refinery operator. We assume that the bitumen in Quebec's market is produced at the Montreal-East refinery in Quebec province, for proximity reasons. We shall therefore model the technology used at this plant, and assume that other Canadian refineries use relatively similar technologies when assessing bitumen impacts for other Canadian markets (scenario analyses). The refining stage is modeled using PRELIM v1.4.1 (Abella et al., 2016). PRELIM – The Petroleum Refinery Life Cycle Inventory Model – is a Microsoft Excel format universal calculator developed by the University of Calgary in Alberta. This calculator allows to use ten input parameters to parameterize different refining configurations and technologies, in order to calculate how oil refining impacts the life cycle of petroleum-based products (Abella et al., 2016). The calculator incorporates GREET 1.8c emissions factors (Argonne National Laboratory, 2014), as well as a database from the American Petroleum Institute (API) physically characterizing a listing of over 100 crude oils from different regions of the world. Once the calculator is configured, LCA calculations are done automatically based on the TRACI characterization method. For each refining unit and co-product, impact results are presented in the form of tables and graphs, and include sensitivity analyses.

We select the Cold Lake conventional heavy crude oil, and the PRELIM technological parameterization is carried out based on our expertise. Details of the parameterization are provided in supplementary material (SM) in the "Methodology of allocation" section.

The choice of a multifunctional process allocation method often has major implications for LCA impact results (Frischknecht, 2012), as is the case with oil refining. The American and European bitumen union's LCAs (Blomberg et al., 2012a; Eurobitume, 2020; Thinkstep, 2019) made different choices when it comes to allocating the impacts of the refining process: the unions choose an economic allocation for their first generation of studies, before moving to a thermodynamic allocation in 2019, that minimizes the impacts of crude refining attributed to bitumen. Indeed, for bitumen, thermodynamic allocation considers only the energy consumption related to its temperature rise in the distillation column, and neglects the phase changes, which are the most energy-intensive.

According to ISO 14044 (International Organization for Standardization, 2006a), the following ranking should be used to allocate multifunctional systems impacts, from most to least recommended: subdivision > boundary expansion > allocation based on underlying physical relationships > imputations. On the other hand, UNEP-SETAC proposes the following classification: subdivision > allocation based on underlying physical relationships in case of combined production > other approaches such as economic allocation or others for joint production (UNEP/SETAC, 2015). There is thus no consensus when it comes to allocation, and in practice, ISO 14044 recommends carrying out a sensitivity analysis (International Organization for Standardization, 2006a). It should be recalled that a production is said to be combined if the ratios between co-products can be varied by changing production parameters (Weidema and Norris, 2002). The allocation based on underlying of physical relationships consists of assessing how the multifunctional system's inputs and outputs vary as a function of variations in co-product ratios, after which each co-product is assigned its share of inputs and outputs. However, in a joint production, the mass proportions between co-products remain unchanged. For bitumen, there is combined production: allocation based on underlying physical relationships could thus be used, following UNEP-SETAC recommendations. In practice, the refiners interviewed state that they did not manage to separate energy consumption based on the production ratios of bitumen and other co-products, with the refinery energy consumption models being reported as dependent on too many factors. In such cases, an allocation is required. We will choose mass allocation, but in the *Discussion* section, we will estimate the consequences of an economic allocation on the LCA results.

4.2.3.2. Calculation of allocation factors. Using data from the PRELIM "input" tab, we recalculated the economic allocation factors of co-products generated from one ton of refined crude due to the different bitumen yield. Table 6 illustrates the corrected massic shares we obtained for each co-product by refining one ton of "*ColdLake Thermal_Alberta.ca*" asphaltic conventional oil, as well as the corrected PRELIM economic allocation factors. It should, however, be noted that oil market prices are quite volatile, which leads to uncertainty when it comes to economic allocation. Details of the calculations are provided in SM (correction of bitumen yield and adjustment of the sum of the massic shares to 100 %).

4.2.3.3. LCI development. We used the PRELIM calculator to obtain input and output flows related to the refining of one ton of crude oil as well as the allocation factors for the different co-products. We implemented these flows in SimaPro, which allowed a recalculation of the impacts of bitumen using any impact characterization method. The model is provided in SM. Moreover, we had to fix mapping issues related to flow inequivalence between PRELIM and ecoinvent v3.6 to avoid double-counting in our implementation. Details are also provided in SM.

4.3. Uncertainties analysis

We wish to compare the accuracy of the AI bitumen LCA model in the context of Quebec's market in 2019 with that of our Quebec bitumen model for the same year. To that end, inputs' uncertainties are quantified using the semi-quantitative Pedigree Matrix approach to assign uncertainty scores to the data (Table 7), with a lognormal distribution. The rules to allocate a score have been detailed by Weidema et al. (Weidema et al., 2013). Uncertainties are propagated using an MCS with 10000 runs (Gantner et al., 2018; Pomponi et al., 2017; Inyim et al., 2016) rather than the more widely used 1000 runs, which has been criticized by Heijungs (2020). Details on the uncertainties propagation method are provided in SM, including justification of Pedigree Matrix scores, where score 1 is the best score.

4.4. Benchmark of bitumen carbon footprints

The carbon footprint of 1 ton of asphalt binder varies based on a number of factors that have been described in the literature review section. We wish to compare our study's results to those of the main bitumen LCA models described in Table 1 and to those of the

Table 6
Co-products mass shares and economic allocation factors calculated using PRELIM calculator from refining 1 ton of conventional heavy crude oil.

Co-Products	Corrected massic shares	Economic allocation
Blended Gasoline	14.15 %	23.57 %
Aircraft fuels (Jet-A/AVTUR)	4.95 %	6.93 %
Ultra-low-sulfur diesel (ULSD)	21.57 %	29.01 %
Reformulated gasoline (Surplus RFG)	0.24 %	0.07 %
Sulphur	0.97 %	0.16 %
Liquefied petroleum gas (LPG)	0.33 %	0.48 %
Petrochemical Feedstocks	0.30 %	0.60 %
Bitumen	57.49 %	39.18 %

Table 7
Foreground Pedigree Matrix scores for the two bitumen LCA models for Quebec's market.

