The Economic Impact of Environmental Innovation

In Canada's Oil Sands—

Economic Concepts and Case Studies

Final Report

Prepared for

The Canadian Association of Petroleum Producers

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Contents

Summary

Innovation and environmental management activities in the oil sands are significant, as they are directly related to the scale of production activities. This study analyzed the economic impact of environmental innovation in Canada's oil sands, both globally and through case studies. It consists of three parts: 1) a review of the literature on integrating environmental innovation into the business value chain; 2) an examination of economic and environmental performance indicators; 3) and the analysis of five environmental innovation cases: caribou habitat restoration; satellite measurement of GHG emissions; use of virtual sensors to improve steam; capture and injection of CO_2 in production residues; and a gas turbine attached to steam injectors. Overall, these five innovations have increased business revenues, lowered production costs and created jobs. The projects examined have potential applications beyond oil sands production; however, in only two cases were steps taken to make these opportunities a reality. The sharing of knowledge and publication of the results obtained provides a definite opportunity for a number of Quebec industries to explore these innovative solutions. Examples of those industries include forestry, mining, heavy manufacturing, environmental management, non-residential construction, as well as civil and industrial engineering.

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Abstract

Environmental innovation and management at the oil sands are significant, because they are directly related to the extent of production activities. This study analyzed the economic impact of environmental innovation at Canada's oil sands, both globally and through case studies. It consists of three parts: a literature review on the integration of environmental innovation into the business value chain; a review of economic and environmental performance indicators; and the analysis of five cases of environmental innovation: restoration of caribou habitat; satellite measurement of GHG emissions; the use of virtual sensors to improve steam quality; injection and capture of CO_2 in production residues; and a gas turbine attached to steam injectors. Together, these five innovations have increased business revenues, reduced production costs and created jobs. The projects reviewed had potential applications beyond the oil sands; however, only two of them had initiated actions to follow-up on these opportunities. Knowledge sharing and the publication of results constitute a definite opportunity for several economic sectors in Quebec to explore these innovative solutions, for example in forestry, the mining sector, the heavy manufacturing industry, environmental management, non-residential construction, as well as civil and industrial engineering.

1. Terms of Reference

The Canadian Association of Petroleum Producers (CAPP) commissioned AppEco to analyze the economic impact of environmental innovation in Canada's oil sands, using both macroeconomic data and case studies. The specific objectives of this study are to:

- Present economic concepts for integrating environmental innovation into the business value chain;
- Examine the economic and environmental performance of Canada's oil sands since 2005;
- Describe the economic activities and outcomes of five cases of environmental innovation in Canada's oil sands;
- Explore the extent to which environmental innovations such as those identified in the case studies can contribute to improving the environmental performance of Quebec industries that have large work forces.

Besides this introduction, this report has five (5) sections. Section 2 presents the study's methodology. Section 3 provides an overview of the economic principles associated with the value chain and the environmental innovation mechanisms that can improve both the economic and environmental performance of companies. Section 4 presents recent statistics on overall economic and environmental performance in the oil sands, both before and after the creation of Canada's Oil Sands Innovation Alliance (COSIA).[1] Section 5 presents the five environmental innovation case studies, as well as the opportunities these innovations represent for Quebec. Section 6 presents the conclusion of this analysis.

AppEco prepared this report independently, without any direction or influence. While benefiting from the relevant suggestions of various stakeholders during its preparation, the analysis, findings and conclusions of this report were developed freely. Therefore, AppEco is entirely responsible for any errors or omissions this report may contain.

[1] COSIA is an organization of oil sands producers whose objective is to accelerate the improvement of environmental performance in Canada's oil sands through collaboration and innovation. Created in March 2012, COSIA brings together experts from industry, government, academia and the general public to improve environmental measurement, accountability and performance in the oil sands in four priority areas: greenhouse gases, soils, water and tailings.

2. Methodology

The analysis combines results from three work stages:

- ***Review of the literature:*** various articles on the economic principles of operational and financial value chains and their environmental management components were collected and reviewed. Their main points were extracted and are presented in the next section. In addition, a summary table of the sources consulted was developed, including the author, the complete citation, the full summary and the comments linking those studies to this report;

- ***Collection and analysis of official statistics***: official sources of data on the environmental and economic performance of the oil sands were consulted to highlight the key indicators available. In several cases, only qualitative indicators were available; accordingly, a summary of major findings is presented;

- ***Case studies***: to illustrate the processes by which environmental innovations occur, their outcomes, and their potential applications beyond the oil sands industries, the activities and results of five environmental innovation projects were analyzed. In this context, AppEco and CAPP have worked with COSIA to identify the most relevant projects to study. The work steps were: contacting the identified companies to confirm their participation; developing two questionnaires, one requesting qualitative responses regarding the project description, the environmental sectors affected, the origin of the innovation, its impacts on the activities and organizations involved, as well as the future aims of the innovation in the oil sands and elsewhere; and a second questionnaire requesting quantitative data on the environmental and economic performance of these innovations, presented in aggregate form to preserve the confidentiality of responses; and analyzing the results. The list of participants, the two questionnaires and the complete qualitative responses are presented in the Appendix.

3. Economic Principles of Environmental Innovation in the Oil Sands Value Chain

Economy and Environment in the Oil Sands

The opposition between the economy and the environment is a false debate. Like physics, philosophy or biology, economics is simply a way of observing and understanding the world around us. Accordingly, it is neither favourable nor harmful to the environment; it is an integral part of it. By definition, all economic activity generates a certain production of goods or services, which has a certain monetary value and comes with a certain resource cost (human, natural, technological, environmental, etc.) necessary to achieve it. Therefore, the economy and the environment are two pervasive and interrelated realities, not two competing concepts.

In this context, oil sands production generates considerable economic value, creating thousands of high-quality jobs. In return, like other heavy industrial activities, it has a significant environmental footprint. This necessarily involves extensive environmental management efforts to minimize its magnitude, both during and after the production process, particularly for the full restoration of the areas exploited. Moreover, the scale of these efforts provides a great deal of opportunity for innovation, while the slightest improvement in operational efficiency becomes profitable thanks to economies of scale. In addition, some of the innovations developed for the oil sands could have a positive impact on other industries.

In recent years, oil sands production has occurred in the context of growing concerns about global warming, a significant part of which is related to the use of hydrocarbons in several sectors of our societies. As a result, the coming decades may see a gradual "decarbonisation" of the economy in favour of renewable energy. Of course, the proportion of renewable energies used in the total consumed will increase in the coming decades. That said, realistic scenarios also predict that global oil demand will increase over the same period, until 2040. The use of oil for cars will peak in the mid-2020s, particularly with the increased presence of electric vehicles, but demand from the petrochemical, trucking, aircraft and shipping sectors will support overall growth through 2040.[2] In this context, Canadian oil companies are expected to continue upgrading existing resources, while redoubling their efforts to reduce their environmental footprint as much as possible, hence the critical importance of innovation.

The following paragraphs outline the economic mechanisms for integrating innovation into the day-to-day environmental management of these companies. The sources cited are listed in Appendix 1.

[2] International Energy Agency, World Energy Outlook 2018: https://webstore.iea.org/download/summary/190?fileName=English-WEO-2018-ES.pdf.

Value Chains: Core Principles

Environmental management activities are integrated into the production processes of companies, also known as "value chains." In fact, there are two simultaneous value chains: first, the operational value chain, which describes the sequence of steps in the production of a given good or service; and second, the financial value chain, which is the net dollar value each of these steps adds to the economic performance of the producing business.

According to Gereffi and Fernandez-Stark (2016), value chain analysis was originally limited to research on firm competitiveness in manufacturing industries. However, the body of knowledge accumulated over time on the importance of value creation at each stage of production has expanded and it can now inform investment decisions, guide growth opportunities and foster innovation or the exploitation of new niches.

Various authors have explored the conceptual aspects linked to value chain management. Firstly, Wagner et al. (2012) found that supply chain management is effective when companies effectively adapt to uncertainty about demand for their products and the resulting customer needs. The more the logistics chain is well adapted to these unexpected changes in supply and demand conditions, the fewer resources will be wasted and the greater will be the company's return on investment.

In a similar vein, Holweg and Helo (2014) note that the architecture of the value chain can change over time, as new business strategies are adopted to deal with market vagaries and spontaneous challenges. Moreover, Lind (2012) believes that managing working capital is an integral part of a company's short-term financing. Effective working capital management for each link in the value chain allows a company to free up capital for more strategic purposes, reduce costs and improve profitability.

