Estimating the disaggregated standard EROI of Canadian oil sands extracted via open-pit mining, 1997-2016

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Abstract

The province of Alberta, Canada, has been the first crude oil producer in Canada since the mid-1940s. Its conventional crude production has declined over the last decades, while production from unconventional sources, i. e. the oil sands, has risen significantly. Two types of crude are produced out of raw oil sands: crude bitumen and synthetic crude. While the first must be blended with light hydrocarbons prior to shipment to high-conversion refineries, the former is produced via upgrading (distillation and/or cracking) of bitumen, resulting in a crude oil stream nearly identical chemically to conventional crude. Past researchers who estimated the net energy delivered by oil sands-derived crude using the Energy Return on Energy Invested (EROI) as an indicator have either estimated the EROI of one type of crude only or analysed the total EROI of oil sands extracted via both open-pit or in-situ mining. No research has estimated the disaggregated EROI of the two types of crude independently, making a rigorous comparison of the net-energy potentials of the two crude streams difficult. This paper provides disaggregated estimates of the EROI of crude bitumen and synthetic crude produced via open-pit mining. I find the Standard EROI ($EROI_{ST}$) of crude bitumen to be 13.02 : 1 on weighted average from 1997 to 2016 and increasing over time. I find 2 alternative $EROI_{ST}$ ratios for syncrude, changing according to the inclusion or exclusion of bitumen-processing as an input: if excluded, I find synthetic crude's $EROI_{ST}$ to be 4.45 : 1 on weighted average over the period. If included, I find the $EROI_{ST}$ to be 1.86 : 1.

Keywords: EROI, oil sands, net-energy analysis; Biophysical Economics

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Introduction

Fossils fuels currently account for 84% of global primary energy consumption (Delannoy et. al., 2021a) with crude oil being the first source (International Energy Agency, 2020: 6). The economic importance of crude oil could hardly be underestimated. Historically, crude oil has allowed a massive enhancement in the economic work humans are able to do via the conversion of fossil fuel into mechanical work (Bonaiuti, 2018). However, being non-renewable, the future of crude oil extraction is faced with the ongoing depletion of conventional sources[2] (Sorrell, et. al. 2009) and, in theory, their progressive replacement by unconventional sources (shale oil, tar sands, etc.) (Hall et. al., 2009: 27) This shift implies changes in terms of the net quantities of energy societies can expect from crude oil, as unconventional sources tend to deliver less net energy than conventional sources (Delannoy et. al., 2021b).

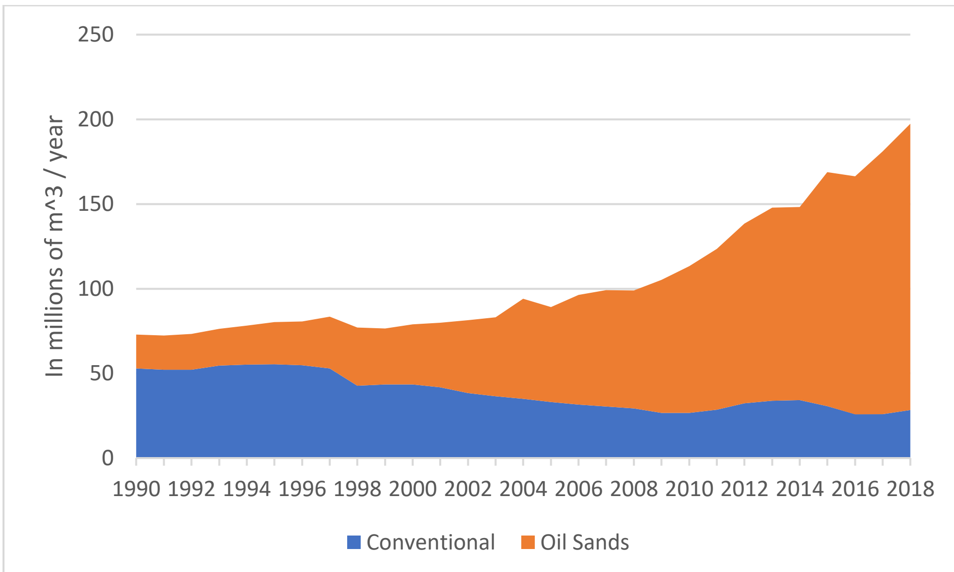
'Net quantity of energy' means the energy value (in joule) an energy carrier can deliver when the energy costs of producing it are subtracted. Net-energy flows are necessary for an economy to maintain or increase its complexity (increasing flow of information, population growth, specialization of labour, etc.) Scholars in Biophysical Economics have developed various metrics to estimate net energy production, with the Energy Return on Energy Invested (EROI) now being the most frequently used. Hall et. al. argue that a minimum EROI of 3:1 at the level of extraction is the minimum fossil fuels must yield to deliver net energy at the point of use, e. g. to drive a truck: for one unit of energy produced at the point of extraction, about two-thirds is diverted or lost in refining, transport and construction of the infrastructures required to consume it (Hall, et. al., 2009: 39-41; Hall et. al., 2014: 144) The EROI of conventional crude has allowed unprecedented economic growth and improvement in the material standards of living of hundreds of millions of people (Hall and Klitgaard, 2018; Lambert et. al., 2014: 155) during the XXth century. However, several studies have shown a declining trend in the EROI of crude oil and gas globally and in the United States over the last decades (Cleveland, 2005; Guilford et. al., 2011), meaning the net energy available for non-productive use (education, recreation, etc.) is likely to decline in the future.

The Canadian province of Alberta, Canada, is an ideal case-study to investigate the net energy potential of unconventional sources of crude. Its conventional crude production has declined over the last decade, forcing producers to shift toward unconventional sources, most importantly the oil sands. Located in the

[2] 'Conventional' crude is defined as a source of crude oil or gas flowing to the surface due the reservoir's pressure or with the addition of additional pressures via the injection of water or natural gas into the well. 'Unconventional' crude refers to sources that are mined as solid and converted into liquids at the surface in man-made facilities (Hall and Klitgaard, 2018: 406).

Athabasca Valley in Northern Alberta (Canada), the oil sands had been deemed unworthy of commercial exploitation for decades following their systematic study by Sydney Ells, an engineer from the Canadian Department of Mines in the early 1920s (Chastko, 2004). The commercial context changed in the 1960s with the construction of the Great Canadian Oil Sands project in Fort McMurray by Sun Oil (now Suncor). Oil sands currently are the first source of crude oil production in the province:

Figure 1 Conventional and unconventional crude production in Alberta, 1990-2018



Source: Canadian Association of Petroleum Producers, 2021.

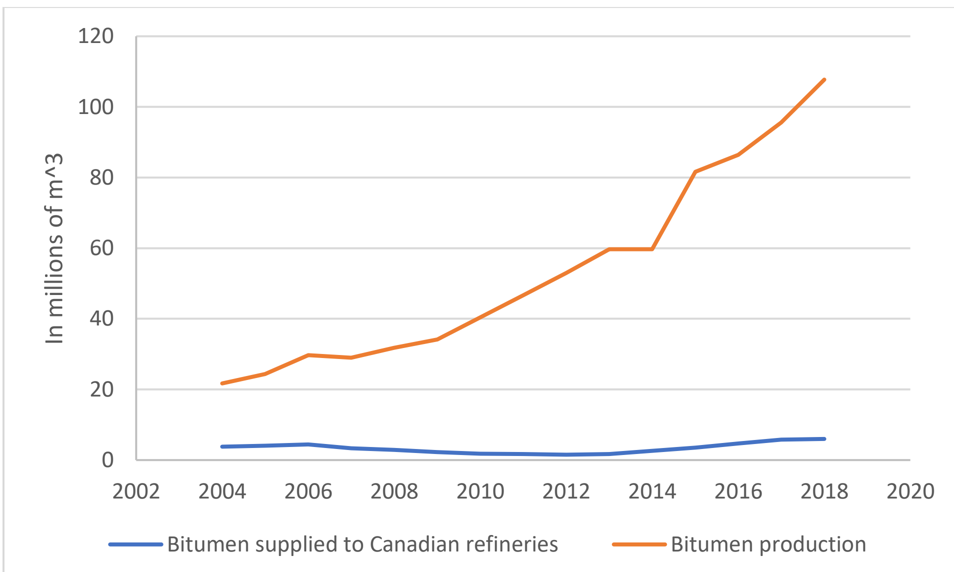
Two types of crude are produced out of the oil sands: synthetic crude (or syncrude) and crude bitumen. Bitumen is a naturally solid, asphaltenes-rich hydrocarbon. In nature, it is mixed with solid particles of sand and clay. After it is mixed with light hydrocarbons, 'diluted bitumen' is sold to high-conversion refineries[3] as a sour, heavy crude feedstock. Syncrude is the light sweet crude resulting from the upgrading, i. e. the thermal cracking and hydro-treating of bitumen prior to its refining into refined petroleum products (Banerjee, 2012: 22). In this paper, I use the term 'crude bitumen' to denote bitumen

[3] Refineries' complexities are measured by the 'Nelson Complexity Index'. This index compares refining facilities via a comparison of the costs of their refining equipment. A basic distillation column is given a value of 1. Additional refining facilities (hydrocracking, hydrotreating, etc.) further expands the value of the index (Energy Information Administration, 2012).

cleansed from the physical particles of sand and clay after extraction and ‘diluted bitumen’ to denote the crude oil feedstock sold to high-conversion refineries.

Whereas the production of crude bitumen and syncrude were roughly equal until the early 2010s, crude bitumen’s production now dominates. The surge happened at the same time as the shale oil revolution in the United States. With the growing supply of tight oil from the Midwest, many refineries in the United States Midwest expanded their refining capacity of heavy crude and increased their imports of Canadian heavy oil (Oil Sands Magazine, 2015; Pickren, 2017). In 2018, more than 95% of bitumen produced in Canada was exported to the United States.

Figure 2 Total crude bitumen production in Canada and bitumen refined by Canadian refineries (in millions of m^3), 2004-2018



Source: Canadian Association of Petroleum Producers, 2021 and Statistics Canada, 2021.

Little is known about the ability of oil sands to deliver net energy. Of the few studies available on this issue, the scopes are limited to net-energy of *one type of crude only* or *aggregated estimate of the total* (crude bitumen and syncrude) net-energy produced via *both open-pit and in-situ mining*. To my knowledge, comparison of the disaggregated net-energy extracted from crude bitumen and syncrude via the same mining method was never conducted. Open-pit and in-situ mining involve different levels of capital expenditures, output of raw bitumen per extraction site, etc., all of which influence net-energy ratios. Therefore, I argue that a rigorous comparison of the potential of the two crude streams to deliver net energy require a comparison when derived from the same mining method.