		Pedigree Matrix indicator score				
	Scope	Relia-bility	Complete-ness	Temporal correlation	Geographical correlation	Further technological correlation
Quebec's model	Extraction	1	3	1	1	2
	Transportation	1	1	1	1	2
	Refining	1	1	1	1	2
Asphalt institute's model	All stages aggregated	3	5	3	3	5

generic ecoinvent model "*Bitumen, hot {Row}*". A histogram will be used to present the results of the models, grouped together for the North American and European areas. Each of the models is presented such as to illustrate the contributions of the different life cycle stages to the carbon footprint of bitumen, when the disaggregation was accessible. In the case of the Athena Institute model, we will rebuild the model with SimaPro from the LCI available in the Athena Institute report (Athena Institute, 2001) as the carbon footprint is not indicated in the report.

5. Results and interpretation

5.1. *Potential impacts of the asphalt binder consumed in Quebec (basecase scenario)*

Table 8 presents the impact scores for bitumen consumed in Quebec after it leaves the refinery (Scenario1), for the ten TRACI impact categories. Overall, this footprint is similar to that obtained using the more recent IW+ characterization method on similar indicators (complementary results provided as SM). For example, the average impact of Quebec bitumen on climate change is 1028 kgCO_2eq/t (mass allocation) with TRACI and 1022 kgCO_2eq/t with IW+.

Crude oil extraction is the main contributor to the carbon footprint: 545 kgCO_2eq/t, i.e., 55 % of the total impact. However, the GHG inventory is mostly (i.e. for scopes 1 and 2) based on voluntary disclosures by the oil producer: the accuracy of this value therefore depends on the quality of the values disclosed as well as on how representative the eight petroleum wells studied are of the asphaltic crude used in Quebec (and Canada for the other markets' assessments). However, our data collection sample is much larger than those used in ecoinvent v3.6 processes (Jungbluth, 2004), which makes the quality of ours better in terms of the "Completeness" dimension of the Pedigree Matrix. If the disclosures are accurate, then the quality of our inventory is also better on the 4 other dimensions of the matrix.

The oil extraction carbon footprint resulting from our model is several times higher than ecoinvent's Alberta oil carbon footprint (v3.6) and 35 % higher than the carbon footprint of the asphaltic crude reported from that AI report using the GaBi database (GWP100 of 403 kgCO_2eq/t of crude). Nevertheless, our result is consistent with the figures published in the literature and probably still underestimate the carbon footprint of the Canadian asphaltic crude slate. For comparison, we recalculated the carbon footprint of the average crude oil extracted in Canada, per ton, at the well gate, based on the study of Masnadi et al., (2018). Details of the calculation are provided in SM. We obtain an average carbon footprint of 630 kgCO_2eq/t for Canadian oil, with the impact for the 5th and 95th percentiles being respectively 545 and 826 kgCO_2eq/t (see details of the calculation in SM). The carbon footprint for the asphaltic crude slate calculated by our extraction model is thus credible, consistent, and very likely an underestimation if 100 % of the asphaltic crude is heavy Canadian crude. Indeed, extracting heavy oil is more energy-intensive than extracting lighter oil. Thus, its carbon footprint should probably not be ranked at the 5th percentile of Canadian oil carbon footprint. In the case of this very likely underestimation, Quebec's and Canadian asphalt binders' carbon footprint are thus also very likely underestimated in our study.

Next, crude transportation by pipeline contributes 221 kgCO_2eq to the carbon footprint of one ton of bitumen, with the average impact of transportation being 53 gCO_2eq per ton of crude transported over one km (tkm) in our base model. In comparison, the default 21 gCO_2eq/tkm for transportation by pipeline ("*Transport, pipeline, onshore, petroleum {RoW}")* (and 6 gCO_2eq/tkm figure for tankers ("*Transport, freight, sea, tanker for petroleum*")) in ecoinvent v3.6 are very low. The carbon footprint obtained when precisely modeling the transportation from Cold Lake to the Montreal refinery is obviously more representative than what would be obtained using a default model, such as done in other benchmarked asphalt binder' LCAs. This can also explain the low contribution to carbon footprint of transportation in other LCAs (e.g., 23 kg per ton of binder in the AI model).

Finally, a large portion of the carbon footprint is attributable to refining. We assessed two separate allocation bases: mass allocation and economic allocation. Mass allocation generates the highest impacts for bitumen – 263 kgCO_2eq/t – compared to the economic allocation (179 kgCO_2eq/t) because of the lower mass value of bitumen versus primary co-products such as fuels, but could be overestimated due to the bitumen yield correction done in PRELIM. The carbon footprint calculated directly in the PRELIM calculator for a mass allocation is: 28.16 kgCO_2eq/refined barrel, i.e., 192 kgCO_2eq/t (with 1 barrel = 0.147 t of oil), also using TRACI v2.1. This lower carbon footprint may be attributable to the non-equivalence of ecoinvent/PRELIM flows. Even if the crude type is replaced with light ones in the PRELIM calculator, the carbon footprint still remains between 20 and 35 kgCO_2eq/barrel, i.e., between 136 and 238 kgCO_2eq/ton. Finally, for a thermodynamic allocation, the AI model estimates the impact of refining to be about 77 kgCO_2eq/t, which is half that of the impact calculated with other allocation types.

Table 8
Environmental impact scores for one ton of non-modified bitumen on the Quebec's market, per life cycle stage and in total, using mass allocation for refining, [TRACI 2.1, ecoinvent V3.6].

Impact category	Unit	Extraction, conventional crude oil, thermal, Alberta, HUSKY	Transportation, pipeline, onshore petroleum, CA-{AB-QC}	Refining, Asphalt Binder, CA-QC	Total
Ozone depletion	kg CFC-11 eq	9.32E-04	1.07E-05	3.48E-05	9.78E-04
Global warming	**kg CO_2 eq**	**5.45E+02**	**2.21E+02**	**2.63E+02**	**1.03E+03**
Smog	kg O_3 eq	8.39E+00	1.07E+01	4.78E+00	2.38E+01
Acidification	kg SO_2 eq	1.43E+00	8.98E-01	0.35E+00	2.68E+00
Eutrophication	kg N eq	0.11E+00	2.56E+00	0.05E+00	2.72E+00
Carcinogenics	CTUh	3.79E-06	3.34E-05	1.33E-06	3.85E-05
Non carcinogenics	CTUh	1.31E-04	9.00E-05	9.27E-06	2.30E-04
Respiratory effects	kg $PM_{2.5}$ eq	9.06E-02	2.75E-01	3.37E-02	4.00E-01
Ecotoxicity	CTUe	3.25E+03	3.36E+03	5.42E+02	7.15E+03
Fossil fuel depletion	MJ surplus	6.66E+03	1.34E+02	2.38E+02	7.03E+03