Environmental Management and Value Chains

Environmental management and clean-up steps are an integral part of the value chains of all industrial companies, including those in the oil sands. Traditionally, these steps have been seen as private cost items that generate public benefits; therefore, companies have not tapped into them very much. However, these companies are increasing efforts to innovate in environmental matters, both to improve their performance and to reduce costs.

In fact, researchers have recently shown that environmental benefits are not incompatible with financial profitability goals, quite the opposite (Breyer et al., 2015). They quantified the benefits of incorporating renewable energy conversion technology into the integrated value chain of a large pulp and paper company in Finland. The results of the analysis showed that the technology was highly profitable for the company, which could in some circumstances generate a 100% return on the cost of that specific investment. However, the authors stress that in order to be economically sustainable and profitable, this technology had to be fully integrated into the company's value chain.

Outcome Measurement and Collaboration

Companies are increasing efforts to improve the measurement of their environmental effects and practices, even beyond their regulatory obligations. In fact, over the past few years, more companies have committed to publishing environmental reports, in addition to annual financial reports. While the publication of such reports remains voluntary, a growing number of companies are adhering to such transparency principles. Researchers found that 80% of the oil companies studied published reports on their sustainable development practises (Cunha and Moneva 2016).

A review of the literature also shows that societal value and benefits are just as likely, if not more so, to be created in the oil sector when private companies are at the heart of resource exploration and exploitation, as opposed to nationalization contexts that can stifle incentives to innovate, both environmentally and operationally (Tordo et al. 2011). This is precisely the case in the oil sands, where producers created COSIA to stimulate environmental innovation and share the fruits of these innovations across the industry. Through this open-source collaborative approach, COSIA is working to identify new technologies or approaches that may have been created in areas besides the oil sands, but can be integrated to fill some gaps. Anyone can submit an idea to COSIA through its Environmental Technology Assessment Portal (E-TAP), from multinational employees to inventors working in their garage.

Since COSIA'S creation in 2012, its member companies have shared 981 distinct technologies and innovations, for a total development cost of $1.4 billion. In 2017 alone, the organization had 308 active projects with a total value of $545 million. COSIA is also partially funding the $20 million international NRG COSIA Carbon Xprize competition to develop innovative techniques that convert CO_2 into high-value products. This kind of innovation has applications well beyond the oil sands and is likely to benefit any country, sector, company or individual producing CO_2.

In short, it is entirely logical to talk about both environmental management and economic profitability, insofar as innovation can ensure that (a) the same expenditure produces a better result; (b) a particular outcome is achieved by spending less; or (c) a combination of both. As such, the full integration of environmental management into the value chain of oil sands companies, the magnitude of these activities and economies of scale in this industry, and the common and public commitment to fund environmental innovation in all its forms are positive and promising, not only for this industry but for Canadian society in general.

4. Economic and Environmental Performance

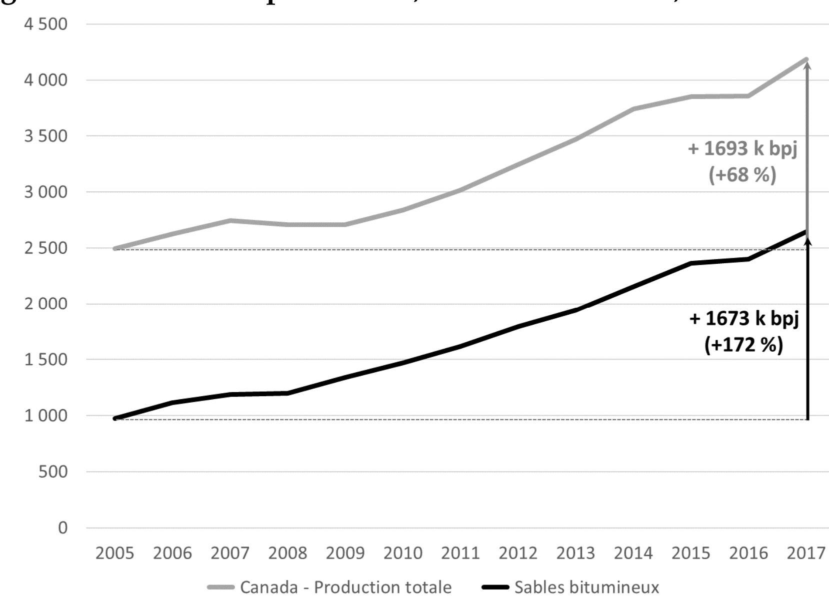
This section summarizes the broad outlines of the economic and environmental performance of the oil sands since 2005. It was developed using public data available from Statistics Canada, Environment Canada and Natural Resources Canada, as well as CAPP's production data for oil and gas producers.

In the first place, if all the data necessary to present the industry's economic performance exist, this is not the case for environmental performance. Indeed, few indicators are available to support the anecdotal evidence that significant efforts have been made to minimize the environmental effects of production. In some cases, it is even a matter of reversing past disturbances, for example when natural habitats are completely restored. Nevertheless, the data available to characterize these two components, as well as some information that complements this picture, are presented below.

Economic Performance

Figure 1 illustrates the comparative growth in oil sands production and that of Canada as a whole from 2005 to 2017. Over the period, oil sands production grew very rapidly, at 172% in just over a decade. Virtually all of the increase in Canadian oil production over the past decade is attributable to the growth in the oil sands.

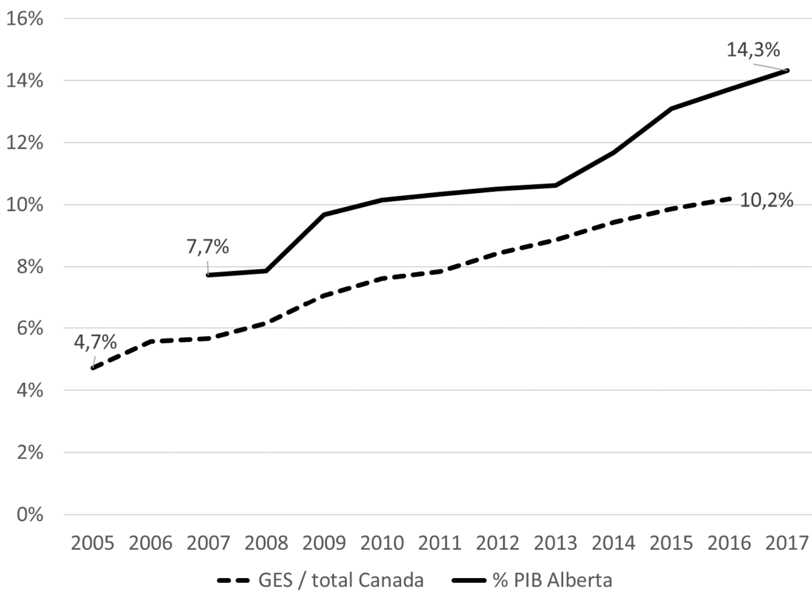
Figure 1. Changes in Canadian oil production, total and oil sands, 2005-2017



Source: CAPP (2018).

Figure 2 compares the growth in economic output (expressed as gross domestic product, or "GDP") and greenhouse gas emissions ("GHGs") (% of the Canadian total) generated by economic activity in the oil sands. Naturally, the parallel increases in these two indicators go hand in hand with the strong growth in physical output (+172%) over the same period: +125% for GDP and +107% for GHG emissions. Oil sands development is energy intensive, resulting in 10.2% of total Canadian greenhouse gas emissions in 2016. However, these emissions grew less rapidly than production, a cumulative result of improvements in the environmental management of the business value chain.

Figure 2. Comparative changes in gross domestic product (GDP, 2007-2017) and greenhouse gas emissions (2005-2016) for the oil sands



Sources: Environment Canada, GHG Emissions for Canada by Canadian Economic Sectors, 1990-2016; and Statistics Canada ({GDP}: Table 36-10-0402-01; and Employment: Table 14-10-0202-01).

On the employment side, capital-intensive production and economies of scale have meant that employment growth has also been strong, but more moderate than output. For example, direct employment in oil sands production in Alberta increased from 15,200 in 2007 to about 25,000 workers in 2017 (+64%).

Oil Sands and the Quebec Economy

The activities of Canadian oil sands producers generate considerable economic spinoffs in Quebec through purchases from Quebec suppliers.

In total, 371 Quebec suppliers had obtained contracts for a total value of $1.2 billion in 2014-15, of which about 80% were in the greater Montreal area. The main economic sectors for these suppliers were transportation, machinery manufacturing and retail trade.