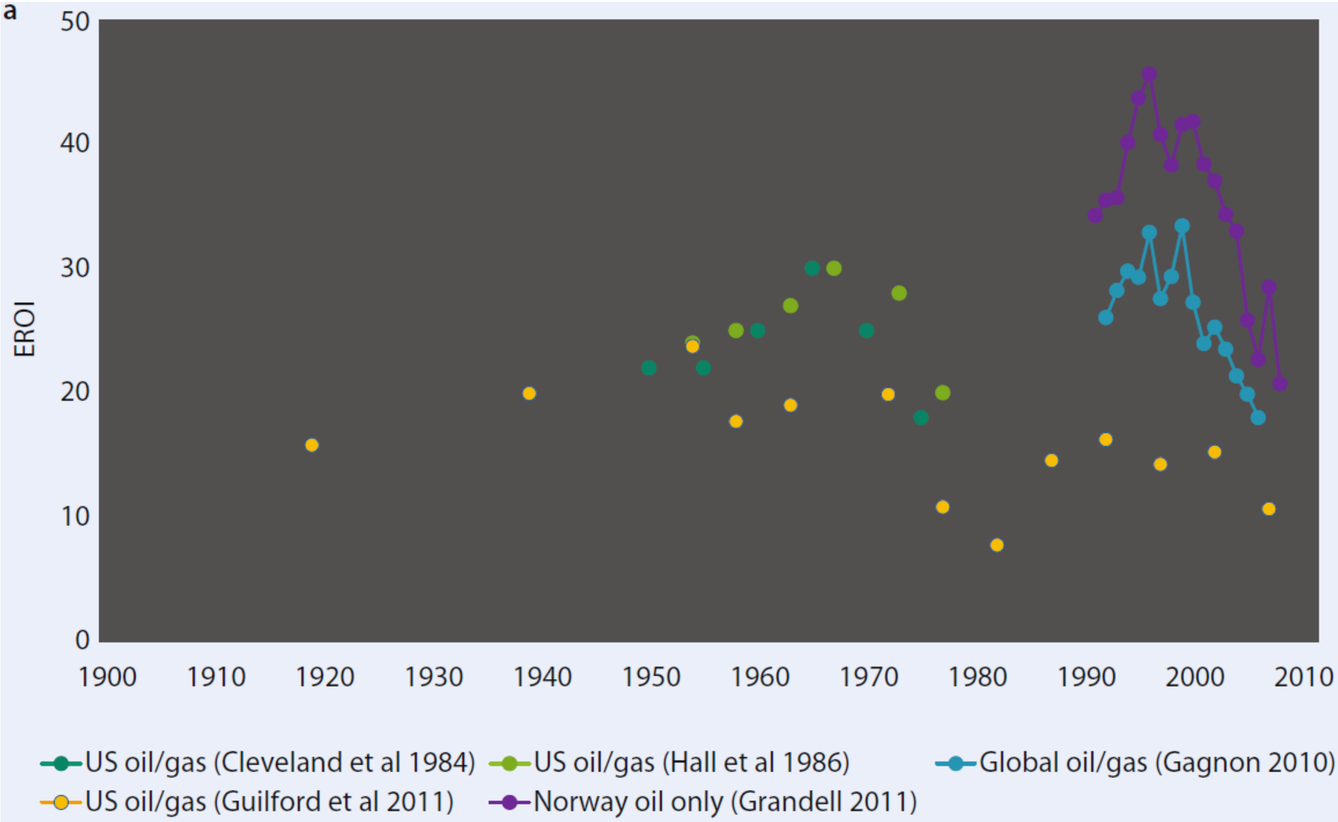
The general question motivating this paper is: are the oil sands providing a source of primary energy fit to sustain a complex economy? Operationalizing this general question into a more specific one, I ask: what is the EROI of diluted bitumen and synthetic crude? I further specify my objective into estimating the EROI of oil sands-derived crude produced via open-pit mining only to make the comparison with other sources of crude more rigorous. My analysis should help decision-makers and investors determine if oil sands provide a source of energy enabling the maintenance of North American economic infrastructures. Because net-energy analysis involves an estimation of the energy value of a crude oil feedstock at the mine gate and because bitumen is sold as feedstock to refineries after dilution with light hydrocarbons prior to shipment, this paper estimates the EROI of diluted bitumen.

This paper provides an estimation of the EROI of Canadian mined diluted bitumen and synthetic crude extracted via open-pit mining from 1997 to 2016 in Alberta, Canada. The paper is divided as follows. Section 1 reviews the literature on EROI in Biophysical Economics. Section 2 provides a technical background on the different types of crude produced out of the oil sands and mining methods. Section 3 introduces the methodology developed to answer my research questions as well as the sources of data used to operationalize my methodology. Section 4 provides 2 examples of the methodology, presenting an estimation of the EROI of diluted bitumen for the year 2008 and 2016. Section 5 presents my results. Section 6 concludes the paper with a discussion of what I view as my research merits compared with previous research, its limitations, areas of future research and a general discussion on whether oil sands can support the energy requirements of a complex economy.

1. Literature review

There is a burgeoning literature on Biophysical Economics and net-energy analysis. A few studies have shown a declining trend in the EROI for fossil fuels. Hall et. al. (2014) and Lambert et. al (2014) examine the implications of a declining EROI on the ability for complex economies to maintain themselves or expand. The authors show that with a growing portion of economies' output to be reinvested in energy production, the discretionary energy and monetary expenditures in areas such as leisure, education and arts are likely to contract in the future, implying a simplification of the economy. Declining EROI ratios across the world are observed in many studies.

Figure 3 Estimates of EROI for crude oil produced in the United States, Norway and globally, 1900-2010



Source: Hall and Klitgaard, 2018: 198

Gagnon et. al. (2009) estimate the worldwide EROI of oil and gas extraction by private companies have peaked in 1999 at 35 :1 and declined to 20 : 1 in 2006. Guilford et. al. (2011) estimate the EROI of U.S. domestic oil and gas decreased from 25 : 1 in the 1970s to 10 :1 in 2007. Cleveland confirms this trend, showing the EROI of crude oil discovery in the United States to have dropped from 100 : 1 on crude found in Texas, Oklahoma and Louisiana in the 1930s to 30 : 1 in the 1970s and 11-18 : 1 in the 2000s. A similar declining trend in the EROI of fossil fuel extraction was observed in Norway (Grandell et. al., 2011). Hall and Klitgaard (2018) report the original work of Guilford et. al. showing the EROI ratio of crude oil and gas discovery in the United Stated decreased to less than 5:1 in the 2010s.

Studies on the EROI of Canadian fossil fuels are more recent. To my knowledge, the first paper is by Freise, who shows a declining trend in the net-energy of conventional oil and gas in Canada. Whereas the EROI of exploring, drilling, gathering and separating oil and natural gas is estimated to have reached a peak of 80:1 in the 1970s, it dropped precipitously to 22:1 in 1980 and 15:1 in 2006 (Freise, 2011: 2087. 2094).

On oil sands specifically, the first estimate on the EROI of oil sands is Rapier, who estimated the ratio at 3.9 : 1 in 2008. A more complete estimation, encompassing the two crudes produced out of raw oil sands produced by the two mining methods was produced by Brandt et. al. (2013). They estimate the EROI of bitumen and syncrude extracted via both in-situ and open-pit mining at different points of the supply chains (refining, transport). Unlike for conventional crudes, the authors notice an upward trend in the net-energy of oil sands. The authors explain this trend by improvements in mining technologies since the early 2000s, such as in froth treatment (separation of raw oil sands into bitumen and solid particles (earth, clay, etc.). They show the EROI of the two crudes streams to have risen from 4:1 in the 1970s to 7:1 in 2010 at the point of extraction (Brandt et. al., 2013: 695).

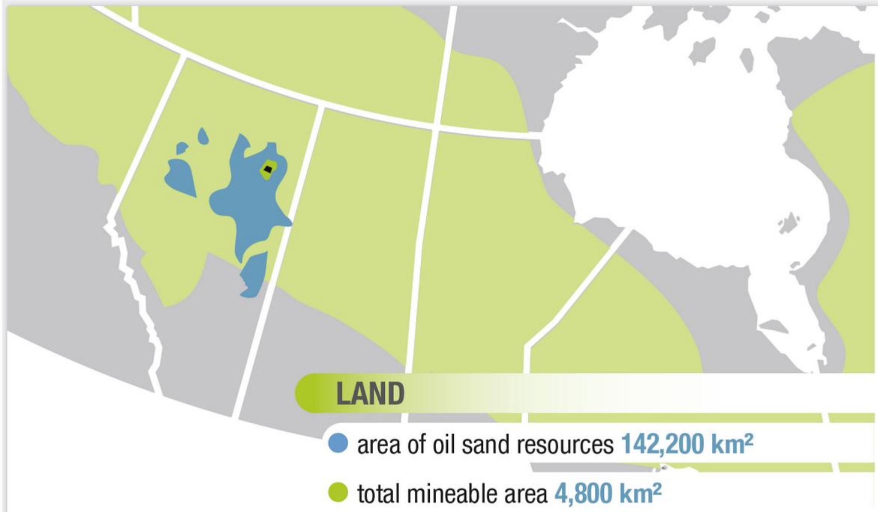
Poisson and Hall (2013) estimated the EROI of synthetic crude extraction between 1994 and 2008 to fluctuate around a ratio of 4:1, in comparison with a range from 11:1 to 16:1 for conventional oil and gas during the same period. The authors excluded both bitumen production as well as in-situ mining from their analysis (2013: 5947) due to data limitations. Like Brandt. et. al., Wang, et. al., (2017) estimated the EROI of both crude streams disaggregated by the mining method. Their estimate range from 3.2:1 to 5.4:1 for crude produced via in-situ and from 3.9:1 to 8:1 for open-pit mining from 2009 to 2015. Using a firm-based methodology to estimate correlations between EROI and return on equity, Wang et. al. (2019) estimate the EROI of bitumen and syncrude extraction at the mine-mouth by four companies to range from 3.5 : 1 to 6.5 : 1 and rising over time between 2010-2016.

The literature reviewed shows the need for the disaggregated estimate of both crude streams potential to deliver net-energy to society when extracted via the same mining method. Such an analysis is required to rigorously compare the crude’s varied energy potentials. The following sections undertake that task.

1. The Canadian oil sands: an overview

Oil sands are located in the Western Canadian Sedimentary Basin in Northern Alberta, covering an area of 142,000 km^2 under the boreal forest. Oil sands are currently estimated to represent 166.3 billion barrels of proven reserves, that it 97% of total crude oil reserves in Canada.