5.2. Life cycle stage contribution analysis

Fig. 2 illustrates the contribution of the life cycle stages per impact category. Oil extraction contributes the most to 6 of the 10 TRACI impact categories, and transportation by pipeline is the highest contributor to smog production, eutrophication, carcinogenic effects, and respiratory effects impact categories. Transportation contributes more than 1/3 of the impact for the following categories: smog production (45 %), acidification (34 %), eutrophication (94 %), carcinogenic health effects (87 %), non-carcinogenic health effects (39 %), respiratory effects (69 %), and ecotoxicity (47 %). Incidentally, the refining stage contributes a lower impact than transportation, except for climate change impact and fossil resource consumption. Details concerning contributors by life cycle stage and an analysis of the highest contributing flows are presented in SM.

5.3. Transportation scenario analysis for other Canada's regional markets

Fig. 3 illustrates the carbon footprint of the asphalt binders modeled with different crude transportation scenarios, as well as the contribution of each stage. The graph highlights variations of −20 % to + 7 % compared to the baseline Quebec scenario (Scenario 1). According to these scenarios, the carbon footprint of bitumen ranges from 826 kgCO_2eq/t in Edmonton, Alberta, to 1098 kgCO_2eq/t in Saint John, New-Brunswick. Train is not a better option than pipeline in terms of contribution to climate change.

Table 9 presents impact scores for the four scenarios. The transportation of crude oil for a local market in Alberta (Scenario 2) generates 18 kgCO_2eq/t. Transportation to the Maritimes (Scenario 3) generates 290 kgCO_2eq/t, i.e., 16 times as much.

5.4. Uncertainties analysis

Table 10 presents the uncertainty results for the AI model and for our model for the global warming impact category, with a 95 % confidence interval, under 2019 Quebec market conditions. The uncertainty analysis results of our model for all TRACI impact categories are provided in SM.

Based on the standard deviation (SD) and standard error of the mean (SEM) parameters, the results show that the AI model is highly uncertain. We attribute this to a lack of representativeness of the data on the temporal, geographic and technology dimensions. Furthermore, Muller (2015) showed that a bad score for Completeness has as smaller impact on uncertainty than does a similar score for the other 4 dimensions. She also showed that the quality of the technological representativeness dimension has the greatest impact on output uncertainty. And incidentally, this score is worse for the AI model than for our model for Quebec's context in 2019.

Fig. 4 presents the carbon footprint probability distribution for each of the two models. It shows the significant improvement in reliability brought by our model to quantify the impact of climate change due to the delivery of 1 ton of bitumen in Quebec in 2019.

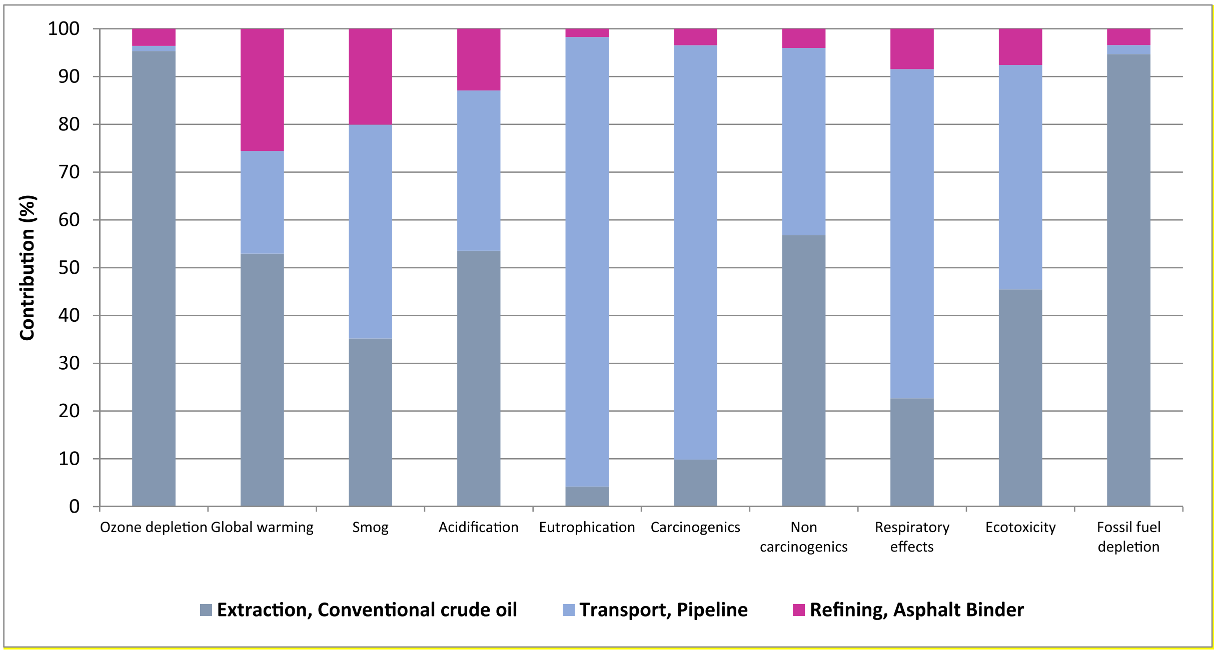

Fig. 2. Stage contributions to the life cycle impacts of asphalt binder production (scenario 1: Quebec's market, no additive) [TRACI 2.1, ecoinvent V3.6].