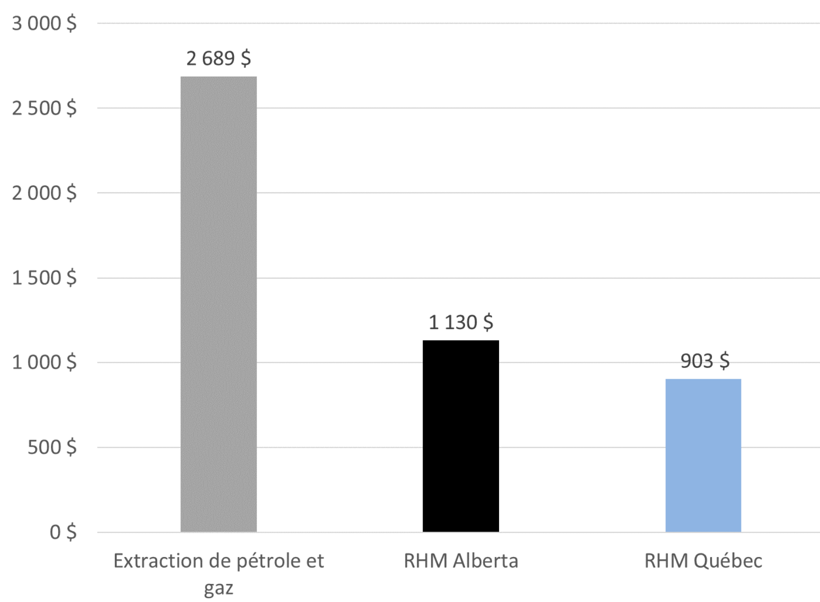
Overall, these expenditures have resulted in significant spinoffs for Quebec's economy.

Approximately 16,200 jobs have been created or maintained as a result of producers purchasing from Quebec suppliers, including 8,600 direct jobs. More than 7,500 jobs on the Island of Montreal are directly or indirectly associated with the amounts received by these suppliers. On average, one job was created or maintained for every $76,100 spent. The portion of GDP that ends up in government coffers as a result of taxation and incidental taxation totals $288 million, of which $215 million goes to the Government of Quebec.

These benefits are recurring and, to the extent that production increases and technological innovations continue in the oil sands, they could grow in the coming years.

Clearly, the relative importance of oil sands employment is lower than that of production, whether measured in units produced or in dollars. In fact, every job produces more than 10 times its relative share of GDP. So these are very productive and therefore very well-paid jobs, as shown in Figure 3. These Statistics Canada data also include conventional extraction.

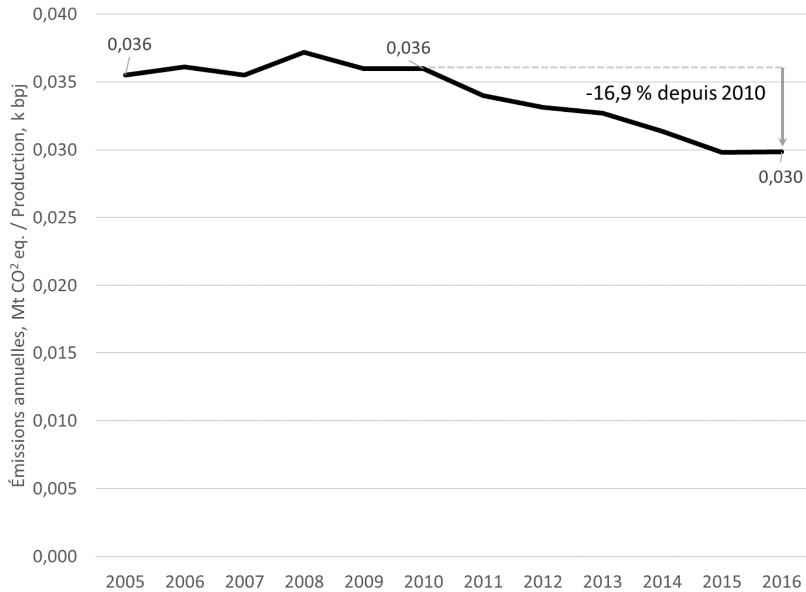
Figure 3. Average weekly earnings (AWE), including overtime—oil and gas extraction industry and averages for Alberta and Quebec, 2017



Source: Statistics Canada, Table 14-10-0204-01.

Average weekly earnings in Alberta's oil and gas extraction industry are close to $2,700, almost three times that of the Quebec average and 2.4 times that of Alberta—inflated by all jobs in the oil industries. Productivity is not just about jobs, it is also about reducing GHG emissions per barrel produced (Figure 4).

Figure 4. GHG emissions per thousand barrels per day—2005-2016, Mt CO_2 Eq. /MBPD



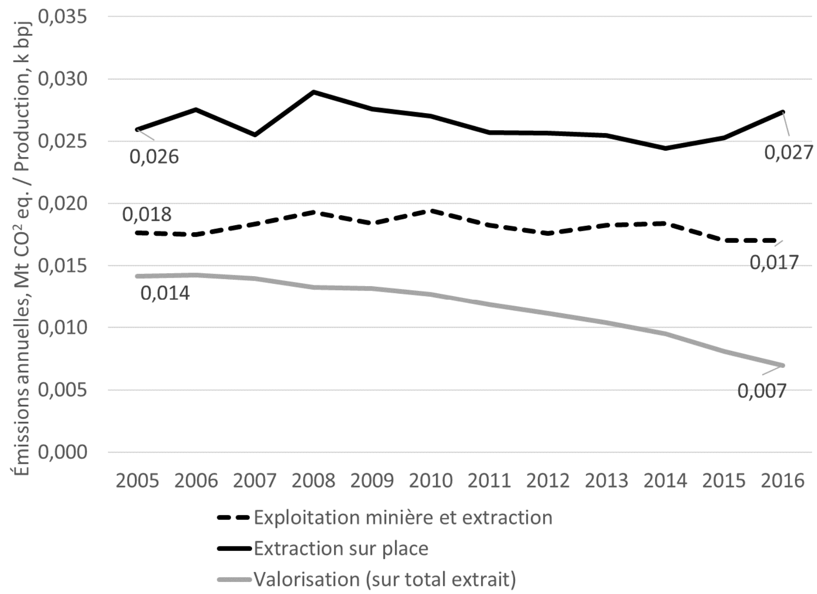
Sources: Environment and Climate Change Canada (emissions) and CAPP (production).

GHG emissions are increasing overall, due to growth in production volumes. However, the same GHG emissions per barrel produced are declining, especially since 2010. In particular, emissions per barrel produced decreased by almost 17% between 2010 and 2016. That said, other more global GHG emission estimates show that even greater progress has been made, including incorporating the missed emissions from Alberta's electricity generation through some of the innovative technologies outlined further down in this report. Taking this latter aspect into account, IHS Markit estimates that GHG emission intensity has actually decreased from 0.038 to 0.028 Mt CO_2 Eq. /MBPD between 2010 and 2016, a total decrease of 26.7%.[3]

These emissions can be broken down by the GHG source, i.e., the type of production (in situ or mining) and upgrading (Figure 5). As a result, much of the reduction in unit emissions, which have been cut in half over the past 11 years, is due to increased efforts to upgrade the resource. For both production processes, GHG emissions have remained stable since 2005.

[3] IHS Markit, "Greenhouse Gas Intensity of Oil Sands Production Today and in the Future," September 2018.

Figure 5. GHG emissions per thousand barrels per day, by source—2005-2016, Mt CO_2 Eq. /MBPD



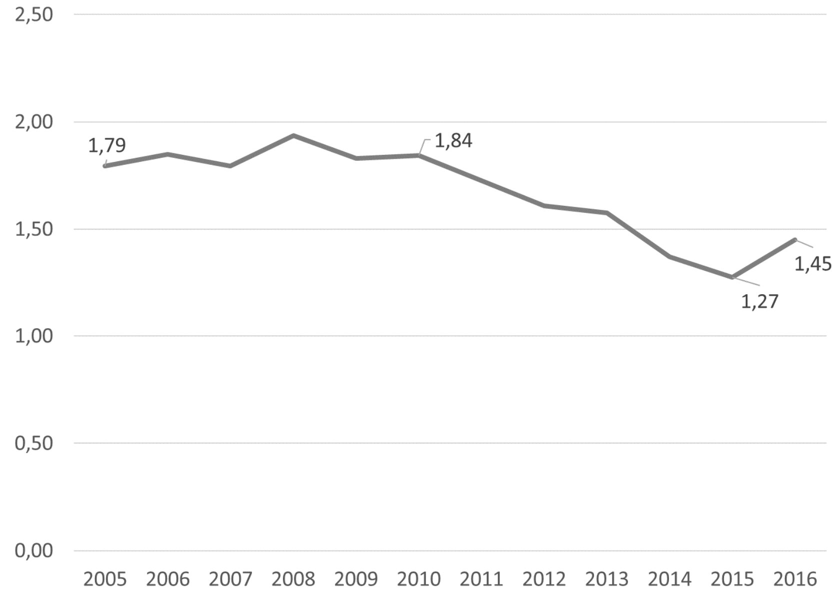
Sources: Environment and Climate Change Canada (emissions) and CAPP (production).