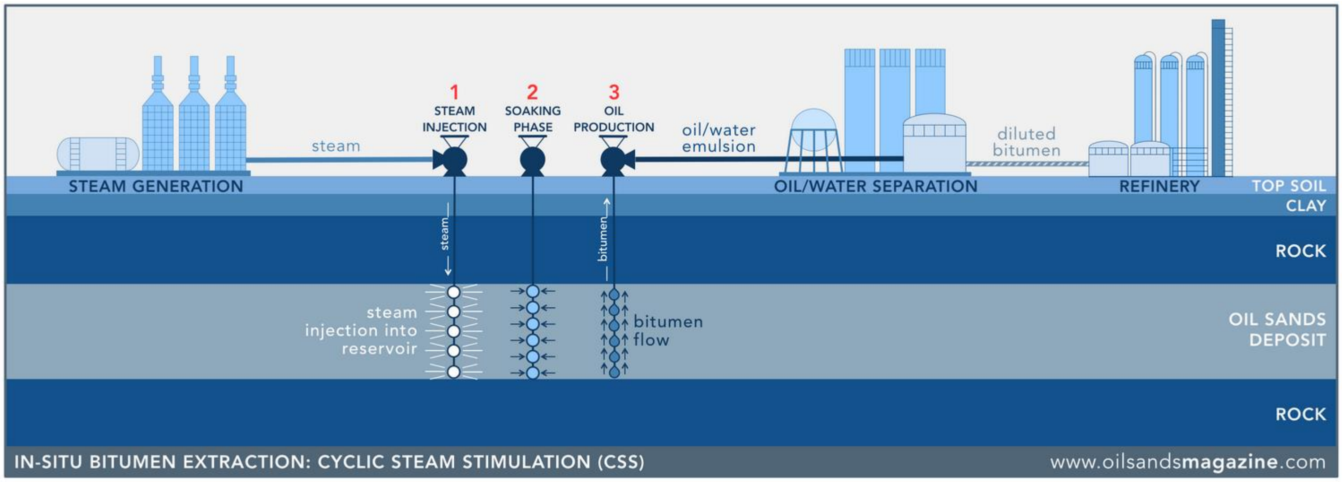
Figure 4 Location of the oil sands deposits in Canada



Source: Natural Resource Canada, 2020

Two methods exist to mine the sands: open-pit mining and in-situ mining. Of all oil sands reserves, it is currently estimated that 20% can be recovered via open-pit mining and 80% via in-situ mining (Canada Energy Regulator, 2020). Open-pit mining is performed when the sands deposits are found at less than 75 meters below the surface (Natural Resource Canada, 2016a). When the overburden is deeper, extraction is executed through in-situ mining, involving the injection of steam at high-pressure in the deep and solid oil sands deposits. As the deposits liquefy, they are pumped to the surface.

Figure 5 Flow diagram of in-situ mining

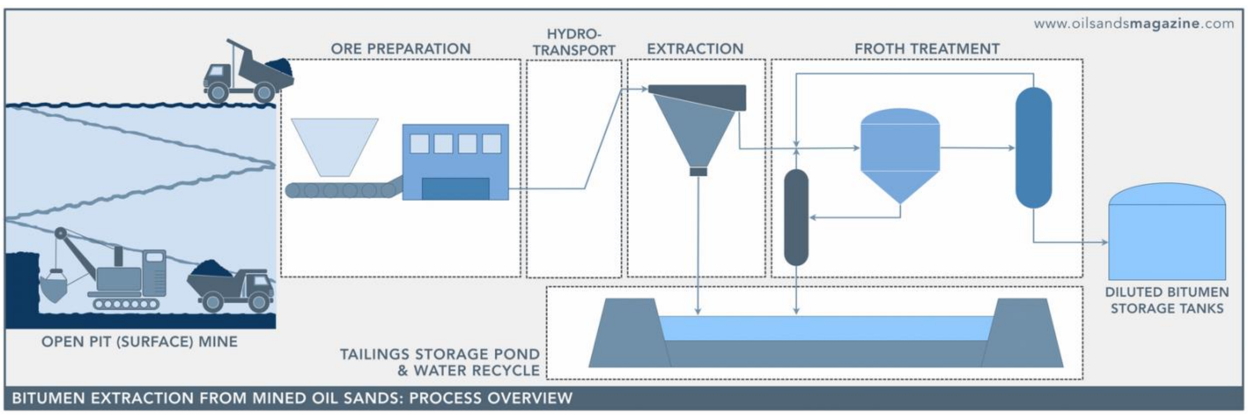


Source: Oil Sands Magazine, 2020a

In 2019, in-situ and open-pit production represented roughly 50% each of total raw bitumen extraction although the share of in-situ mining is expected to rise in the future. In 2020, there were 10 active mines in Alberta extracting sands via open-pit mining whilst in-situ mining was performed at 161 sites (Oil Sands Magazine, 2020a, 2021; Alberta Energy Regulator, 2021).

Open-pit mining involves the cleaning and fluidification of bitumen via the mechanic removal of land covering the sands and its transfer to installations where the masses of earth, clay, sand, and raw bitumen that are mixed in nature are crushed and water-washed before being pumped to processing units where the solid elements are separated from the bitumen by gravity (Oil Sands Magazine, 2021b). The bitumen slurry is then hydrotransported into an extraction unit where bitumen is processed into bitumen froth. Crude bitumen is the product of froth treatment.

Figure 6 Flow diagram of a generic open-pit mining facility



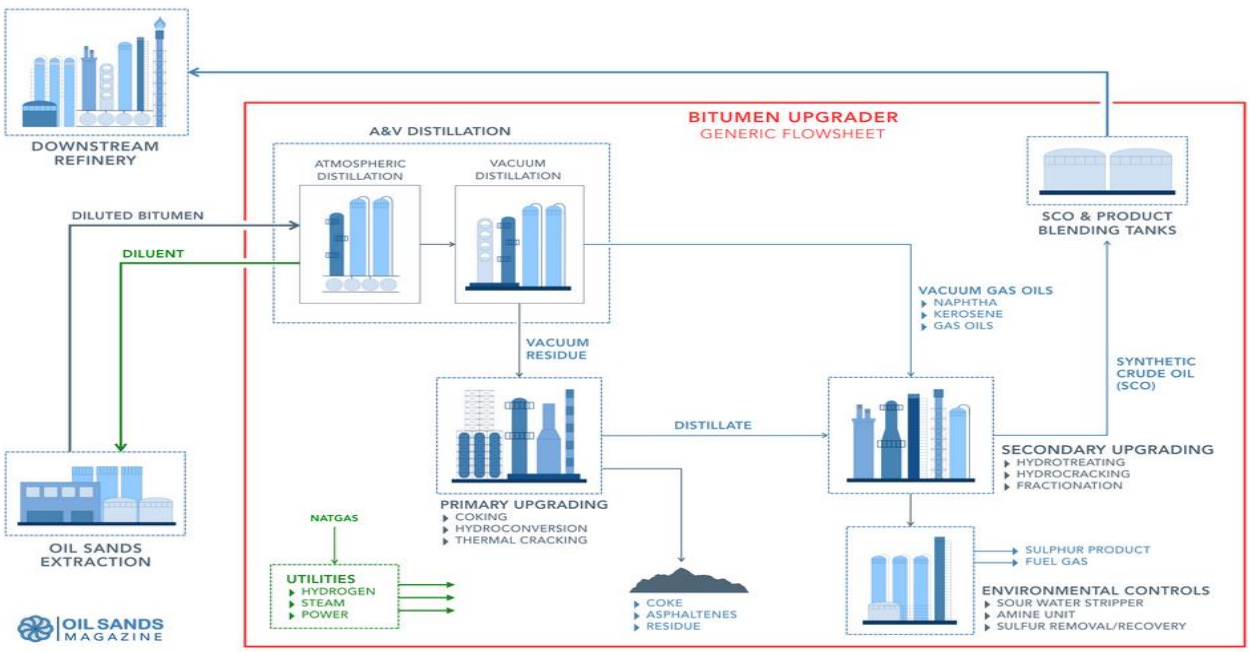
Source: Oil Sands Magazine (2021a).

Crude bitumen is too heavy to meet pipeline companies' specifications on crude fluidity (with an average API[4] of 10^{o}) and corrosivity (a function of sulphur content, which in the case of bitumen can be as high as 5%) (Oil Sands Magazine, 2020b). Bitumen must be blended with lighter hydrocarbons (condensate, natural gas or naphtha) to be fluid enough for shipment to refineries through pipelines, thus becoming diluted bitumen. If not transported to a refining facility, bitumen can be upgraded into syncrude, whereby bitumen is transformed into a product physically and chemically very close to conventional crude. Upgrading is performed in two steps. Primary upgrading increases the ratio of hydrogen to carbon of

[4] 'API gravity' is a scale expressing the density of crude and petroleum products. The higher the API gravity, the lighter is the product or source of crude. Conventionally, crudes with an API of 22 or below are defined as 'heavy' (EIA)

bitumen molecules, either through coking or hydroconversion via distillation and/or cracking, i. e. breaking the chains of hydrocarbon into lighter chains by submitting crude to intense heat. Secondary upgrading is achieved by hydrotreating, a catalytic process performed with the addition of hydrogen to the hydrocarbon in the presence of a catalyst, using natural gas to generate heat and hydrogen. Syncrude is nearly identical to conventional crude in terms of chemical composition (Oil Sands Magazine, 2020a). It can therefore be sold to simple refiners (see note 3). Whilst certain mining facilities upgrade bitumen on-site (Suncor, Mildred Lake, etc.) others ship diluted bitumen to upgrading facilities off-site (Alberta energy Regulator, 2021b).

Figure 7 Flow diagram of a generic bitumen upgrading facility



Source: Oil Sands Magazine, 2020c

2. Methods and materials

2.1 Methodology: Protocol to determine standard EROI

The development of methodologies to estimate the EROI values of energy carriers is one of the most important contributions of Biophysical Economics to economic research. EROI is a ratio between energy produced, or output (numerator) and energy required to produce it, or input (denominator)[5]:

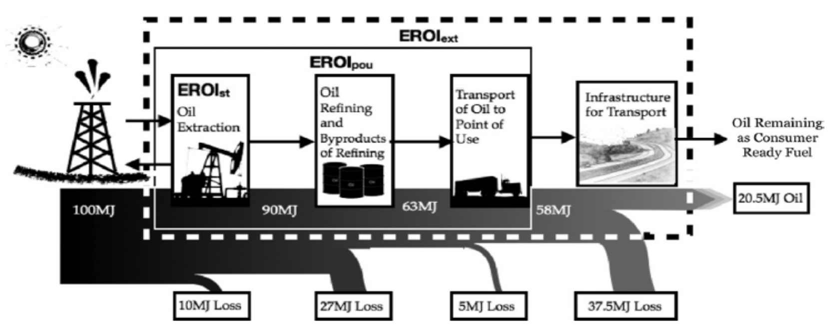
[5] A list of symbols used can be found in Appendix I.