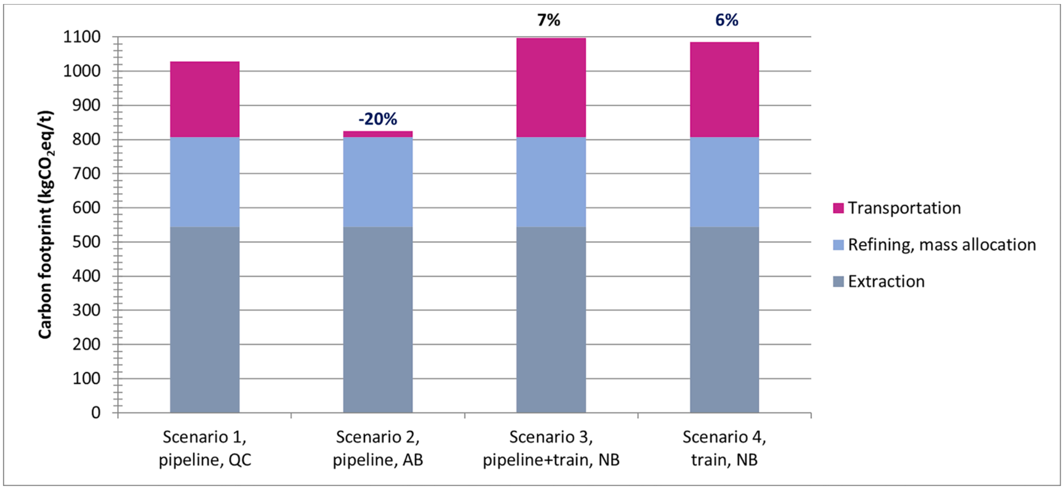

Fig. 3. Transportation scenario analysis: carbon footprint for Canada's bitumen regional markets, per 1 ton of non-modified asphalt binder [TRACI 2.1, ecoinvent V3.6].

Table 9
Crude oil transportation impacts per scenario for Canada's regional markets, [TRACI 2.1, ecoinvent V3.6].

Transportation stage		**Scenario 1**	**Scenario 2**	**Scenario 3**	**Scenario 4**
Impact category	**Unit**	Pipeline, QC 4143 km	Pipeline, AB 495 km	Pipeline + Train, NB 5383 km	Train, NB 4945 km
Ozone depletion	kg CFC-11 eq	1.07E-05	8.09E-07	2.40E-05	5.30E-05
Global warming	**kg CO_2 eq**	**2.21E+02**	**1.77E+01**	**2.90E+02**	**2.78E+02**
Smog	kg O_3 eq	1.07E+01	9.73E-01	3.10E+01	8.10E+01
Acidification	kg SO_2 eq	8.98E-01	7.41E-02	1.59E+00	2.76E+00
Eutrophication	kg N eq	2.56E+00	2.15E-01	2.69E+00	5.29E-01
Carcinogenics	CTUh	3.34E-05	3.09E-06	3.99E-05	2.60E-05
Non carcinogenics	CTUh	9.00E-05	7.41E-06	1.01E-04	4.53E-05
Respiratory effects	kg $PM_{2.5}$ eq	2.75E-01	7.77E-03	3.34E-01	2.35E-01
Ecotoxicity	CTUe	3.36E+03	2.80E+02	4.06E+03	2.81E+03
Fossil fuel depletion	MJ surplus	1.34E+02	1.17E+01	2.54E+02	4.79E+02

Table 10
Uncertainty analysis for the Climate change indicator results of two bitumen binder LCA models for the Quebec market [TRACI 2.1, ecoinvent V3.6].

	Uncertainties parameters results with confidence interval of 95 %							
Climate Change – IPCC 2007	Unit	Mean	Median	Standard deviation	Coefficient of variation (%)	2.5 % percentile	97.5 % percentile	Standard Error of the Mean
Quebec's model	kg CO_2 eq	1027	1015	93	9.08	882	1246	0.93
Asphalt institute model	kg CO_2 eq	1077	634	1482	138	82	4780	14.82

5.5. Comparison of bitumen carbon footprints

Fig. 5 compares the carbon footprints of asphalt binders modeled in our study with those previously published in the literature: they vary between 143 and 1098 $kgCO_2eq/t$, respectively for the Eurobitume 2020 study and our study in the case of New-Brunswick's market. For almost all the studies, crude oil production is the main contributor to climate change (Yang, 2014; de Bortoli, 2018a; Thinkstep, 2019; Eurobitume, 2020). However, our literature review showed a significant variation in the crude slate considered in bitumen LCAs – either asphaltic-specific or not –, due to the variability of the supply chains between markets, as well as their temporal evolution (Blomberg et al., 2012a; de Bortoli, 2018b; Eurobitume, 2020): the average (asphaltic) crude barrel therefore varies over time, as does its impact.

Our Canadian assessments display the highest carbon footprint range, with values between 826 and 1098 $kgCO_2eq/t$, versus 637

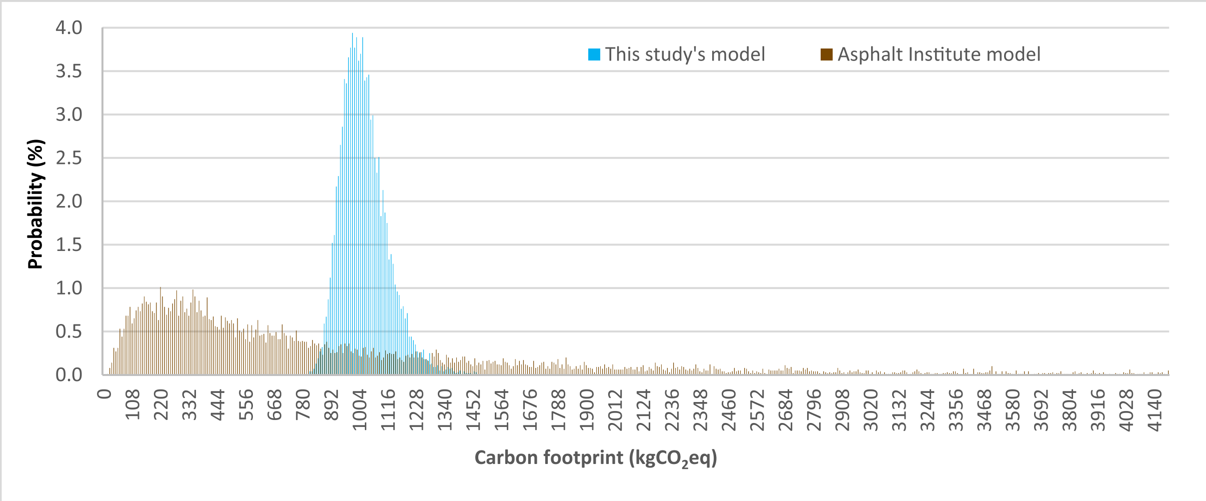

Fig. 4. Probability distribution of the bitumen's carbon footprint calculated with our model versus the AI model, in the context of Quebec in 2019 [TRACI 2.1, ecoinvent V3.6].