An additional aspect of this picture concerns the variability of emissions by operating site. In 2017, the difference between the minimum and maximum GHG emissions from oil sands facilities was 88 kilograms (kg) of CO_2 equivalent per bbl (so 39 to 127 kgCO2e/bbl).[4] As a result, the lifetime GHG emission intensity ("well-to-wheel") ranged from about 1% below to 16% above the U.S. average. In other words, the most environmentally efficient facilities in the oil sands generate less GHG per barrel than the average well in the United States.

Figure 6 compares the emission intensity of the two major Canadian oil industries. Compared to conventional oil production, GHG emissions are improving more rapidly in the oil sands. Between 2005 and 2015, the ratio of GHG emissions per barrel produced in the oil sands divided by those from conventional production decreased from 1.8 to 1.3 (-27.8%). In 2018, this same ratio increased to 1.45, the first trend reversal in the last six years. Since the absolute GHG emission intensity in the oil sands remained virtually unchanged between 2015 and 2016, this means that there has been a decrease in the intensity with regard to conventional oil.

[4] Ibid. note 4.

Figure 6. Ratio of GHG emissions per barrel produced (Mt CO_2 Eq. / MBPD), oil sands to conventional oil production, 2005-2016



Sources: Environment and Climate Change Canada (emissions) and CAPP (production).

The most recent results indicate that these improvements are actively continuing. By 2030, the GHG emissions intensity of oil sands production could be 16-23% below 2017 levels. Over the entire life cycle of oil, these advances would reduce emissions intensity in the oil sands by up to 2-7% more than that for refined crude oil in the United States on average. Other technologies not included in these forecasts are currently being tested and represent a potential for transformational change and thus an even greater impact on reducing GHG emissions.[5]

The Government of Alberta adopted the Climate Leadership Plan in November 2015, which includes, among other things, measures to eliminate coal emissions by 2030; incentives for innovation; an economy-wide carbon price; a 100-megatonne cap on oil sands emissions; and a new allocation system for large emitters, which will result in additional emission reductions.

Environmental Performance—Other Information

Other background information on the environmental performance of oil sands production includes:

- Canada's oil sands cover an area of 142,000 km^2, or about one fifth of Alberta's land mass. Approximately 3% of this area, or 4,800 km^2, is used for mining extraction. The remaining oil reserves are present on 97% of the oil sands development surface and can be extracted by "in situ" drilling methods requiring little ground surface disturbance and leaving no residue.[6] Of note, companies are required to restore and rehabilitate all lands following oil sands

[5] Ibid. note 4.
[6] CAPP (http://appstore.capp.ca/oilsands/units/22, August 2015 version).

extraction. The land must then return to a self-regulating ecosystem capable of accommodating local flora and fauna. In the oil sands area, the Government of Alberta has committed to conserve and protect more than 2 million hectares, in addition to the 4.5 million hectares protected north of the oil sands;[7]

- As with any exploration and development done on a global scale, oil sands bitumen extraction produces residues (tailings) consisting of water, clay, unrecovered bitumen, solvents and dissolved chemicals. These residues are stored in large tanks similar to tanks where solids can settle. One of the newest technologies is the production of dry stackable tailings, which have great advantages over existing technologies in reducing water requirements by half and accelerating the rehabilitation of lands that have been disturbed.[8] Regulations require that the volume of fine fluid tailings be reduced and that the ponds be ready for reclamation no later than five years after decommissioning;[9]

- Production in the oil sands requires a lot of water.[10] Under normal conditions, approximately 3 to 4.5 m^3 of new water is required for each m^3 of bitumen produced.[11] Between 80% and 95% of the water used in oil sands development is recycled. The industry continues to invest in research and development to reduce the consumption of fresh water required to produce each barrel by improving recycling rates, using lower-quality water (for example, salt water) where possible, and developing new technologies. The water management framework for the Athabasca River provides for the restriction, monitoring and taking water samples from the river on a weekly basis, as well as the preservation of the quality of regional surface and groundwater resources. Among other things, the amount of water withdrawn must not exceed 3% of the flow of the Athabasca River; in practice, it is often less than 1%.

In short, oil sands production represents significant and growing economic activity, both for the western provinces (primarily Alberta) and the rest of Canada. This generates a significant share of Alberta's gross domestic product (GDP), as well as thousands of high-paying jobs. Like any large-scale industrial activity, oil sands production generates an environmental footprint commensurate with its magnitude, primarily related to air, land use, water, and tailings. For several years now, the combined efforts of the industry and the introduction of regulations have made it possible to contain and reduce this footprint as much as possible. However, there is little

[7] Natural Resources Canada: https://www.nrcan.gc.ca/energy/energy-sources-distribution/crude-oil/7-facts-oil-sands-and-environment/18091.
[8] Natural Resources Canada: https://www.nrcan.gc.ca/energy/energy-sources-distribution/crude-oil/environmental-challenges/5855.
[9] Natural Resources Canada: https://www.nrcan.gc.ca/energy/publications/18752.
[10] If the oil sands are close to the surface of the soil, they are simply extracted (open-pit mining) and mixed with water, which causes the bitumen to rise to the surface of the sand-water mixture. If the bitumen deposits are located below the surface, extraction is conducted underground (in situ extraction). Extraction is usually done by injecting steam into a horizontal well, heating the bitumen before it flows into a second well, from which it is pumped to the surface.
[11] Natural Resources Canada: https://www.nrcan.gc.ca/energy/energy-sources-distribution/crude-oil/water-management-oil-sands/river-water-import/5869.

macroeconomic data to provide an overall picture of this environmental performance. Nevertheless, the following case studies provide concrete examples of projects that are changing the way the environment is treated, as well as presenting undeniable economic potential.

5. Environmental Innovation Case Studies

COSIA identifies, develops, and shares environmental innovations in the oil sands to disseminate them as much as possible throughout the entire industry. In particular, all 308 active innovations listed by COSIA are categorized according to their environmental domain (GHG, water, land and tailings management) and the level of progress towards their implementation in production facilities (discovery, design, development, deployment).

Among COSIA's various active projects, four companies provided information on a total of five innovations. These five cases were selected for their diversity, both in the areas affected and their innovation's level of progress towards implementation. In addition, while these innovations are primarily related to the oil sands, all of them could have applications in other industries, such as mining, electricity, forestry, manufacturing, etc. Here is a brief profile of the five innovations:[12]

- ***Case 1: LiDea—Caribou Habitat Restoration***: This project features proven restoration methods typically used in the forestry industry, plus two innovations. First, amphibious vehicles are used to restore caribou habitat, which makes it possible to work the land year round. As well, forest stand modification is done by modulating tree trunks to create a physical barrier along seismic lines. This forces the movement of wolves along these corridors and allows caribou to breed more.

- ***Case 2: GHGSat—Measuring Greenhouse Gases***: This project uses satellites to measure GHG emissions from tailing ponds and mines, known as fugitive emissions. This tested technology could replace the current method used to estimate emissions by improving the accuracy and frequency of measurements. The project could also reduce the potential risk to employees conducting ground measurements, thereby reducing the financial and human costs associated with these operations.

- ***Case 3: Virtual Sensors—Once-Through Steam Generators (OTSGs)***: Most OTSGs operate with a vapour quality ranging from 75% to 80%, which is the percentage of water converted to steam. It is very important to optimize the vapour quality at around 80%, because if the ratio is too high, there is a risk of scaling and fouling the generator tubes, which reduces their efficiency. A mathematical model predicting the vapour quality of an OTSG has been developed by virtual sensor technology, which uses existing measurements to calculate the unknown values of a quantity of interest using advanced algorithms. The objective is to reduce OTSG downtime and optimize maintenance operations.