1) $EROI = \frac{E_o}{E_i}$

Where E_o stands for 'energy output to society' and E_i stands for 'energy input for that process', both in the same units, normally joule.

EROI is a measure of energy quality, that is the ability of a unit (joule) of energy to generate net energy. When energy output is divided by the units of energy required to produce it, one can speak of net-energy flows and the higher the EROI ratio, the more an energy source produces net-energy flows. When EROI exceeds 1:1, one can speak of an energy source whilst a ratio inferior to 1:1 indicates an energy sink. Because of energy loss in the transport and refining process, the EROI an energy source must meet at the point of extraction must be higher than 1 : 1 (Hall et. al., 2014: 144). Considerable variations exist in the EROI values of fossil fuels depending on quality correction, the intrinsic quality of the fuel in nature (its usefulness, such as electricity being more useful from an economic standpoint than an equivalent quantity of chemical energy (Lambert et. al., 2014: 154)) or the boundaries of analysis adopted (discussed in Murphy et. al. (2011)). 'Boundaries' refer to the choice of the groups of inputs to be accounted for in the denominator, depending on the segments of the supply-chain included (extraction, refining, distribution, etc.) Standard EROI ($EROI_{ST}$ in figure 8 and henceforth) measures the inputs and outputs of energy carriers leaving extraction facilities (well-head or at the 'mine-mouth'), i.e. when directly extracted from nature, as with a coal mine, a crude oil well, etc. It is the measure most appropriate for the objective of this paper dealing with oil sands extraction and upgrading prior to refining.

Figure 8 Boundaries in EROI analysis



Source: Hall et. al., 2014: 142

Two kinds of inputs are considered when estimating $EROI_{ST}$: energy (natural gas, electricity, etc.) used directly on site plus the energy required to produce the goods and services (steel and concrete, financial and transportation services enabling production, etc.) used on-site but produced elsewhere in the economy, what I refer to as 'off-site'. Therefore, two sources of inputs are accounted for in the denominator of the EROI ratio estimated here:

$$2)\ EROI_{st} = \frac{E_o}{(E_i + IND_i)}$$

Where IND_i stands for 'energy embodied in indirect inputs'.

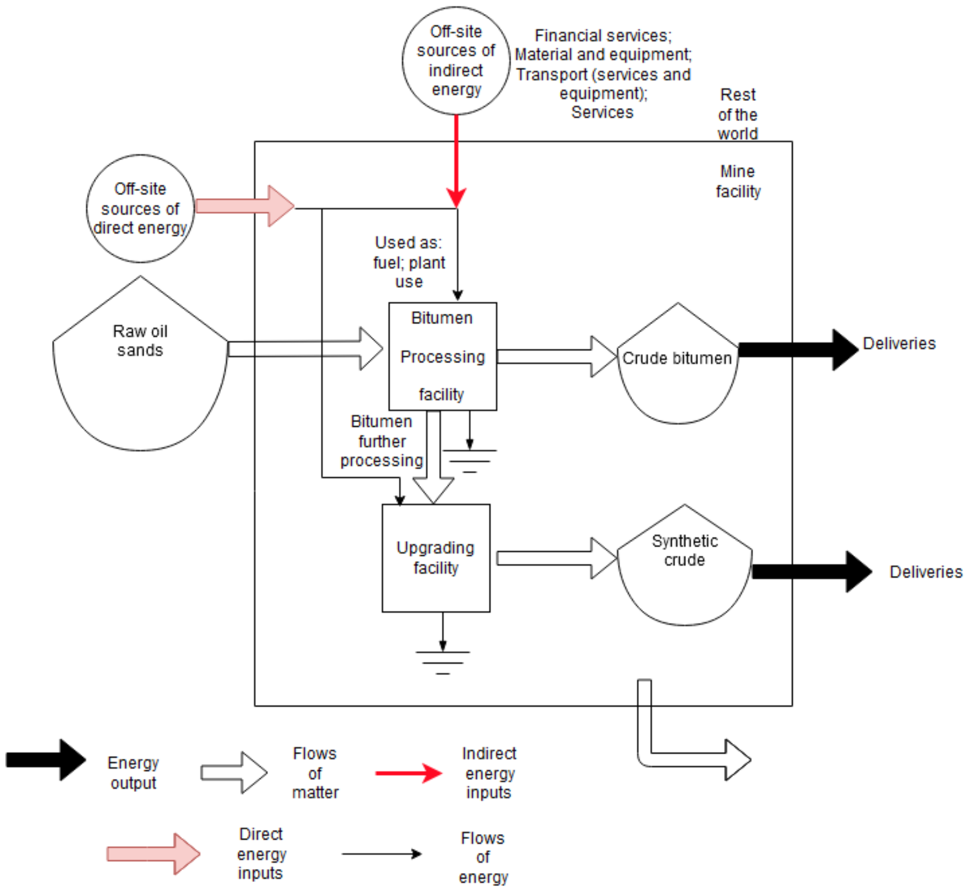
Two methods exist to quantify the energy embodied in the production of inputs: 1) process-analysis and 2) input-output analysis. Whereby process analysis is akin to a 'bottom-up' approach where the energy values of different production stages are first estimated separately and then aggregated, input-output analysis converts economic input-output tables into sector-specific energy values (Murphy et. al., 2011: 1891). The methodology I use involve a combination of both. I use process analysis to convert publicly available data on direct energy input and output from volume into energy units for each oil sands open-pit mine in Alberta from 1997 to 2016. I estimate the embodied energy of indirect inputs by converting monetary expenditures into energy values using data from Statistics Canada, the country's national statistical agency.

The next section presents the conceptual model developed to determine the boundaries of my analysis of mining facilities, my sources of data and the assumptions and method used to estimate critical information when unavailable from public datasets.

2.2 Boundaries of analysis: a conceptual model of oil sands mines

I define here the boundaries of analysis used to estimate the $EROI_{ST}$ of oil sands mining at the mine-mouth. I define the energy *outputs* of the systems as the *flows of fossil fuels and electricity leaving the mining/upgrading facilities* (full back arrows in figure 5). I define the *inputs* as the *direct energy flows* plus the *embodied energy of indirect goods and services* consumed in the mine and upgrading facilities (full pink and thin red arrow respectively in figure 5). These boundaries reflect the real-world flows of energy involved in 1) bitumen *mining or* 2) *mining plus upgrading* facilities. Therefore, I do not consider other downstream processes, such as the inputs and outputs implied in transport and refining nor do I consider upgrading facilities importing bitumen from off-site (Nexen Long Lake upgrader, Shell Scotford upgrader, etc.) The three upgrading facilities analyzed in this paper (Suncor, Syncrude Mildred Lake and Syncrude Oil Sands) all upgrade bitumen mined on-site. Figure 5 is a material and energy flow diagram modeling the boundaries defined here:

Figure 9 Material and energy flow diagram of an oil sands mining facility



My study aims at estimating the $EROI_{ST}$ of oil sands-derived crude extracted via open-pit mining only. Therefore, I estimate the aggregate energy values of direct inputs and outputs of all open-pit mines in Alberta by summing their individual values for each mine, therefore estimating the energy values of the 'open-pit mining' sector as whole. This methodology is relatively easy to perform as the number of oil sands open-pit mines is small (from 2 in 1997 to 8 in 2016). Furthermore, the data are more ventilated on energy inputs for open-pit mining than they are for in-situ mining. Indeed, the Alberta Energy Regulator (ARE) provides data on natural gas (in m^3) and electricity (MW) consumed by each mine in open-pit mining, whereas reports on in-situ facilities provide data on steam production and injection rate (in m^3/day) only (AER, 2020-2021). To my knowledge, precise figures on the conversion of direct energy inputs used to produced steam in in-situ mining do not exist. Publicly available data on in-situ mining therefore cannot be used to estimate the energy value of direct energy inputs used in this sector. As I aim to study the $EROI_{ST}$ of syncrude derived from open-pit mining only, I exclude from my analysis the upgrading facilities purchasing diluted bitumen extracted from in-situ mining facilities mentioned in page 13.

Estimating the energy value of indirect inputs cannot be performed at the mine's level. No data on purchases of material or financial services per mine (to my knowledge) exist. My research necessitated an estimation of the energy value of indirect inputs at the scale of the oil sands sector as a whole and then a disaggregation for the share of energy value for indirect inputs used in open-pit mining.

2.2 Materials

This sub-section presents the data used to estimate the energy values of the output, direct and indirect inputs in open-pit mining. I was able to use governmental statistical agencies data only. EROI values are best estimated when analysts can use government data (Hall et. al., 2014) as these data sets tend to be more consistent and vetted by professionals (Peter Victor, personal communication).

2.2.1 Energy output

I used the Alberta Energy regulator (2021b) *Statistical Reports #39* (ST-39 hereafter) (AER, 2021) to estimate the energy values of the output of the mines. These reports contain data on the monthly and annual stocks and flows of fossil fuel in volume units (m^3)[6] and electricity (in MW) delivered to and out of active mines in the province. ST-39 uses two categories to report the output of mines. 'Deliveries' refers to flows exiting the site. 'Production' refers to fossil fuel produced by mines that can be further used on-site as inputs in production, such as bitumen mined and blended with syncrude before shipping.[7] I use the category 'deliveries' as the mines' output. Because mining facilities deliver other fossil fuels used in mining and blending, (natural gas, naphtha, etc.), these deliveries were incorporated into the mines' inputs and outputs (following Wang et. al., 2019). The $EROI_{ST}$ of diluted bitumen therefore incorporates the energy value of the fossil fuels it is blended with.

2.2.2 Direct energy input

I use data from ST-39 to estimate direct energy inputs. The reports identify 3 possible destinations of energy carriers in open-pit mining : 1) further processing (product undergoing additional processing on-site); 2) delivered (exiting the mine's gate); 3) fuel and plant use (used on-site for other purpose than fuel,

[6] By convention, in Canada, 1 m^3 is 6.2898 barrel (Canada Energy Regulator, 2016).
[7] The definitions were provided to the authors in a private e-mail from the AER and are available upon request.

for example synthetic crude used to lower the viscosity of crude bitumen in blending). On the origin of the carriers, they are reported as either 4) produced on-site or 5) imported to the mine from exterior sources.