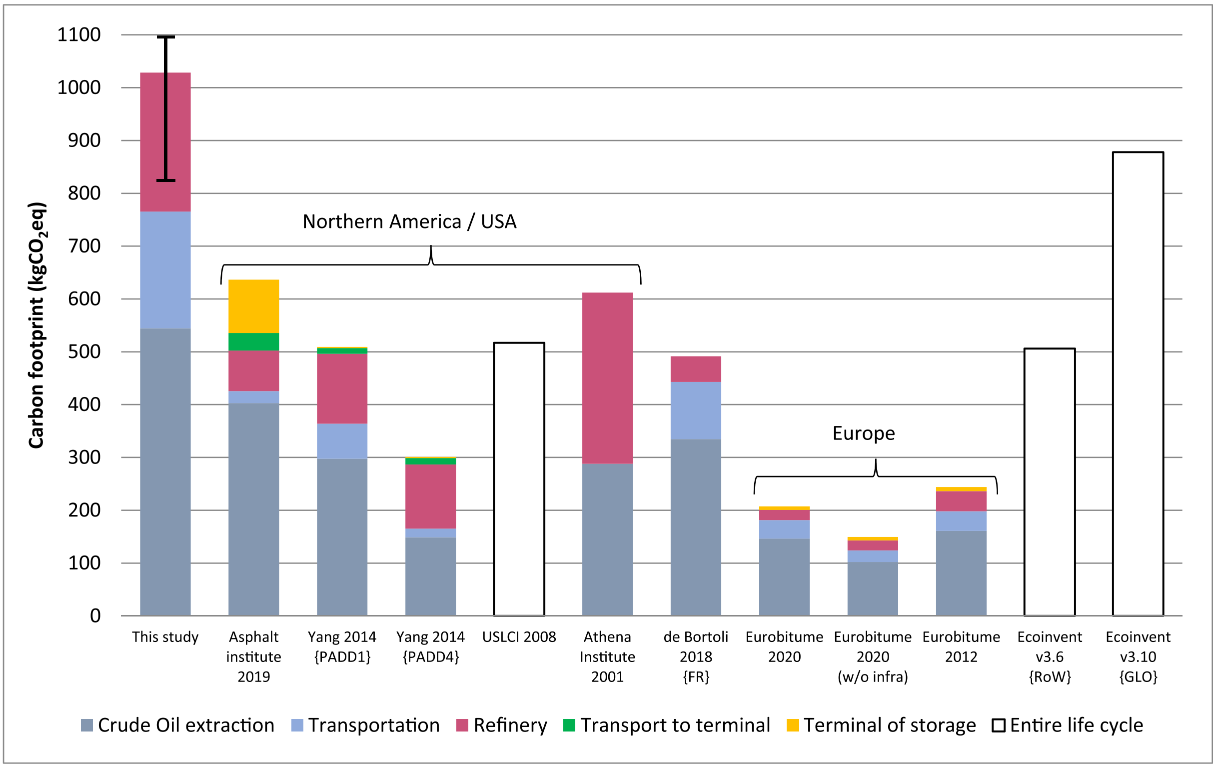

Fig. 5. Comparison of bitumen carbon footprints, per ton of non-modified asphalt binder.

$kgCO_2eq/t$ for the AI-modeled bitumen to the terminal gate (Thinkstep, 2019). The carbon footprint of Canadian asphalt binders estimated in our study is around 50 % greater than that estimated in the AI's report, notwithstanding the parameters of the latter, which should lead to superior results: broader assessment perimeter, extending all the way to bitumen management at the terminal, and crude slate including 44 % of oil sands (Thinkstep, 2019). Indeed, the crude oil carbon footprint calculated for the AI was only estimated to be 426 $kgCO_2eq/t$, including transportation to the refinery. However, 44 % of this crude slate is from oil sands, characterized by notoriously very high-emission extractions, without even considering the emissions from the dilution operations prior to transportation by pipeline. The paradox is explained by the fact that, in the AI model, 80 % of the crude from oil sands was considered being dilbit, which has the lowest oil sands product carbon footprint according to GaBi (495 $kgCO_2eq/t$), while only 16 % was synthetic oil with a carbon footprint of 900 $kgCO_2eq/t$ and 3 % was synbit with a 705 $kgCO_2eq/t$ carbon footprint. But the asphaltic crude slate was not specified by all the companies surveyed as written in the AI report, generating uncertainty on the crude slate. As the asphaltic crude has a paramount contribution on the carbon footprint of the binder, this definitely brought uncertainties in the context of the AI study. Finally, in the last version to date of ecovinent (v3.10), the process "*bitumen adhesive compound production, hot*" displays a carbon footprint in the range of our study (827–934 $kgCO_2eq/t$ depending on the region, with the GWP100 from IPCC 2013), after the last updates of oil extraction in the database. But the production model is not representative of the products studies here (i.e., coming from the distillation of crude oil).

Compared to the literature, our study shows also much higher impacts for crude oil transportation (to refinery). This is attributable to a difference in transportation modes (e.g., pipeline instead of tanker) and/or to the underestimation of the impact of transportation by pipeline by the default ecoinvent process, particularly in regions of the world with a carbon-intensive electricity mix.