- ***Case 4: Management of Tailings by Adding and Capturing CO_2***: "NSTs" (non-segregated tailings) allow oil sands tailings to be drained through centrifugation prior to being sent to the waste pond. The CO_2 from the capture facility is injected and sequestered into the tailings. Adding CO_2 to the treated waste further improves the capture of fine particles and

[12] Full descriptions of the projects, as well as responses to qualitative questions, are presented in Appendix 2.

accelerates their dehydration. The water thereby removed is already heated and can be used in production.[13]

- ***Case 5: OTSG Natural Gas Turbine:*** The OTSG Natural Gas Turbine (GT-OTSG) operates on the same principle as a traditional OTSG, supplemented by a natural gas electric generation unit capable of supplying its facilities. This technology was the subject of a pilot project in Surmont. It allows units to operate with greater flexibility and efficiency. In addition, it reduces reliance on Alberta's electricity generation facilities (the majority of which are coal-fired), thereby reducing net GHG emissions.

In those five cases, oil sands production operations were the driving force behind the innovations. In the first two cases, the innovations had potential or immediate applications in other industries (forestry, electricity), but the initial development effort was carried out in the oil sands and adapted to their specific context. OTSGs are a major component of bitumen extraction operations, which explains why several innovations (including the last three presented here) were developed for and around this equipment.

Environmental and Economic Impact of Innovations

The responses received regarding the impact of innovations vary widely and are often more qualitative than anything else, both for the environment and for economic indicators of companies involved in projects. This reflects in part the differences in the progress and scale of innovations. Some cases are still waiting for the publication of data on the impact of measures, while others are already achieving cuts in production costs or additional revenues in the tens of millions of dollars.

Another factor explaining the lack of organizational impact for some projects is that several of them are carried out in an environment of continuous innovation, that is, where teams are dedicated to researching and developing technological innovations in environmental management, production processes, etc. In some cases, the work is done in-house, while in others, oil companies collaborate with subcontractors and academics to carry out their projects. One of the comments was that "our team is constantly looking for environmental innovations. However, at a basic level, they must have the potential for financial profitability to be implemented; otherwise the innovation will never see the light of day."

Table 1 presents the environmental impact sectors for the five innovations studied. In principle, all five projects reduce or capture GHG emissions; however, actual measures of the magnitude of these effects were not available for all these projects. Water management and monitoring were each affected by two innovative projects, while the territory and tailings were each covered by one project. For example, each project touched on an average of two environmental sectors.

[13] At its Horizon site, the Canadian Natural company established the Applied Process Innovation Centre (APIC) whose objective is to accelerate the development and commercial-scale implementation of promising new technologies. This centre also facilitates direct cooperation among industry, academic and government peers.

Table 1. Environmental sectors covered by case studies

Environmental sectors	1	2	3	4	5	Description of innovation components/processes/mechanisms
Greenhouse gases	√	√	√	√	√	(Case 1) Conversion of operating sites from CO_2 source to CO_2 sink—empirical data not yet published. (Case 2) Possible increase in accuracy and frequency of measurements from oil sands operations to facilitate the reduction of greenhouse gas emissions. (Case 3) More accurate and efficient operation of steam generators, leading to reduced variability in vapour quality and reduced GHG emissions. (Case 4) Capture of CO_2 through an upgrader and injection into tailings, reducing GHGs. (Case 5) Indirect reduction of GHG emissions due to reduced reliance on Alberta-generated electricity.
Territory	√					(Case 1) Restoration of caribou forests and habitat.
Tailings management				√		(Case 4) More efficient capture of fine particulate matter and reduction of area required for tailings ponds.
Water			√	√		(Case 3) Improved vapour quality, involving more efficient use of heat (latent) to recover oil. Decrease in the amount of water required for production. (Case 4) Adding CO_2 to tailings increases water clarity, thereby reducing the amount of water required for tailings ponds.
Monitoring	√	√				(Case 1) Provision of useful data on vegetation growth, wildlife movement and behaviour in restored areas. (Case 2) Use of satellite technology to measure GHG emissions from tailing ponds and mines.

Note: (Case 1): LiDea—Caribou Habitat Restoration; (Case 2): GHGSat—Measuring Greenhouse Gases; (Case 3): Virtual Sensors—Once-Through Steam Generators (OTSGs)*; (Case 4) Management of Tailings by Adding and Capturing CO_2; (Case 5) OTSG Natural Gas Turbine. *

Overall, given the various factors and nuances above, these five innovations generated the following net economic impacts (annual and recurring):

- Minimum total savings of at least $45 million in production costs, including improved efficiency of reforestation operations and natural gas savings;[14]
- Additional revenues for oil companies due to increased production efficiency;[15]
- The creation or maintenance of 20 to 25 net jobs, the result of increased funding for various projects less the reduction in the number of workers required before the implementation of these innovations. These jobs are in addition to the total already committed to current and ongoing activities related to these five innovations.

[14] Some economies are obvious but have not been monetized.
[15] Confidential data.

Progress, Application to Other Sectors and Diffusion of Innovations

These innovations are currently being implemented to varying degrees, ranging from the pilot projects to exploiting the full economic and environmental benefits of the innovation. Project 1, the Caribou Habitat Restoration is underway and is expected to continue until 2026. For Project 2, the satellites are already in operation, measurements have been collected for a full year, and research on the use of satellite technology is underway to assess the accuracy and frequency required to measure GHG emissions. For Project 3, the new model has been deployed to eight OTSGs and a deployment is planned for the remaining 23 OTSGs, in addition to a heat recovery steam generator. Project 4 was implemented by Canadian Natural and shared with the oil sands industry through COSIA. The testing phase of Project 5 is being implemented only at the Surmont facilities.

All these environmental innovations have potential applications beyond the oil sands:

- Innovative approaches to caribou habitat restoration can be used in any context that requires the restoration of large areas of the boreal forest;

- GHGSat, which operates the GHG emission analysis satellites, has several clients who operate in various emitting industries, including mining, landfills and agriculture;

- Virtual sensors can be useful in any other steam-generating sector that uses OTSGs, just as the GT-OTSG unit could be attached to similar equipment used outside the oil sands;

- As for capturing CO_2 from non-segregated tailings, this technology is applicable to any mining industry generating tailings that are stored in ponds similar to those in the oil sands.

Only two of the five innovations have active projects for their dissemination outside the oil sands. First, GHGSat is accelerating its efforts to commercialize the innovation. New investments were announced to build two new satellites and an aircraft sensor, develop analytical tools and deliver measurements to a rapidly growing number of customers around the world. Canadian Natural has begun discussions with other major oil companies with respect to virtual sensors. For the other three innovations, no active dissemination to other industries is planned. Public information on these innovations is published on COSIA's Web site and in industry publications. In doing so, all have access to the innovations developed and respondents generally remain open to cooperation on various similar projects.

One possible reason for the lack of interest in the external dissemination of some innovations is that the productive load in the oil sands is time consuming and profitable. Why develop elsewhere when local operations take all the time available? Also, in the case of innovations initiated by oil companies, it makes sense for them to pursue innovation efforts in their own field, rather than looking to diversify elsewhere. That said, the opportunities for collaboration certainly exist for companies in other sectors whose processes are very similar to those used in the oil sands.

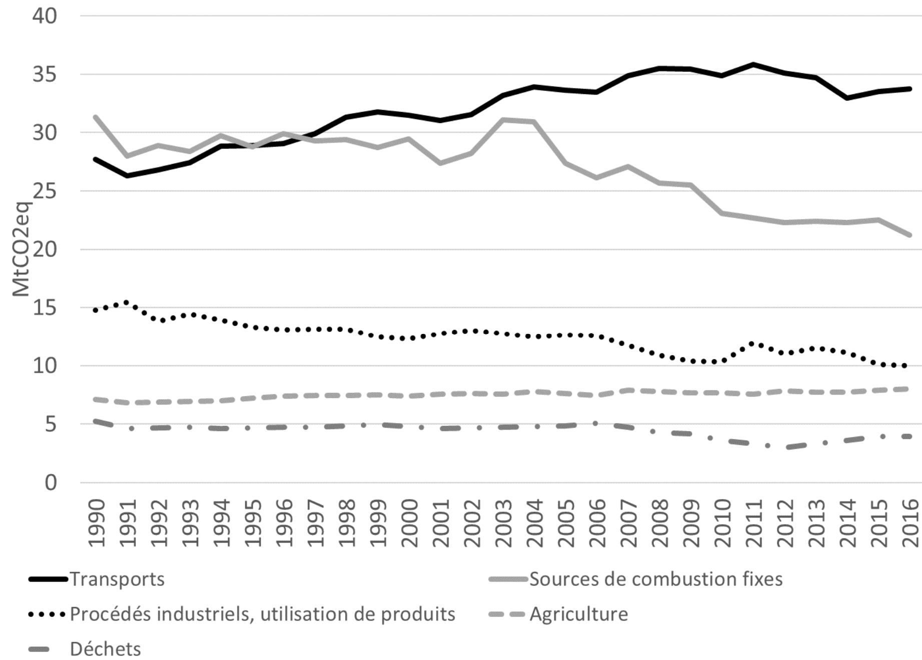
Applicability to Quebec's Economy

First of all, we must remember that Quebec emits more than half as many GHGs per capita as the rest of Canada, particularly because of its vast hydroelectric facilities. This was true in 1990 and is even more so today, when the average Quebecker emits 9.3 tCO_2eq compared to an average of 22.4 for other Canadians.[16]

That said, Quebec must nevertheless continue to implement promising measures to reduce its GHG emissions and do its part to counter global warming. In that regard, Figure 7 shows the evolution of Quebec's GHG emissions, broken down by their five major sources. Transportation is the largest source of emissions, at 34 $MTCO_2$ Eq. in 2016. Within this category, the largest emitters are road transportation, as well as off-road vehicles, primarily those used for manufacturing, mining and construction activities. They are followed by stationary combustion sources (21 $MTCO_2$ Eq.), which include mainly manufacturing industries, residential, commercial and institutional sectors, petroleum refining industries and mining. Quebec's other three sources of GHG emissions are, in order, industrial processes and product use; agriculture; and waste.