The challenge was to select the category accounting for genuine energy inputs according to $EROI_{ST}$ methodology. I seek to avoid double-counting as, for instance, with a fuel delivered on-site and stored to be used as an energy source later. I choose to account for direct energy inputs when energy carriers are reported as being *used as energy or for processing on site but received from off-site*. Using AER's parlance (and following Wang et. al. 2019) three categories of uses for direct inputs were accounted for: inputs used as 1) fuel; 2) plant use and 3) further processing. Following this logic, when a mine reported natural gas undergoing further processing, it was accounted as inputs as it is imported from off-site. Equation (3) represents how I calculate the energy value of direct inputs of mining using these:

$$3)\ E_i = \left(E_f + E_p + E_{fp} \right)$$

Where E_f stands for 'energy used as fuel', E_p stands for 'energy used as plant use' and E_{fp} stands for 'energy further processed from off site', reflecting the categories used the AER's reports.

To estimate the chemical energy of direct outputs and inputs, I report the quantity of energy identified in equation 3 and convert them into thermal (gigajoule) units. Table 1 presents the conversion factors used in this research. Following Delannoy et. al. (2021a: 5), I assume the conversion factors to be constant across the period covered in this study.

Table 1 Conversion factors to convert volumetric units of fossil fuel and electricity to energy values

Name of the fuel and unit of measure	Energy density
Bitumen (in m^3)	42.80 GJ/m^3
Synthetic crude oil (in m^3)	39.40 GJ/m^3
Natural gas (in 10^3 m^3)	37.30 GJ/ 10^3 m^3
Naphtha (in 10^3 m^3)	35.17 GJ/ 10^3 m^3
Coke (in tons)	29 GJ/ton
Electricity (in MW)	3.6 MW

Source: Canada Energy Regulator, 2016; Statistics Canada, 2004 and Alberta Energy Regulator, *Statistical Report* #98; 2021c

2.3 Indirect inputs

A thorough analysis of energy embodied in indirect inputs requires data on the energy spent in the production of these inputs. An important issue to address is boundaries: should one include the energy required in the construction of the infrastructures to produce the inputs? The training of the engineers involved in production? Ideally, such issues are dealt with using Input-Output (I-O) analysis (Miller and Blair, 2009). When energy use estimates are not available, monetary expenditures on inputs can be used when one knows the energy intensity of the sector of the economy these inputs come from. I use a three-step methodology involving the extensive use of two sources of data: the Supply and Use tables and Physical-flow accounts, both generated by Statistics Canada.[8]

Supply and Use tables represent monetary flows among sectors of the economy and are derived from I-O analysis. They somewhat differ from standard I-O analysis which is commodities-based, illustrating how commodities produced by certain economic sectors are used as intermediate inputs or final demand by others, all in monetary units. Supply and Use tables represent the economy as matrix flows of monetary expenditures by sectors, forming sets of symmetric tables where the 'use' tables illustrate the purchase of goods and services as inputs by different sectors (Statistics Canada, 2021a; Miller and Blair, 2009: 186). They divide the economy into sectors/columns (in 2016, 241 sectors) whilst rows divide the economy into sources of inputs (goods and services. In 2016, a little over 490 inputs). Each box represents the monetary expenditure in one sector for the purchase of the input identified in the row.

Over 150 inputs were consumed consistently by the oil sands production sector from 2009 to 2016, i. e. the period during which oil sands extraction is represented in the tables. I used these recurrent inputs in my calculations, thereby excluding occasional expenditures for certain goods or services. I regroup these inputs into four categories of goods and services: 1) Material & Equipment; 2) Transportation: equipment and services; 3) Services and 4) Financial Services.

Finding the monetary value of the inputs in oil sands extraction is straightforward for the years 2009-2016. Starting in 2009, Statistics Canada reports two fossil fuel extraction sectors: 'Conventional oil and gas' and 'Oil sands Extraction'. The monetary values spent by the oil sands extraction sector prior to 2008 can only be estimated as Statistics Canada reports expenditures for the 'Oil and gas extraction' sector only. I estimate the monetary values of inputs used by the oil sands extraction sector prior to 2009 by using the ratios of money (in Canadian dollars) spent in the purchase of each indirect inputs by the oil sands sector

[8] The tables for the years 2008 until 2016 are available on Statistics Canada's website. Tables from 1997 until 2008 were ordered directly to Statistics Canada by the author and received online.

for each year from 2009 to 2016, divided by the total monetary value of inputs spent by the oil sands and the conventional oil and gas sector during the same year:

4) $Share\ of\ input\ 1\ in\ oil\ sands, 2016\ (in\ \$CAN) = \frac{IND_{1-OS}^{2016}}{IND_{1-CON}^{2016} + IND_{1-OS}^{2016}}$

Where ‘$IND_{1\text{-}OS}$’ stands for ‘ $CAN spent for indirect input 1 in the oil sands’ and ‘$I_{1\text{-}CON}$’ stands for ‘$CAN spent for indirect inputs by the conventional oil and gas sector’.

Equation 4 is performed for the 150 inputs consistently purchased by the sector from 2009 to 2016. After, I calculate the mean of the ratios. The means are used as coefficients to calculate the inputs used by the oil sands sector. I multiply the coefficients by the total value of each and every indirect inputs accounted for by the ‘Oil and gas extraction’ sector for years prior to 2009, such as in equation 5. In this example, the average ratio targeted is for 2009 and based on the average of ratios from 2009 to 2010, for illustrative purposes.

$$5)\ IND_{1-OS}^{2009}\ (in\ \$) = \left(\frac{\left(\left(\frac{IND_{1-OS}^{2009}}{IND_{1-CON}^{2009} + IND_{1-OS}^{2009}} \right) + \left(\frac{IND_{1-OS}^{2010}}{IND_{CON}^{2010} + IND_{1-OS}^{2010}} \right) \right)}{2} \right) x\ IND_{1-CON}^{2008}$$

Table 2 provides an example of this methodology for four indirect inputs, providing the share of expenditures in oil sands extraction over total expenditures in the oil and gas sector.

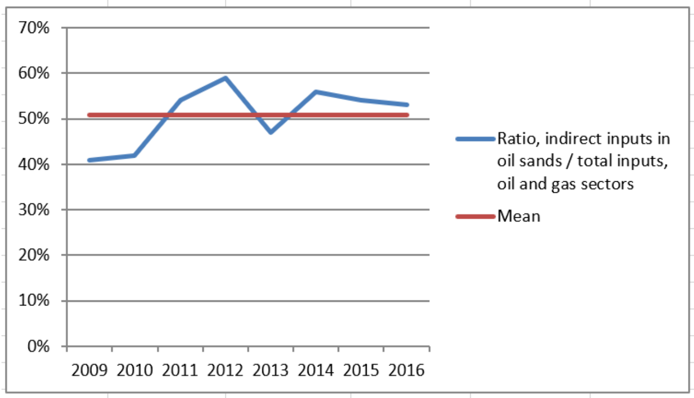
Table 2 Monetary expenditures (in millions of constant 2016 $CAN) by Oil sands extraction (OS) and share (in %) of oil sands expenditures on total oil and gas (conventional oil and gas + oil sands)

	2011		2012		2013		2014		2015		2016	
Input	$ OS	%	$OS	%	$OS	%	$ OS	%	$ OS	%	$ OS	%
Gasoline	75	24	73	21	86	18	75	18	65	19	57	17
Tires	11	64	15	78	38	31	43	45	52	49	41	49
Truck transport services	45	47	52	45	64	55	66	65	57	64	51	64
Investment banking	86	37	77	40	77	38	99	40	55	43	59	45

Sources: Statistics Canada, Supply and Use tables, 2010-2016. Author’s calculations

I calculate the mean of the averages for 159 inputs as reported in figure 10. The average of the different ratios ranges from a minimum of 41% in 2009 to a maximum of 59% in 2012. I assume that the average monetary values of indirect inputs spent by the oil sands extraction sector from 2009 to 2016 for each input are constant, so that the same ratios per input are used for each year from 1997 to 2008. This assumption does not closely reflect reality because of the rapid rise in capital expenditures in oil sands extraction from 1997 (1,914.5 millions of current $CAN in 1997 in in-situ, open-pit mining and upgrading to 11,662 M$CAN in 2018, versus 11,670 M $CAN to 15,822 M $CAN for conventional oil and gas (CAPP, 2021)). Unfortunately, because of the absence of disaggregated data per type of indirect inputs in each sub-sectors, I know of no better method.

Figure 10 Mean ratio (51%) of indirect inputs in unconventional oil over total oil and gas extraction.



Source: Statistics Canada, (2020). Supply and use tables, 2009-2016. Author's calculations.

The monetary values are adjusted for inflation in 2016 constant Canadian dollars using the most general inflation-index available, the Consumer Price Index for the province of Alberta (Statistics Canada, 2021b). The Alberta index is chosen as I am assuming that oil sands mines seek their inputs as close as possible to their installations.

Once the monetary values of the inputs are identified, I multiply them by the energy intensity of the sector of the economy from which their production originates for the corresponding year. Statistics Canada's *Physical-flow accounts* report the energy density of over 100 sectors of the economy in gigajoules spent per every 1,000 current Canadian dollars of production. Since there are more goods and services reported in the Supply and Use tables than the number of sectors in the Physical-flow accounts, I regroup each indirect input from Supply and Use tables into the sector which is, in my best judgment, the closest in the Physical-flow accounts. Using this last set of data, I estimate the embodied energy of indirect inputs used in the oil sands sector (in joules) such as in equation 6:

6) $IND_{1-OS}^{2016} = I_{1-OS}^{2016} \; x \; ED_{1}^{2016}$

Where 'ED_1^{2016}' stands for 'energy density in corresponding sector 1 in the Physical-flow accounts in 2016' (in GJ/$).

The result of equation (6) gives the total embodied energy of one category of indirect input in the oil sands extraction sector as a whole. To isolate the share used in open-pit mining only, further disaggregation is required.

2.4 Estimating the share of indirect inputs in mines producing both diluted bitumen and synthetic crude

My research tries to determine the $EROI_{ST}$ of diluted bitumen and synthetic crude production separately. Consequently, I need an estimate of the indirect inputs used in the production of each.

To estimate these shares, I first identify the quantities of bitumen and synthetic crude produced during the year under analysis. I sum them and divide the share of syncrude and dilbit produced in the year under study by the total. I assume the share of the output of diluted bitumen and syncrude to approximate the share of indirect inputs required by crude bitumen and synthetic crude oil production. In other words: if total oil sands production in 2021 was 40% of bitumen and 60% of synthetic crude, I attribute 40% of indirect inputs to the former and 60% to the latter. This assumption most certainly does not closely reflect reality since syncrude production is more capital intensive. However, to my knowledge, there is no way to precisely disaggregate the share of indirect inputs used in syncrude production based on available data.