Emissions related to refining also vary greatly in the studies. That is due to the variability of the allocation and other methodological choices, a lack of transparency, consistency, and maybe completeness, in the reporting of emissions and of production data, and to the diverse nature of the facilities and crude processed (Athena Institute, 2001). For example, cracking the long hydrocarbon chains of a heavy crude to produce the most volatile products requires more energy than cracking a lighter crude (Athena Institute, 2001). Fig. 5 shows that the carbon footprint for refining modeled by the Athena Institute, that is the oldest data, is also the highest: 324 $kgCO_2eq/t$. This could partly be explained by energy efficiency improvements in refineries over time. The lowest impacts from refining appear in the European studies, where emissions by European refineries (Blomberg et al., 2012a; de Bortoli, 2018a; Jungbluth, 2007) were modeled using the CONCAWE (European Refining Association) model (Catalá et al., 2013) and distillation energy values reported by producers. The energy needed to refine one ton of heavy oil to produce one ton of bitumen (mass allocation) calculated in our model, using PRELIM, is 2455 MJ, as compared to 5 times less that figure (510 MJ/t) in the second Eurobitume study (Blomberg et al., 2012a). The heavier nature of the crude considered in our study does not explain this difference, based on the simulations carried out with PRELIM on lighter crudes: the orders of magnitude of the carbon footprint per ton of distilled oil remain similar. Four hypotheses could account for this lower consumption thus emissions by European models: (1) the energy efficiency of the refining technologies in Europe is close to 5 times better than the one modeled in PRELIM (due to technologies or to the feed mix used), (2) energy consumption by refineries was underestimated in the Eurobitume study, (3) the economic allocation reduces drastically the refininf energy allocated to bitumen, or (4) there is an error in the model. Case (1) is rather unlikely given the international range covered by PRELIM. In the AI model, the choice of thermodynamic allocation – considering only the energy consumed to increase the temperature of bitumen without more energy-intensive phase changes of the co-products concerned like vaporization or condensation – explains the low carbon footprint of refining (77 $kgCO_2eq/t$). However, this impact is almost four times higher than that calculated in the Eurobitume v3 (2020) model with a thermodynamic allocation, and twice as high as that calculated with the Eurobitume v2 LCIs according to an economic allocation (Blomberg et al., 2012a). The fact that the North American union model purports to consider energy losses in the refinery associated with the production of bitumen (Thinkstep, 2019) is unlikely to explain the differences with the European models that do not account for these losses (Eurobitume, 2020). Also, we recommend a verification of the refining energy consumption and related emissions allocated to bitumen, whatever the allocation type, in the next bitumen LCAs carried out in Europe.

6. Discussion

6.1. LCI databases globally highly underestimate the carbon footprint of oil extraction

Our results, including those of the comparative study, shine a light on the clear underestimation of the carbon footprint of crude extraction allowing to produce asphalt binders. Neither the carbon footprints of the ecoinvent inventories nor those of GaBi correspond to the values reconstructed using actual data of producers, such as those used in the study by Masnadi et al., (2018). Based on their study, we did recalculations (see SM) and found that the carbon footprint for Canadian oil (all types combined) ranges between 545 and 826 $kgCO_2eq/t$ at the well gate (resp. 5th and 95th percentiles), for an average value of 630 $kgCO_2eq/t$. The ecoinvent v3.6 LCI for Alberta oil leads to a carbon footprint of 140 $kgCO_2eq/t$ (GWP100a, IPCC 2013). For the US, our calculations, based on the data of Masnadi et al., indicate that the average value at the well gate should be approximately 365 $kgCO_2eq/t$, whereas the ecoinvent inventory also gives 140 $kgCO_2eq/t$ for this market (for GWP100a, IPCC 2013). Considering the origins of crude modeled in the AI study, (Thinkstep, 2019, p. 29), we calculated, based on the data of Masnadi et al. (2018), that the carbon footprint of average crude may rather be around 490 $kgCO_2eq/t$ (see SM), leading to a final carbon footprint of 724 instead of 637 $kgCO_2e/t$ (i.e., potential underestimation of 14 %). However, the carbon footprint of asphaltic crude considered in the AI study using GaBi database is only 403 $kgCO_2e/t$ at the well gate, which may thus be a 35 % underestimation compared to the Canadian market considered in our study. For Eurobitume, the following asphaltic crude slate was considered in 2012 (resp. 2020): 61 % Russian oil (30 %), 18 % Middle East oil (45 %), 11 % South American oil (15 % including Central America as well) and 10 % European oil. Using the data of Masnadi et al. (2018) leads to a carbon footprint of these mixes at the well gate of 263 $kgCO_2eq/t$ versus 408 $kgCO_2eq/t$ with ecoinvent v3.6, which, in comparison, strongly overestimates the footprint of Russian crude (approx. 596 $kgCO_2eq/t$ versus 301 $kgCO_2eq/t$ with the data of Masnadi et al.). Thus, in this case, the carbon footprint for the crude modeled in Eurobitume 2012 would be overestimated by 36 %. On the contrary, in its 2020 version, the crude oil's carbon footprint of Eurobitume is estimated to be approximately 88 $kgCO_2eq/t$ with ecoinvent inventories, versus 224 $kgCO_2eq/t$ with the national carbon footprints from Masnadi et al., which represents a 154 % underestimation in the Eurobitume model. The most recent bitumen LCA models of both unions published as of 2023 seem thus to underestimate the carbon footprint of oil used by a factor of 1.14 to 2.54.

Knowing that a significant proportion of bitumen GHG emissions comes from crude production, all crude extraction processes must be updated in ecoinvent (mostly done in ecoinvent v3.9–3.10 after this study but still incomplete) and GaBi. This conclusion is generally shared by the meta-analysis of Meili et al. (2018a). Significant errors could be avoided in carbon footprint assessments, and thus in recommendations for improvement of the ensuing environmental practices. New open access and regional models for the extraction of crude oil must be developed, and producers must facilitate access to their data by extraction site given the high inter-well variability of impacts (Meili et al., 2018). Unfortunately, over the last decade, access to operating data has generally been restricted and data has instead been aggregated (Meili et al., 2018).

6.2. An attempt to consider fugitive emissions better

It is now common knowledge that GHG emissions reported from crude extraction are globally largely underestimated in oil producers' reporting, national inventories, and in some environmental databases (e.g., M. Lavoie et al. 2022). In particular, methane emissions are getting more attention. The scientific literature reports methane emission underestimate ratios up to 15, with most findings around a ratio of [1.5–3] (Chan et al., 2020; Conrad et al., 2023; Johnson et al., 2023; Liggio et al., 2019; MacKay et al., 2021; Seymour et al., 2023). Indeed, these underestimations include a natural variability related to the different nature of crudes, their processing, and regulations in different parts of the world. In particular, Mackay et al. estimated methane emissions in six crude production area at 6650 sites in Western Canada using equipped trucks, and reported from almost 0 methane emissions in the methane-regulated Peace River area to emissions reaching [10.3–53.7] gCO_2eq/MJ of crudein the Lloydminster area, with a median value there of 32.1 gCO_2eq/MJ, (MacKay et al., 2021), i.e. 1.28 gCH_4/MJ with the GWP100 of 25 used in the study (IPCC 2013). Yet, derived from Husky's reported data in the Carbon Disclosure Project, we only modeled a direct emission of 0.55 g of methane per kilogram of crude extracted. This means that either the wells we studied have very low methane emissions, or that these emissions are not captured well in the report. We thus propose to investigate a potential underestimation of the carbon footprint of the asphalt binder consumed in Canada due to missing fugitive emissions based on the latest research.