[16] Source: Environment and Climate Change Canada.

Figure 7. GHG Emissions by sector—Quebec, 1990 to 2016



Source: Environment and Climate Change Canada.

In addition to GHG emissions, it is also possible for Quebec to improve its environmental performance in other areas, such as land management, water use in industrial processes or environmental impact monitoring methods. All of these areas could directly benefit from significant private investments made in the oil sands. Quebec has a number of companies that can benefit from these environmental innovations, specifically those in the industries identified in Table 2.

Table 2. Jobs in industries likely to benefit from environmental innovations developed in the oil sands, Quebec 2017

Industry	2017
Manufacturing—heavy industries	308,307
Other industries	766,677
Professional, scientific and technical services	194,735
Construction	186,174
Administrative services, support services, waste management services and sanitation services	167,557
Transportation and warehousing	162,699
Utilities	28,580
Mining, quarrying, oil and gas extraction	17,659
Forestry, operations and support	9,273

Source: Statistics Canada. Table 14-10-0202-01 Employment by industry, annual.

There are over 300,000 Quebec workers in the heavy manufacturing industry (metal products, transportation equipment, machinery, wood products, pulp and paper, etc.), while more than 760,000 others work in industries such as professional and technical services (including engineering firms), construction, environmental management, transportation, etc.

In this regard, Table 3 matches the environmental sectors affected by the five innovations described above with those Quebec industries. For these five innovations, as for the other 303 currently listed by COSIA, concrete results are published so that all companies can benefit from the progress made and thus accelerate the implementation of these new technologies (https://www.cosia.ca/resources/project-research).

Table 3. Matching of Quebec industries and environmental sectors targeted by innovation activities in the oil sands

Environmental domain	Greenhouse gases	Territory	Tailings management	Water	Monitoring
Manufacturing	√	√	√	√	√
Professional and technical services		√	√	√	√
Construction	√		√		√
Waste management	√		√		√
Transport	√				√
Utilities					√
Mines	√	√	√	√	√
Forestry, operations, support	√	√			√

For the most part, the oil companies that have developed these innovations generally settle for applying them as best they can to their own operations. However, suppliers such as GHGSat are taking advantage of this opportunity to demonstrate their knowledge, and are expanding their businesses to other sectors that can also improve their environmental performance. Nevertheless, the fact remains that these real-time environmental innovation laboratories, funded entirely by the private sector, represent a certain untapped potential for Canadian companies, which may not be aware of the extent of these innovative activities and the trustworthiness of results achieved to date. As such, the Government of Quebec and economic development stakeholders seem ideally positioned to act as a catalyst for the dissemination of these innovations, for the benefit of our businesses, our economy and our environment.

6. Conclusion

This study analyzed the economic impact of environmental innovation in Canada's oil sands, both generally and through case studies.

First, a review of the literature on the integration of innovation in the business value chain was conducted. One finding is that it is entirely compatible to talk about both environmental management and economic profitability, insofar as environmental management is fully integrated into the business value chain. COSIA's collaborative approach allows all companies to maximize the effectiveness of their environmental management activities in the medium term, by evaluating and implementing technological solutions. This minimizes their costs, maximizes their environmental performance, or both, creating environmental benefits for the whole country as compared to the status quo. In addition, the scope of these activities and economies of scale in this industry, as well as the shared and public commitment to fund environmental innovation in all its forms, are all positive and promising features for this industry and Canadian society in general.

Following this, various performance indicators were examined. Overall, oil sands production represents significant and growing economic activity, both for the western provinces (primarily Alberta) and across Canada. This generates a significant share of Alberta's gross domestic product (GDP), as well as thousands of high-paying jobs. Like any major industrial activity, oil sands production generates an environmental footprint commensurate with its magnitude. Over the past several years, the combined efforts of the industry and the introduction of regulations have reduced this footprint. Accordingly, it would be desirable to have more macroeconomic data on environmental performance, which would allow for a more complete quantification of the industry's progress.

Among the 308 active projects listed by COSIA, five innovations have been identified and analyzed: caribou habitat restoration using innovative methods; measurement of GHG emissions with satellites; use of virtual sensors to improve steam quality; CO_2 injection and capture in tailings; and the development of a gas turbine attached to vapour injectors for energy efficiency. These five innovations all demonstrated positive effects (or demonstrations were under way) on reducing GHGs, while promoting soil restoration, more efficient water use, concentrating production residues, and conserving energy. Overall, these five innovations have increased business revenues, lowered production costs and created jobs. The five projects examined had potential applications beyond oil sands production; however, two of them have been the focus of efforts to make these opportunities a reality.

Finally, the sharing of knowledge and the publication of the results obtained provide a definite opportunity for companies in several other industries to explore these innovative solutions, e.g., forestry, mining, heavy manufacturing, environmental management, non-residential construction, as well as civil and industrial engineering. For Quebec, these real-time environmental innovation laboratories, funded entirely by the private sector, represent a definite untapped potential for businesses here. As such, the Government of Quebec and economic development stakeholders seem ideally positioned to act as a catalyst for the dissemination of these innovations, for the benefit of our businesses, our economy and our environment.

In the end, three main findings emerge from this analysis. First, innovation and environmental management activities in the oil sands are significant, because they are directly related to the magnitude of extraction. Second, these innovations help improve both the environmental performance of producers' operations and their profitability through the development of new "cost-efficient" technologies. Finally, some of these innovations can also be adopted by Quebec's economic sectors, thereby increasing their overall potential for environmental performance.

Appendix 1

Review of the Literature—Studies Consulted

Table A.1. Studies consulted in the review of the literature

Nº	Author (year)	Full Reference	Summary (full text as published)	Study Highlights
1	Breyer (2015)	Christian Breyer *et al.*, « Power-to-Gas as an Emerging Profitable Business through Creating an Integrated Value Chain », *Energy Procedia*, vol. 73, 2015, p. 182-189.	Power-to-gas (PtG) technology has received considerable attention in recent years. However, it has been rather difficult to find profitable business models and niche markets so far. PtG systems can be applied in a broad variety of input and output conditions, mainly determined by prices for electricity, hydrogen, oxygen, heat, natural gas, bio-methane, fossil CO2 emissions, bio-CO2 and grid services, but also full load hours and industrial scaling. Optimized business models are based on an integrated value chain approach for a most beneficial combination of input and output parameters. The financial success is evaluated by a standard annualized profit and loss calculation and a subsequent return on equity consideration. Two cases of PtG integration into an existing pulp mill as well as a nearby bio-diesel plant are taken into account. Commercially available PtG technology is found to be profitable in case of a flexible operation mode offering electricity grid services. Next generation technology, available at the end of the 2010s, in combination with renewables certificates for the transportation sector could generate a return on equity of up to 100% for optimized conditions in an integrated value chain approach. This outstanding high profitability clearly indicates the potential for major PtG markets to be developed rather in the transportation sector and chemical industry than in the electricity sector as seasonal storage option as often proposed.	This article examines the cost effectiveness of power-to-gas technology and its benefits to the environment, particularly in meeting renewable energy use targets. Converting electricity to gas technology can be used in a variety of ways, the authors remind us, including seasonal energy storage, the production of hydrogen and methane in transportation, heating, and the chemical industry. Specifically, the authors sought to assess the benefits of incorporating electricity-to-gas conversion technology into the integrated value chain of a pulp and paper company based in Lappeenranta, Finland. Results of the analysis show that this is a highly profitable technology, which in some circumstances can generate a 100% return on investment. However, the authors stress that in order to be commercially viable, this technology must be fully integrated into the company's value chain. Finally, the authors conclude that CO_2 reduction targets in the transportation sector could be difficult to achieve in the required time, without innovation in current technologies. For some industries, however, electricity-to-gas conversion technology offers an economically sustainable and cost-effective option. The case of the pulp and paper mill analyzed by the authors illustrates the usefulness of the technology for the chemical industry, which has great potential for conversion to renewable energies in all processes using hydrogen as a feedstock. In their view, this would be just one example of profitable niches that should be identified in future research.
2	Cunha and Moneva (2016)	Darliane Ribeiro Cunha et Jose M. Moneva, « Environmental reporting of global oil	The growing demand for environmental information from the stakeholders and the interest of companies in making their commitment to the environment visible have contributed to the	The authors of this report examined the mechanisms oil companies use to legitimize their environmental practices to stakeholders. The study involved a sample of 40 international oil companies between 2007 and 2013.