I estimated the energy value of indirect inputs for the 2 crude streams by multiplying the total energy value of indirect inputs (see equation 6) by the share of diluted bitumen and syncrude production mined on total to estimate the share of indirect inputs used in the production of each such as in equation 7:

$$7)\ IND_{1-OSb}^{2016} = (IND_{1-OS}^{2016}\ x\ ED_1^{2016}) * \left(\frac{bitumen\ produced\ in\ 2016\ (in\ m^3\ )}{total\ oil\ sands\ produced\ in\ 2016\ (in\ m^3)}\right)$$

Where 'IND_{1-OSb}^{2016}' stands for 'embodied energy in indirect input 1 used in bitumen mining in 2016' and 'total oil sands' refers to the sum of bitumen and syncrude produced in the year under analysos.

The very last step of the methodology involves the attribution of the share of embodied energy of crude bitumen mined through open-pit mining, since I exclude bitumen mined through in-situ mining. As crude bitumen is produced both by open-pit and situ-mining, equation 7 does not reflect the indirect inputs necessary for each crude type.

I first report the total crude bitumen produced in the year under analysis using data from the Alberta Energy Regulator Statistical reports #3 (ST-3). I divide the quantity of bitumen produced through open-pit mining by the total quantity of bitumen produced in the year analyzed as in equation 8

$$8)\ IND_{1-OS-bop}^{2016} = (IND_{1-OS}^{2016}\ x\ ED_{1}^{2016}) * (\frac{bitumen\ produced\ (in\ m^3\ )}{total\ oil\ sands\ produced\ (in\ m^3)})) * \frac{open\text{−}pit\ bitumen\ (in\ m^3)}{total\ bitumen\ mined\ (in\ m^3)}$$

Where '$IND_{1-OS-bop}^{2016}$' stands for 'embodied energy in indirect inputs used in open-pit bitumen mining'.

The EROI of one crude slate in then calculated using the result of equation 8 to the 150 inputs under study in the denominator:

$$9)\ EROI_{ST} = \frac{E_o}{\left(E_i + IND_{1-OS-bop}^{y} + IND_{2-OS-bop}^{y} + IND_{3-OS-bop}^{y} + IND_{n-OS-bop}^{y}\right)}$$

3. Theory/Calculation

This section presents an example of the method outlined in section 2 for the years 2008 and 2016.

3.1 Energy output and direct energy input:

Table 3 shows how to estimate the energy value of energy outputs by converting data on the deliveries of energy carriers from mines from volume into energy units using data from Suncor, the largest oil sands mine by output in 2008 and 2016:

Table 3 Energy value of output, Suncor, 2008, 2016:

Mine's name	Type of output and use	Quantity (in physical units)	Energy density (in TJ)	Type of output and use	Quantity (in physical units)	Energy density (in TJ)
	2008			2016		
Suncor	Synthetic crude delivered	13,155,517 m^3	518,327	Synthetic crude delivered	16,136,913 m^3	635,794
	Bitumen delivered	140,789 m^3	6,026	Bitumen delivered	6,710,528 m^3	287,211
	Diluent naphtha delivered	1,148,689 m^3	41,008	Diluent naphtha delivered	2,707,175 m^3	95,211
	Process gas delivered	303,140 10^3 m^3	11,307	Process gas delivered	818,534 10^3 m^3	30,531
	Electricity exported	1,322,417 MW	4,761	Electricity exported	2,757,5861 MW	9,927
	Natural gas delivered	591,900 10^3 m^3	22,427	Natural gas delivered	13,077 10^3 m^3	495

	Coke delivered	344,653 MW	9,995	Coke delivered	307,784 tons	8,926
Total output (in TJ)			613,851			1,068,095

Source: ST-39, 2016

Estimating the energy value of direct inputs was done following the same process. I exclude the embodied energy of bitumen processing for now to discuss the issue of whether to incorporate it or not in $EROI_{ST}$ estimations in the discussion section:

Table 4 Energy value of input, Suncor, 2008, 2016:

Mine's name	Type of output and use	Quantity (in physical units)	Energy value (in TJ)	Type of output and use	Quantity (in physical units)	Energy value (in TJ)
	2008			2016		
Suncor	Bitumen – further processed	16,837,218 m^3	720,633	Bitumen – further processed	19,268,578 m^3	824,695
	Process gas used as fuel	504,086 10^3 m^3	18,802	Process gas used as fuel	702,809 10^3 m^3	26,215
	Coke used as fuel	845,945 tons	24,532	Coke used as fuel	452,146 tons	13,112
	Synthetic crude used as fuel + plant use	283,761 m^3	11,180	Synthetic crude used as fuel	311,674 m^3	12,280
	-			Synthetic crude – Plant use	40,281 m^3	1,587
	Natural gas – further processing	368,542 10^3 m^3	13,964	Natural gas – further processing	391,779 10^3 m^3	14,845
	Natural gas used as fuel			Natural gas used as fuel	1,008,258 10^3 m^3	38,203
	Natural gas – plant use	1,140,976 10^3 m^3	43,232	Natural gas – plant use	8,760 10^3 m^3	332
	Electricity purchased	5,124 MW	18	Electricity purchased	2,296,351 MW	8,267
Total input			111,855			114,840

3.2 Indirect energy input

Estimating the embodied energy of indirect inputs is a three-step process: 1) indirect inputs used in oil sands extraction are identified; 2) their monetary values are converted in 2016 $CAN; 3) multiplied by the energy intensity of the sector for the year under study. Table 5 below exemplifies my method with 8 inputs from the four different categories of indirect inputs.

Table 5 Energy density of indirect inputs used in the oil sands extraction sector in 2016

Category of input	Name of the input	Monetary value of the input, in current 1,000 Canadian dollars	Name of the closest sector in the Physical-flow accounts	Energy density of the sector (GJ/1000$ of production at basic prices)	Embodied energy of the input, in TJ
Material and equipment	Diesel and biofuels products	215,855	BS32400 Petroleum and coal products manufacturing	16.74	3,054
	Iron and steel pipes and tubing	487,492	BS33200 Fabricated metal products manufacturing	8.06	2,737
	Logging, mining and construction machinery and equipment	1,014,130	Support activities for mining and oil and gas extraction	5.80	3,236
Transportation and services	Freight transportation arrangement and custom brokering services	347,352	Transit, ground passenger and scenic and sightseeing transportation, taxi and limousine services and support activities for transportation	5.63	1,4231
Services	Support services for oil and gas extraction (except exploration)	2,315,417	Support activities for mining, and oil and gas extraction	7.44	14,942
	Architectural, engineering and related services	1,727,034	Legal, accounting and architectural and engineering and related services	2.22	2,234
	Office administrative services	629,144	Administrative and support services	2.50	826
Financial services	Holding company services and other financial investment and related activities	1,509,821	Other finance, insurance, real estate services and management of companies and enterprises	3.39	6,794

	Deposit intermediation services indirectly measured	218,112	Depository credit intermediation and monetary authorities	3.39	661

Source: Statistics Canada, Supply and Use table, 2016 and Phyiscal-flow accounts, Direct plus indirect energy and greenhouse gas emissions intensity, by industry (Table 38-10-0098-01)

I have shown above that Supply and Use tables disaggregate monetary expenditures in inputs for conventional oil and gas and oil sands extraction from 2009 to 2016 only. Estimating the energy value of the inputs from 1997 to 2008 therefore require: 1) identifying the monetary value of expenditures in the oil and gas extraction sector in the year under analysis and convert in constant 2016 $CAN and 2) performing equations 4 to 6:

Table 6 Approximate monetary value of the indirect inputs in the unconventional oil sands sector in Canada in 2008 (in 2016 constant $CAN)

Category of input	Name of the input	Monetary value of the input, Oil and gas extraction (in constant 1,000,000 $CAN)	Average value (in %) of inputs in non-conventional / total oil and gas sector, 2009-2016 (in %)	Name of the closest category: physical-flow accounts	Energy density of the sector (GJ/1000$ of production at basic prices)	Embodied energy of the input, in TJ
Material and equipment	Diesel fuel	424	43	Petroleum and coal product manufacturing	16.74	3,054
	Iron and Steel pipes and tubes (except casting)	970	35	Fabricated metal product manufacturing	8.06	2,737
	Logging, mining and construction machinery	1,094	51	Machinery manufacturing	5.80	3,236
Transportation and services	Freight transportation arrangement and customs brokering services	383	66	Scenic and sightseeing transportation and support activities for transport	5.63	1,4231
Services	Support services for oil and gas extraction	6,276	32	Support activities for mining and oil and gas extraction	7.44	14,942

	(except exploration)					
	Architectural, engineering and related services	1,727	56	Architectural, engineering, legal and accounting services	2.22	2,234
	Office administrative services and head office services	1,376	24	Administrative and support services	2.50	826
Financial services	Holding company services and other financial investment and related activities	4,175	48	Other finance, insurance and real estate services and management of company and enterprises	3.39	6,794
	Deposit intermediation services indirectly measured (FISIM)	487	40	Other finance, insurance and real estate services and management of company and enterprises	3.39	661

Source: Supply and Use table, 2002-2016 and Phyiscal-flow accounts, Direct plus indirect energy and greenhouse gas emissions intensity, by industry (Table 38-10-0098-01). Author's calculations

Embodied energy values must be further disaggregated for the embodied energy of inputs used in the production of syncrude and crude bitumen respectively. This is done by multiplying the total energy value of indirect inputs by the share of the 2 crude streams from total production. In 2008, 45.73% of oil sands production (in m^3) was bitumen. The share had risen to 61.51% in 2016 (Alberta Energy regulator, Statistical Report #3, 2008; 2016). After the respective share of total production are identified, the embodied energy per type of input is multiplied by crude stream (equation 7):

Table 7 Estimation of the share of embodied energy in indirect inputs for crude bitumen, 2008 2016

Category of indirect inputs	Total embodied energy, oil sands, in TJ	Share of bitumen in total oil sands production, in %	Share of total embodied energy, diluted bitumen producing mines, in TJ	Total embodied energy, oil sands, in TJ	Share of bitumen in total oil sands production, in %	Share of total embodied energy, diluted bitumen producing mines, in TJ
	2008			2016		
Financial services	9,149		4,184	5,046		3,104