We did not find any specific quantification of fugitive emissions in the Cold Lake region. As the same recovery technique for heavy crude oil is used in Lloydminster, Peace River, and Cold Lake (Weber, 2017), and that MacKay et al. reported extreme methane emissions in Peace River (close to 0) and Lloydminster (very high median of 1.28 gCH_4/MJ), we will estimate fugitive emissions for the crude from Cold Lake by considering Lloydminster's emissions as a highest range proxy. Considering the average net calorific value of the Canadian crude of 42.8 MJ per kilogram (United Nations Statistics Division, 2020), we recalculate a carbon footprint of the crude extraction up to 1905 gCO_2eq/kg including well's methane emissions, instead of our original 545 gCO_2eq/kg of crude using the GWP100 in TRACI from the IPCC Assessment Report (AR) 4 (2007). Then, correcting the calculation considering the latest AR6 IPCC GWP100a for methane, raising from 25 to 29.8 between the two reports, the final crude extraction carbon footprint reaches 2166 gCO_2eq/kg. These new estimates multiply by respectively 3.5 and 4 the carbon footprint of the crude oil. It also leads to a carbon footprint of the asphalt binder at the refinery gate in the basecase scenario of respectively 2389 (AR4) and 2650 (AR6) gCO_2eq/kg.

By comparison, the AI's LCA leads to 502 gCO_2eq/kg of asphalt binder on the same system boundaries, after excluding impacts after the refinery gates, i.e., from transport (33 gCO_2eq/kg) and storage at the terminal (101 gCO_2eq/kg). In the end, the AI's carbon footprint of the binder is, respectively, twice, 4.8 and 5.3 lower than the estimates in our base case study, without, and with the CH_4-corrected value with AR4 GWP, and the CH_4-corrected value with AR6 GWP. All the detailed calculations are provided in SM. This re-estimation considering fugitive emissions presents some limits though, due to lack of transparency in crude production statistics by technology, and their related emissions. The accurate asphaltic crude extraction carbon footprint in Canada likely stands between 545 and 2166 gCO_2eq/kg. But this minimum range is highly unlikely when considering that this is the 5 % lowest percentile of carbon footprint reported by Masnadi et al. for Canada (2018), and that these researchers, basing their work on the OPGEE tool, think they still underestimated fugitive emissions (Garthwaite, 2018), especially from venting. Finally, the importance of fugitive emissions in the methane non-regulated area demonstrated by MacKay et al. calls for urgent regulation of methane leaks, especially as we recalculated based on IEA's data (International Energy Agency, 2021) that methane emissions from oil & gas would be responsible for more than 2 $GtCO_2eq$ annually, i.e. 5.7 % of the global GHG emissions reported by Ritchie et al. (2023).

Moreover, pipelines, refineries, and other operations and sites processing petroleum-based products are all potentially subject to fugitive emissions. The National Inventory Report (NIR) of Canada estimates that 2.4 $MtCO_2eq$ were emitted over the year 2019 due to fugitive releases from pipeline transportation in Canada (Government of Canada, 2023b), accounting for around 1.3 % of the emissions of the oil & gas sector. But we already discussed the systematic large underestimate of oil & gas methane emissions in the Canadian NIR, making this figure potentially underestimated. Yet, recent studies in other countries corroborate the low contribution of pipelines to fugitive emissions (Huang et al., 2021; Lu et al., 2023). For instance, a study focused on several pipelines in China shows that the contribution of these fugitive emissions to the carbon footprint of the crude transportation stage is low, accounting for less than 3.5 % (Huang et al., 2021). Nevertheless, considering the systematic trend to underestimate these emissions, they must be better investigated in the future.

When it comes to fugitive emissions at the oil refinery, Lavoie et al. showed that average CH_4 emission rates measured using an aircraft-based mass balance approach were 11–90 times higher than the facility-reported methane emissions in the US, with a weighted average of 42 (Lavoie et al., 2017). If this ratio applies, we recalculated that based on our initial inventory, it adds, resp. for AR4 and AR6 GWP, an extra 26 and 31 gCO_2eq/kg of asphalt binder from the refinery stage based on a mass allocation, but less using other allocation possibilities. Calculation details are made available in SM.

In the end, without even considering the emissions due to transportation to terminal and storage, virgin asphalt binder could reach a carbon footprint up to 2680 gCO_2eq/kg when considering specific crude slates to produce good quality binder, fugitive emissions of the average crude oils from Lloydminster and at the refinery, and the latest IPCC GWP for the methane, i.e. 5.3 times the highest value reported so far in the literature. Such a carbon footprint would completely change the scale of the organizational emissions reported by the road construction industry, considering asphalt binder was already a main contributor to its climate impact (de Bortoli and Agez, 2023), and would also modify the best strategies to reduce GHG emissions from road infrastructure: replacing virgin asphalt binder for instance by increasing recycling (reclaimed asphalt pavement or RAP) would probably become more beneficial than reducing the temperature of asphalt concrete production to mitigate the climate impacts of this industry. But correcting the emissions due to crude oil processing will also moderately increase the impact of asphalt mixing that is mostly done using fossil fuel, also calling for lower production temperature. Nevertheless, the GHGs from the combustion will remain stable, while only the less contributing emissions from the production of the fuel will increase.

These new carbon footprints of asphalt binders and crude oil extractions may also impact the environmental comparison of concrete versus asphalt pavements, despite a large part of cement carbon footprint is due to limestone calcination direct emissions. Indeed, high increases in crude extraction carbon footprints concern most of the crudes in the world as showed by Shen et al. (2023), and will thus impact the carbon footprint of many economic activities, as 40 % of global emissions are estimated coming from fossil fuel (International Energy Agency, 2022). Better crude oil (and coal) emissions accounting will also increase the carbon footprint of cements and concrete for instance, thus concrete pavement, as concrete is largely produced based on fuel. Yet, asphalt binder has a better environmental potential from recycling than concrete. Indeed, when incorporating RAP into new material, no or little rejuvenators are necessary to replace virgin bitumen by recycled one under a certain share of RAP: the RAP is simply mixed with virgin materials. Thus incorporating RAP should largely reduce the impact due to a carbon-intensive bitumen, while recycling concrete, on the other hand, has more limited environmental potential as the cement is not rejuvenated. In the end, we cannot conclude from this study if asphalt pavements emit more or less than concrete pavements in Canada, as there is a deep need to review and update most of the data and models used in environmental accounting. Rather, we must conclude that: (a) accurate GHG accounting is now an emergency in the face of the current climate crisis, (b) voluntarily disclosures and current reporting processes are globally failing to robustly support efficient environmental policy making, and (c) governments need to urgently intervene to make environmental accounting more robust, to support best decisions and ensure humanity safety.