Nº	Author (year)	Full Reference	Summary (full text as published)	Study Highlights
		companies », *International Research Journal of Finance and Economics*, No. 158, 2016, pp. 84-99.	increase of environmental reporting by companies, either voluntary or compulsory, through the annual reports and in other reports. The aim of this paper is to analyze the practices of disclosure environmental non-financial information of 40 companies from the global oil sector. The content-analysis research technique was used. The results show an increase in the publication of the sustainability reports of the global oil companies, and at the same time a low level of environmental non-financial information reported when analyzing the individual environmental indicators. The lack of standardization and non-mandatory reporting of environmental information limits the homogeneity and transparency of the information. It is verified that having the sustainability report with the use of standards such as ISAE 3000 and AA1000AS can provide greater reliability and evidence that this group of companies try to operate in accordance with market parameters. This procedure is another mechanism that a group of investigated global oil companies use to legitimize themselves. However, the study shows that the level of assurance of the sustainability report in most companies is low.	The authors noted that a growing number of companies have committed over the past few years to making environmental reports public, in addition to their annual financial reports. Although publication of such reports remains voluntary, the authors observed an upward trend in the percentage of companies adhering to this transparency principal from 2007 to 2013. The study found that 80% of companies published reports on their sustainable development practises. The most frequently reported environmental indicators for the companies analyzed included energy use, water quality, biodiversity, the volume of emissions, discharges and industrial residues. In addition, the authors found that, in 2013, 28 of the 40 companies (70%) were following the *Global Reporting Initiative* guidelines, the international standard guide for sustainable development jointly developed by the United Nations Environment Programme (UNEP) and CERES (Coalition for Environmentally Responsible Economies).
3	Gereffi (2016)	Gary Gereffi et Karina Fernandez-Stark, *Global Value Chain Analysis: A Primer*, 2nd edition, Duke Center on Globalization, Governance & Competitiveness, Social Science Research Institute, July 2016.	No summary available.	The report presents the basic analytical underpinnings of global value chains. The authors developed an analytical framework for researchers interested in studying the functioning of global value chains, understanding the determinants of value creation within them in various industries, and harnessing the opportunities that flow from them more effectively. They explain how the value creation process works through the stages of making a product, from the initial design to delivery to the consumer, and even beyond. They

Nº	Author (year)	Full Reference	Summary (full text as published)	Study Highlights
				present a holistic view of this process in the context of multinational companies that have ramifications in various countries around the world. They emphasize that segments of the chain can be identified and distinguished by the value they add to the process of manufacturing a product or providing a service. The authors point out that the analysis of global value chains was originally limited to research on the competitiveness of firms in manufacturing industries. Today, this analysis has expanded in several directions, including informing industrial policy, guiding SMEs with regard to opportunities to integrate into these value chains, and encompassing emerging industries such as offshore outsourcing services. According to the authors, globalization has paved the way for a new era of international competition that is better understood by examining the global organization of industries and the place of key players in value chains within them. However, the authors note that many SMEs, particularly in developing countries, face a range of constraints on their ability to actively participate in global value chains. The Duke Center on Globalization, Governance & Competitiveness, where the authors work, has developed a model to foster the development of effective interventions to enable SMEs to succeed in this environment. According to the authors, the first step in a successful intervention requires linking producers and buyers to facilitate market access for SMEs. This link requires informing buyers or large companies that are leading the way on the commercial potential of procuring from small producers, and then facilitating interactions until they are able to manage the relationship autonomously and

Nº	Author (year)	Full Reference	Summary (full text as published)	Study Highlights
				sustainably.
4	Harger (1994)	J. R. E. Harger et D. Troost, "Environmental education and training of global scientists for sustainability", dans David Waddington (ed.), *Global Environment Change in Science Education and Training*, Series I: Global Environmental Change, vol. 29. Springer-Verlag, 1994, pp. 59-69.	No summary available.	The authors argue that it is important to begin educating individuals about environmental science as early as possible, ideally right from high school. This education must emphasize the importance of assessing the real state of the world ("reality checks") to see if it corresponds to the image depicted in the public discourse. This education should foster the development of the scientific mind (seeking answers to environmental questions through science) and critical thinking (challenging misconceptions about the state of the environment). According to the authors, educational institutions must ensure that students are exposed from an early age to field experiments that require a keen sense of observation and attention to detail when conducting environmental analysis. They argue that "field studies should be an integral part of an interdisciplinary program that enables current and future generations to learn about marine, terrestrial and atmospheric ecosystems, as they relate to ecological and sustainable development in a constantly changing world."
5	Holweg (2014)	Matthias Holweg et Petri Helo, « Defining value chain architectures: Linking strategic value creation to operational supply chain design », *International Journal of Production Economics*, vol. 147, 2014, p. 230-238.	Over the past three decades scholars have developed comprehensive insights into the operational and strategic aspect of designing and managing the supply chain. Reviewing this ample body of knowledge, however, one cannot help but notice a persistent disunion between the "value chain" view that considers aspects of value creation and appropriation, and the operational "supply chain" view that considers strategies and tools for designing and operating efficient inter-firm networks. Commonly these views do not interact: value creation has the aim of capturing the maximum value-added in financial terms, the	In this article, the authors show that decisions about "the value chain architecture" change over time. They adapt to external or contextual changes as the business strategy evolves. To illustrate their point, the authors present a longitudinal case study analyzing the evolution of value chain architecture in the multinational ABB company from 2004 to 2009. They use qualitative data based on interviews with key stakeholders in the company's supply chain management department, as well as quantitative data on the structure and performance of the distribution network within the company.

Nº	Author (year)	Full Reference	Summary (full text as published)	Study Highlights
			supply chain view aims for designing operationally efficient supply chains. In contrast to their treatise within the academic literature, from a practical point of view these two aspects are both necessary (and thus in their own right insufficient) components to a firm's supply chain strategy. In this paper we thus turn to an exploratory case study to identify what such a combined view of the value and supply chain would entail. We refer to this purposeful creation as the "value chain architecture" and propose five fundamental decisions that define the latter: (1) the nature of value provision (driven by the core competence of the firm), (2) the operational footprint decisions for manufacturing, sourcing and distribution, (3) the approach to risk management, (4) the order fulfillment strategy (and implicit in that, the type of product customization), and (5) the buffering strategy. We conclude with an exploration of the application and utility of the "value chain architecture" concept in both academia and practice.	The authors deduce that five fundamental dimensions define the value chain architecture: 1. **Value provision:** the separation of parts supply plants and product assembly plants at the regional level contributes to changing the place of value creation and specializes the roles within the chain. 2. **The operational footprint** is determined by areas of activity in the market, in conjunction with profitability measures, time frames and other operational performance indicators. 3. **Risk management aspects** relate to local/global supply in terms of being able to reliably deliver certain components within the ABB network. 4. **Order fulfillment strategy and personalized service:** changing the location of the order processing centre has an impact on the range of products offered to the customer as well as internal efficiency. 5. **The buffering strategy**, which can be changed by defining a strategic and secure inventory location and by improving delivery performance in plants located near customers.
6	Lind (2012)	Lotta Lind, « Working capital management in the automotive industry: financial value chain analysis », *Journal of Purchasing & Supply Management*, vol. 18, 2012, p. 92-100.	Financial value chain analysis is used to examine working capital management by cycle times in the value chain of the automotive industry during 2006–2008. The applied method offers a holistic view of the value chain from raw materials to the end customers. The average cash conversion cycle of the value chain of the automotive industry was 67 days. According to the study, the change of cycle times of working capital followed mainly the	In this article, the authors point out that working capital management is an integral part of a business's short-term financing. Effective working capital management allows a company to free up capital for more strategic purposes, reduce financial costs and improve profitability. The objective of this study was to examine the management of working capital in the automotive industry's value chain from 2006 to 2008 using a financial