Services	35,603	45.73%	16,281	36,168		22,247
Material and equipment	21,962		10,043	29,302	61.51%	18,024
Transport	6,548		16,281	15,525		9,382
Total	73,262		37,056	86,041		52,757

Finally, the share of crude bitumen produced via open-pit mining was isolated by identifying the share of total crude produced via open-pit mining and in-situ mining. In 2008, 34.68% of crude bitumen was produced via open-pit mining. The share had risen to 45.38% in 2016. Thus, I use the ratios found in Table 7 to further disaggregate:

Table 8 Share of energy value for bitumen produced via open-pit mining: 2016

	Energy value of the inputs, Oil sands sector (in TJ)		Share of bitumen, oil sands		Share of energy value of the inputs for bitumen (in TJ)		Share of bitumen produced by open-pit		Share of energy value for bitumen produced via open-pit (in TJ)	
	2008	2016	2008	2016	2008	2016	2008	2016	2008	2016
Financial services	9,149	5,046			4,184	3,104			1,451	1,402
Transport	6,548	15,525			6,548	9,382			2,271	4,237
Material and equipment	21,962	29,302	45.7%	61.5%	10,043	18,024	34.68%	45.2%	3,483	8,139
Services	35,603	36,168			16,281	22,247			5,646	10,047
Total	73,262	86, o41			37,056	52,757			12,851	23,825

Now I estimate the EROI of crude bitumen and syncrude at the mine's mouth. Table 3 and 4 applied to Suncor only whereas tables 7 and 9 applied to 9 inputs only. As my calculations involved total bitumen mining, I provide here the data obtained after summing the energy output and direct input for the whole mining sector:

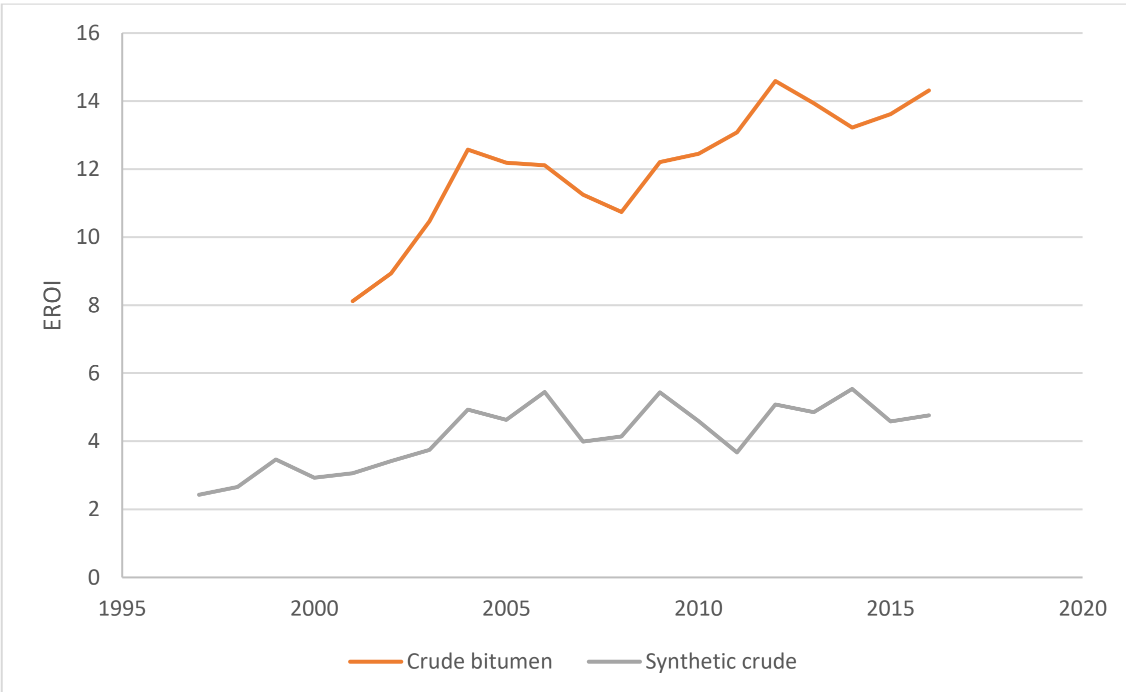
10) $EROI_{ST}^{2016} diluted\ bitumen = \dfrac{1{,}801{,}462}{(\ 101{,}943 + 23{,}941)} = 14.31$

11) $EROI_{ST}^{2008} diluted\ bitumen = \frac{773{,}705}{(60{,}414+12{,}851)} = 10.56$

4. Results

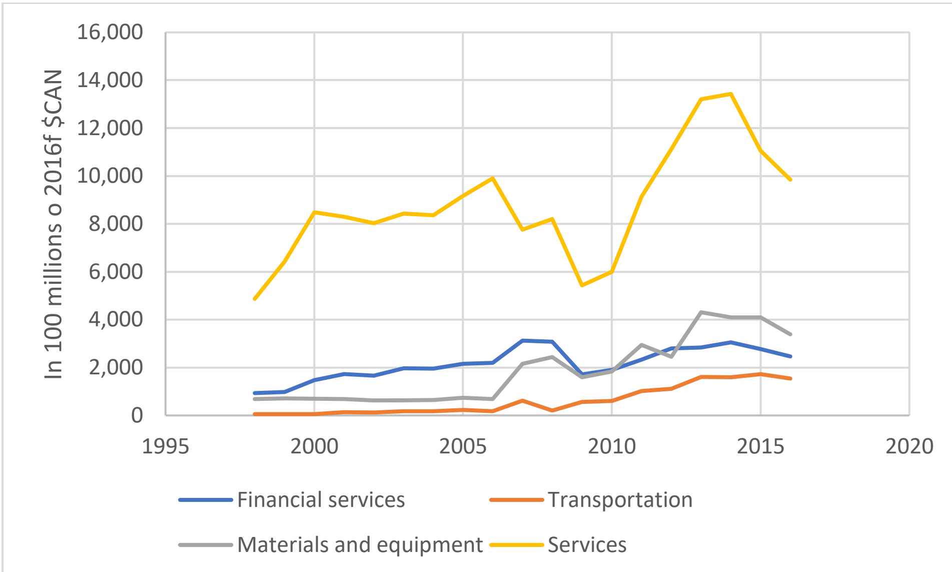
Figure 11 presents the $EROI_{ST}$ ratios for synthetic crude and diluted bitumen production produced through open-pit mining in Alberta from 1997-2016 using the $EROI_{ST}$ method:

Figure 11 $EROI_{ST}$ of synthetic crude (in orange) and diluted bitumen (in blue) production from 1997 to 2016 (annual measures)



The average EROI for syncrude across the period is 4.30 : 1 and 12.11 : 1 for diluted bitumen. To reflect the increasing EROI and output of diluted bitumen across the period, I calculate the weighted average EROIst of diluted bitumen to be 13.02 : 1 In comparison, the weighted average is 4.45:1 for syncrude. Figure 11 shows the difference in the $EROI_{ST}$ ratios for diluted bitumen and synthetic crude to be significant and slightly increasing over time. The $EROI_{ST}$ of synthetic crude reaches a peak of 5.54 in 2014 whereas diluted bitumen's $EROI_{ST}$ reaches its peak of 14.59 in 2012 and increases steadily over the period. This result can be understood in relation with the data on total syncrude and bitumen production presented in figure 1. Indeed, I believe the increase in the $EROI_{ST}$ of crude bitumen to be a function of its rapidly increasing production in comparison with relatively constant monetary expenditures (in constant 2016 $CAN) in indirect inputs over the period (in figure 12). Monetary expenditures are constant for 3 of the four groups of indirect inputs, except for services, the expenditures for which nearly double in the year after the global financial crisis. However, the induced difference in embodied energy does not explain the variations observed in figure 12. Indeed, the average embodied energy of services is 2.96 GJ/1000 $CAN in comparison with 8.45 GJ/1000 $CAN for material and equipment, 9.16 GJ/1000 $CAN for transportation equipment and services and 1.73 GJ/1000 $CAN for financial services.

Figure 12 Monetary expenditures in inputs in the Oil Sands Extraction sector, 1998-2016, in millions of 2016 constant $CAN



Furthermore, the increase is consistent with the tendency for the $EROI_{ST}$ of oil and gas to increase during the early years of activity of a mine observed in the literature (Hall et. al., 2014: 146). I estimate the energy value of crude bitumen processed into synthetic crude and included it in a third measure of EROI. Unlike other inputs, to simply convert 1 m^3 of crude bitumen by its equivalent chemical energy is insufficient. Syncrude production involves the mining of crude bitumen and its upgrading. The challenge is to account for bitumen as an input without calculating the total chemical energy in crude bitumen as the direct energy input, since a significant portion of that chemical energy is preserved in the output. I address this issue by calculating the energy input embodied into crude bitumen processed by the heat loss incurred through processing. To do so, I first calculate the chemical energy of bitumen further processed into synthetic crude. After, I calculate the energy of synthetic crude produced in each syncrude-producing mine (Canadian Natural Resources Limited, Syncrude Mildred Lake and Suncor). The difference between the chemical energy of crude bitumen processing and synthetic crude produced is roughly equal to the heat loss of the bitumen-input. Mathematically,

12) $HL_S = Bitumen\ processed\ (in\ tj) - (1 - (\frac{syncrude\ produced\ (in\ tj)}{bitumen\ processed\ (in\ tj)})$

The heat loss involved in syncrude production (HL_S) is then added to the direct energy inputs E_i of syncrude production. Equation 3 for syncrude production thus becomes:

$$13)\ E_i = (E_f + E_p + E_{fp} + HL_S)$$

For example, in 2016, I estimate the processing of 46.44 millions of m^3 of bitumen into syncrude resulted in a heat loss of 306,149 TJ. Therefore, the $EROI_{ST}$ of syncrude production in 2016 according to this method was:

$$14)\ EROI_{ST}^{2016}\ syncrude = \frac{1{,}693{,}272}{(321{,}997 + 306{,}159 + 33{,}569)} = 2.09$$

I argue that equation 14 captures the energy value of bitumen as an input to syncrude production. I found the heat loss to vary little across mines except for Suncor. Indeed, if the average heat loss across the 1997-2016 period at Suncor is 34.57%, a closer examination shows the average to be almost 50% between 1997-2003 and then declines to a comparable level with the 2 other mines. This difference may reflect the introduction of new upgrading technologies and different levels of energy efficiencies. The data I consulted for this research do not allow any other explanation.