6.3. Pipeline transportation contributes more than expected

A comparison of our Canadian pipeline transportation model with the generic ecoinvent model showed that this mode of transportation may have a higher impact on the environmental performance of bitumen than what was previously assessed in the literature. Our base case model provides a carbon footprint of 53 gCO_2eq/tkm, more than twice as large as that of the generic ecoinvent model (21 gCO_2eq/tkm for GWP100 from IPCC 2013, process “*transport, pipeline, onshore, petroleum, ROW*” of EI3.6). This default model considers an average electricity consumption drawn from the literature (20 Wh/tkm), an electricity mix representing different regions of the world (Australia, New Zealand, Africa, Asia, Latin America and Northern America) (Jungbluth, 2007), as well as infrastructure amortization. The infrastructure data were extrapolated from 2011 world market data, when processes for electricity productions are based on the statistics of the International Energy Agency (IEA) from 2016 for the shares of electricity technologies and of the OECD from 2014 for the electricity market composition in 2014. Our model, in comparison, is based on the 2018 COPTEM model implemented with updated electricity mixes specifically feeding each pipeline used to transport the crude to the refinery. Thus, the temporal, geographical and technological representativeness of our pipeline transportation process is better than that of the ecoinvent process. Our results illustrate how important it is for pipeline transportation models – used to assess the impact of petroleum products – to be representative, as well as the need to develop parametric models allowing to assess regional pipeline transportation.

6.4. The impact of methodological choices is major

Our study shines a light on how highly sensitive bitumen LCA results are to methodological choices. Some methodological choices allow to present a reduced carbon footprint, specifically: narrow system boundaries; a crude slate that leads to a lower impact and not specific to bitumen production, for instance, lighter than an asphaltic crude, requiring less energy to crack; a background database or a process choice that minimizes impacts; or an allocation type approach for refining that is beneficial to bitumen as compared to other co-products. With respect to this last point, we conducted a sensitivity analysis with the corrected PRELIM allocation factors presented in Table 5: under an economic allocation, the carbon footprint of Quebec bitumen is 910 $kgCO_2eq/t$, i.e., 9.12 % lower than under a mass allocation. The preceding results highlight the now-classic LCA issue of harmonizing methodological choices for comparison purposes (de Bortoli et al., 2023). The matter of databases also raises the issue of transparency and accessibility of data. Although ecoinvent is still the reference database, many of its inventories must be updated and/or parameterized, in various sectors but especially in construction (de Bortoli, 2023).

Furthermore, the overall lack of uncertainty assessment is clear in the case of LCA of asphalt binders. The AI study applies a rather qualitative approach to assess data collected for the foreground processes as well as the background data, but does not quantify uncertainty (Thinkstep, 2019, sec. 5.4). The Eurobitume v3 study presents an uncertainty analysis of foreground processes based on the semi-quantitative Pedigree Matrix data assessment, which allows to apply statistical methods of uncertainty propagation such as MCS. The analytical equation proposed by the Pedigree Matrix approach has the advantage of combining both the base uncertainty (stochastic error) of data on a process and the additional uncertainty calculated from Pedigree criteria scores.

7. Conclusions

Our systematic review of published bitumen LCA models as well as our new models developed for several Canadian markets indicate that the environmental impacts of asphalt binders vary significantly. These impacts depend both on methodological choices, and above all, on data quality. Our study highlights a global, often significant, underestimation of the carbon footprints of asphalt binders that have been published to date. These underestimations are mainly associated with the general underestimation of the emissions from asphaltic crude extraction, the poor quality of pipeline transportation models, and the choice of refining impact allocation approach over time in asphalt union's publications that reduced the impact attributed to bitumen as compared to other petroleum co-products. These underestimations could have highly negative consequences due to presumed environmental best practices in road construction relying on inaccurate LCAs. These inaccurate LCAs could lead to recommendations of "good practices" that are, in fact, more harmful to the environment. In the case of Canada, our models lead to the highest carbon footprints for asphalt binders published to date − 826–1098 kgCO_2eq/t − but could still be underestimated due to the lack of accessible crude extraction data from producers. Especially, hard-to-account-for fugitive methane emissions could raise this carbon footprint up to 2680 gCO_2eq/kg. These results have strong practical implications for public authorities, the road industry, and its stakeholders. Indeed, as the carbon footprint of bitumen is higher than previously estimated, it may prioritize high-recycling rates in asphalt mixtures over low-temperature asphalt mixing to reduce pavement environmental impacts, and it may impact the ranking between concrete and asphalt pavements. Moreover, better accounting of fuel production will also modify the impact of many other materials and activities, and more LCAs need to be conducted with better LCIs.

Because a lot of work needs to be conducted to understand the environmental impact of bitumen on different markets, we therefore urge the community to be more vigilant in building bitumen LCA models and in the choice of the bitumen model used in road LCAs, as failing to do so could lead to inaccurate environmental rankings and mitigation solutions. Next, we call on professionals involved in the bitumen production chain – oil companies, pipeline operators, refiners – to share their data to facilitate the environmental improvement of production practices. Finally, we highlight the crucial need to develop more high-quality LCIs – with good temporal, geographical and technological representativeness, robust sampling and reliable field data –, first for the extraction of oil, which has a significant environmental impact in a number of products and services, and then for oil transport and refining.

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CRediT authorship contribution statement

Anne de Bortoli: Conceptualization, Funding acquisition, Investigation, Methodology, Project administration, Supervision, Visualization, Writing – original draft, Writing – review & editing. **Olutoyin Rahimy:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Software, Validation, Visualization, Writing – original draft, Writing – review & editing. **Annie Levasseur:** Funding acquisition, Project administration, Resources, Writing – review & editing.

Data availability

Calculation files are accessible in the supplementary information, and csv models can be asked directly to the authors.

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Appendix A. Supplementary material

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