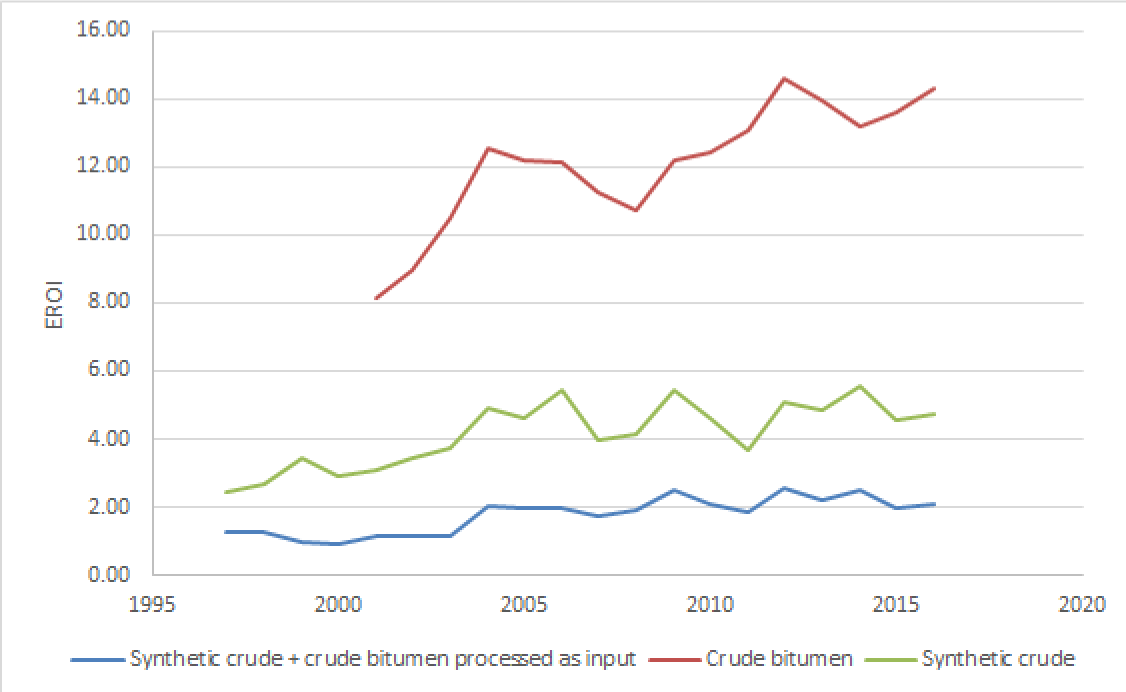
Table 9 Average heat loss of crude bitumen processed into syncrude for syncrude-producing mines, 1997-2016

Mine	CNRL	Syncrude	Suncor		
Time period	1997-2016			1997-2003	2004-2016
Energy input of processing (Bitumen (in tj) – Syncrude (in tj)	21.41%	21.67%	34.57%	49.82%	26.38%

Source: AER, ST-39 1997-2016. Author’s calculation.

As shown in figure 13, including crude bitumen processing as an input to syncrude production bears an important impact on the EROIst of synthetic crude production. The ratio drops from a weighted average of 4.45 : 1 to 1.86 : 1 across the period. For 1998 and 1999, the $EROI_{ST}$ ratio is barely positive, meaning syncrude production was close to be an energy sink.

Figure 13 EROIst ratios with syncrude including crude bitumen processing as an input



6. Discussion

This section concludes my paper with a discussion of how my analysis adds to, or differs from previous research, its limitations and areas of future research. My results on the trend of $EROI_{ST}$ of oil sands do not diverge significantly from those found in the literature. My estimates on the $EROI_{ST}$ of syncrude are close to those of Poisson and Hall. They, as well as Wang et. al., and Brandt et. al., and myself, identified an upward trend over the period covered in their study. I believe that the recent history of oil sands extraction and crude bitumen mining explains this upward trend. Massive capital investments in the late 1990s and early 2000s have declined since the mid-2000s, with production now benefiting from earlier capital investments. A hypothesis complementing this interpretation is that recent development of mining facilities *might* mean improvements in productivity (rising output over constant indirect inputs) over the period, meaning superior output over constant indirect inputs.

I argue that my results are more robust than those found in previous studies on the EROI of oil sands. Whereas Poisson and Hall estimate the net-energy ratio of syncrude only, my study includes crude bitumen. Due to the absence of financial data on the purchase of indirect inputs in the sources used by Brandt et. al. (2013) (AER Statistical Reports #39 and 43), the authors had to estimate the financial value and energy intensity of indirect inputs. With my primary sources, I am able to use publicly-available data on the monetary expenditures in indirect inputs. Furthermore, I use the physical-flow accounts to identify the energy intensity of the sectors of the Canadian economy from which these inputs arre produced. Finally, the data I consult are more recent.[9] I believe my data are more precise than Wang et. al. Indeed, due to data limitations at the moment of writing[10], they did not use disaggregated expenditures in indirect inputs in the oil sands sector, rather using the energy intensity of the total oil and gas extraction sector as a proxy. Instead, I am able to estimate them using primary sources from 2009-2016 and via a prorationing method prior to 2009 as shown in section 2.4.

The results presented in this paper are limited in many ways. First, whereas synthetic crude production started in Alberta in the late 1960s, the first mine to produce diluted bitumen only, Syncrude Aurora, became operational in 2001. Consequently, considerably less data is available for interpretation for trends in diluted bitumen production, a problem only time can help address. Second, I am not able to estimate the EROI of oil-sands derived crude at the point of use ($EROI_{pou}$) by society. $EROI_{pou}$ is a more comprehensive measure of net energy that incorporates into the denominator the energy costs associated with producing and delivering end-use products to consumers, such as gasoline for car driving. Further research should include the net-energy of refining processes and transport of oil sands-derived products further downstream. Such studies would inevitably find a lower $EROI_{pou}$ value than the $EROI_{ST}$ estimated in this paper (Hall et. al., 2014: 142). Hall et. al. shows that refining uses approximately 10%-equivalent of energy in a barrel of crude, minus a further 17% of a barrel's output which ends up as non-fuel products. Furthermore, an additional subtraction of 0.52 MJ per-ton mile of crude for pipeline transport must be included in the denominator to account for $EROI_{pou}$. (2009: 39-40). To engage on this research avenue, high quality data exist for the Canadian refining sector in supply and use tables. Whereas very good data exist on the import of Canadian crude across the various PADD's in the United States (EIA, 2021), no data exist (to my knowledge) on the output generated from Canadian import disaggregated by crude streams (conventional and oil sands), nor are there data available on the indirect inputs used by U.S. refineries. I am therefore skeptical that meaningful research can be produced soon on the $EROI_{pou}$ of oil sands-derived end-products in the United States.

My results could be improved by using more realistic ratios of indirect inputs used in the oil sands industry vis-à-vis conventional oil and gas across time, thereby allowing to prorationate the share of indirect inputs

[9] The latest data available to Brandt et. al. were from 2010.

[10] Authors mention the most recent data available on CANSIM were from 2013 (p. 829).

used by oil sands extraction from 1997 to 2008 (see table 6) more realistically or when prorationing for the share of indirect inputs used in crude bitumen mining (see table 8). Realistic comparisons of capital, financial and services expenditures in in-situ and open-pit mining would allow more precise estimations of the embodied energy of indirect inputs used in these operations.

My study assumes energy conversion ratios of energy carriers to be constant (see Table 1). However, concentration of chemical energy in different fossil fuels (natural gas, bitumen, etc.) is known to vary across time and place: more precise estimates would use empirically validated energy conversion ratios for direct inputs. Finally, as shown in section 2.4, I assume the ratio of expenditures in indirect inputs observed from 2009 to 2016 in the conventional and unconventional oil production sectors to be constant. To my knowledge, no dataset exists that would allow me to propose a more realistic assumption. For all these reasons, a margin of error certainly exists in my results, although I am unable to quantify it at the present time.

I conclude this paper with a paradox to be further explored in future research. I have shown that should we include crude bitumen processing as an input to syncrude production, the $EROI_{ST}$ of syncrude reaches a peak of 2.57 : 1 in 2012. This results means that only 61% of the chemical energy of syncrude leaves at the mine-mouth when accounting for the energy costs of producing it. This result is comparable with the EROI of shale oil (Cleveland and O'Connor, 2011) or of corn-based ethanol (Hall et. al., 2011). Should my results be accurate, it would mean this crude stream does not meet the 3:1 threshold required to maintain the complexity of a modern economy. Thus, syncrude extraction and refining might exist thanks to energy subsidies from conventional oil and gas, since the refining, transportation and use (roads, bridges, etc.) infrastructures of fossil fuels exist thanks to fossil fuels whose $EROI_{ST}$ is superior to 3:1 (Hall et. al., 2009: 45). However, as a lighter source of crude, it fetches a higher price on the market than diluted bitumen does, therefore raising the issue of the relationship between EROI and profitability, to be carried out in future research. A few authors have studied the relationship between EROI and profitability of crude oil. King and Hall (2011) shows that all else equal, a theoretical relationship between EROI and profitability exists whereby at a given EROI, an increase in the energy intensity of investment in fossil fuel production implies that a lower price of energy can prevail on the market for profitable production to occur (2011: 1818). Empirically, Wang et. al. compared the return on equity and $EROI_{ST}$ of four oil sands companies' output of oil-sands derived crude. They find that no significant relation exists between the two. Because energy production occurs in an economic context where private and public energy-producing companies must generate profit to survive, I argue that purely energy-based indicators won't help to predict the behavior of actors on the market. Furthermore, despite its lower $EROI_{ST}$, syncrude is a more useful type of crude than bitumen, as the former can be sold directly to refineries. More studies are required to shed light on this seeming paradox between EROI, energy quality, price and profit.

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Declaration of competing interest

The author declares he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix I

List of symbols

Symbol	Description	Unit
E_i	Direct energy input	Joule
E_O	Energy output	Joule
IND_i	Indirect energy input	Joule
$EROI_{ST}$	Standard EROI	Joule
E_f	Energy used as fuel	Joule
E_p	Energy used as plant use	Joule
E_{fp}	Energy further processed from off-site	Joule
IND_{x-OS}^{y}	Money spent in the purchase of input x by the oil sands industry in year y	$CAN
IND_{x-CON}^{y}	Money spent in the purchase of input x by the conventional oil industry in year y	$CAN
IND_{1-OS}^{y}	Energy value of indirect input 1 used in the oil sands sector in year y	Joule
ED_{1}^{2016}	Energy density of sector 1 of the Canadian economy (reported in the Physical-flow accounts)	Joule/$CAN
IND_{1-OSb}^{y}	Energy embodied in the indirect input 1 used in bitumen production	Joule
$IND_{1-OS-bop}^{y}$	Energy embodied in the indirect input 1 used in bitumen produced via open-pit mining	Joule