Nº	Author (year)	Full Reference	Summary (full text as published)	Study Highlights
			change of cycle time of inventories. The position of the stages of the value chain measured by the cash conversion cycle did not change substantially from 2006 to 2008.	value chain analysis. The authors sought to analyze the management of working capital throughout the value chain, from raw material suppliers to end customers. The results of their analysis showed that the cash conversion cycle (defined as the working capital to sales ratio) was positive at each stage of the automotive industry value chain, averaging 67 days. They noted only slight differences in cash conversion cycles between 2006 and 2008, which indicates, according to them, that the relationship between sales and working capital can be considered constant within the industry's value chain.
7	Tordo (2011)	Silvana Tordo, Brandon S. Tracy and Noora Arfaa, *National Oil Companies and Value Creation*, World Bank Working Paper, March 2011, 139 pp.	No summary available.	The authors point out that unlike most commodities, oil is strongly influenced by international policy and can be a major factor in a country's socio-economic development. They argue that these characteristics of the oil sector largely explain why many producing countries have opted, at least at some point in their history, for direct government involvement rather than a more liberal system of governance. To illustrate their point, they reveal that national oil companies (NOCs) control about 90% of the world's oil reserves and 75% of production (similar figures apply to natural gas), as well as many major oil and gas infrastructure systems. The total exclusion of private industry participation in oil exploration and production would be rare, however. The authors examined the available data on the objectives, governance and performance of 20 NOCs globally, and drew conclusions on the rules and policies most likely to generate social value from NOCs. In their paper, the authors argue that an NOC creates social value if it generates profits for society that exceed the maximization of the financial return on investment from exploitation of

Nº	Author (year)	Full Reference	Summary (full text as published)	Study Highlights
				the resource. In particular, their analysis sought to answer the following question: are some government approaches or policies more likely than others to promote value creation? Is good geology a prerequisite for creating value for the NOC? Are there any advantages to submitting NOCs to competition from private oil companies? Accordingly, the authors sought to identify factors that could influence the NOC's value creation. To this end, they targeted five categories of potential factors: geology and geography, the state context, the governance and organization of the petroleum sector, the business strategies and corporate governance of the NOC. A regression analysis was conducted to understand the relationships between these variables and the creation of value by the NOC. The analysis confirmed the importance of geology, petroleum sector governance and NOC corporate governance for value creation. However, the authors stress the importance of remaining cautious in interpreting these results, given the poor quality of available data. Finally, the authors conclude that protecting NOCs from private competition has deleterious effects on value creation over time and can discourage them from developing effective and sustainable strategies.

Nº	Author (year)	Full Reference	Summary (full text as published)	Study Highlights
8	Wagner (2012)	Stephan M. Wagner et al., « The link between supply chain fit and financial performance of the firm », *Journal of Operations Management*, vol. 30, 2012, pp. 340-353.	The bottom-line financial impact of supply chain management has been of continuing interest. Building on the operations strategy literature, Fisher's (1997) conceptual framework, a survey of 259 U.S. and European manufacturing firms, and secondary financial data, we investigate the relationship between supply chain fit (i.e., strategic consistencies between the products' supply and demand uncertainty and the underlying supply chain design) and the financial performance of the firm. The findings indicate that the higher the supply chain fit, the higher the Return on Assets (ROA) of the firm, and that firms with a negative misfit show a lower performance than firms with a positive misfit.	In this article, the authors sought to examine whether the priorities of the business supply chain are effective and well aligned with their business objectives. According to them, supply chain management is effective when companies adapt effectively to uncertainty about demand for their products and resulting customer needs. To achieve this, they need to know the characteristics and capabilities of their supply chain to respond appropriately to unexpected changes in demand or supply for their product. As a result, the more the logistics chain is adaptable the greater the company's return on investment. The authors therefore sought to measure the financial impact of effective supply chain management and the extent of its performance using objective financial data. From September 2007 to April 2008, they collected data from manufacturing executives in the United States, the United Kingdom, Germany, Austria, Switzerland and France. They obtained data on 259 of the largest manufacturing companies in those countries. Their analysis showed that supply chain adequacy, the correlation between supply and demand uncertainty and the responsiveness of the logistics chain, is closely linked to the company's financial performance. They conclude that it is imperative that companies strive to design their supply chains to better respond to the vagaries of demand for their products. Instead of over-investing in measures to increase supply chain responsiveness, they should invest in measures to increase supply chain efficiency (for example, through inventory reduction).

Appendix 2

Case Studies: Survey Instruments and Qualitative Results

Case Study Respondents

Project 1: LiDea
Name: Sonja Franklin, Cenovus
Partners: Alberta Innovates, BP Canada, Canadian Natural, Devon, Suncor, MEG Energy, Huskey, Shell/Devon Canada, Imperial, Canadian Natural

Project2: GHGSat—Measurement of GHG Emissions
Name: Laura Frank, Imperial
Partners: Suncor, GHGSat, Sustainable Development Technology Canada, Boeing, LOOKNorth, Canadian Space Agency

Projects 3-4: Virtual Sensors/CO_2 Residues
Name: Julie Woo, Canadian Natural
Partners: University of Alberta, Suncor

Project 5: Gas Turbine and Steam Generator
Name: Katherine Springall, ConocoPhillips
Partners: Total E&P Canada

Economic impact of environmental innovation at Canada's oil sands
Case studies of environmental innovation

Instructions

This survey comprises two parts: (1) textual questions (please write your answers below): your answers will be reported at length, plus a supplementary analysis/synthesis; and (2) numerical questions: your answers will remain confidential, only consolidated results will be shown for the 5 cases combined.

Please complete both parts of the survey and return them. We will then plan a call to review and complete your answers.

* * *

Text questions

Description of project/innovation/technology/process/activities

1. The attached description of your project/innovation was obtained via COSIA (*description inserted at last page of questionnaire*). Would you like to add to, comment on, or change anything from this description?

Your answer to Q.1:

NOTE: TO SIMPLIFY, YOUR PROJECT/INNOVATION/ETC. WILL BE REFERRED AS "INNOVATION" IN THE QUESTIONS BELOW.

2. Please indicate the environmental area(s) to which your innovation contributes significantly, and explain how, using short bullet-point descriptions?

Environmental Area	√		Description of innovation Component(s)/process (es) / Mechanism(s)
	Yes	No	
Greenhouse Gases			
Land			
Tailings			
Water			
Monitoring			

Innovation history

3. Year of inception

Your answer to Q.3:

4. Did your innovation begin with the oil sands or with another industry? Please specify.

Your answer to Q.4:

5. What sparked the innovation? Specifically, which aspect(s) of the "old way of doing things" led you to your current solution?

Your answer to Q.5:

6. How did the innovation change your firm's activities and organization: size, investments, employment, etc.? Please provide a descriptive answer, as specific figures are requested in numerical questions.

Your answer to Q.6:

Project results—complete Excel spreadsheet

Project future

7. Describe your innovation's current implementation at oil sands, i.e., upcoming, one or many company(s), new industry standard?

Your answer to Q.7:

8. Has your innovation generated spin-off applications into other economic sectors, or do you expect it to do so?

Your answer to Q.8:

9. Please elaborate on your current plans to follow-up on these spin-off opportunities?

Your answer to Q.9:

Thank you for your collaboration!

Environmental and Economic Performance Questionnaire

a. The Environmental Component

Impact of innovation on economic and environmental performance					
Environmental performance					
Instructions : in the green cells below, break down your innovation into its main components and their respective contribution to environmental performance. Example : Component A of the innovation has reduced GHG emissions from 2 t CO2 eq. / day					
Areas	Nature of intervention (if breakdown is possible)	Indicator (name)	Unit	Before intervention (value)	After intervention (value)
Greenhouse gases	Component A	GHG emissions	t CO_2 eq. / day	2,0	1,0
Areas	Nature of intervention (if breakdown is possible)	Indicator (name)	Unit	Before intervention (value)	After intervention (value)
Greenhouse gases					
Land					
Tailings					
Water					
Monitoring					

Environmental and Economic Performance Questionnaire

b. The Economic Component

Impact of innovation on economic and environmental performance		
Economic performance		
	Before intervention (value)	After intervention (value)
Production costs (only associated to project / technology), $		
Oil company		
Third party(ies)		
Revenues (only associated to project / technology), $		
Oil company		
Third party(ies)		
Employment (net creation associated to project / technology), n FTE		
Oil company		
Third party(ies)		
* FTE : full-time equivalent.		

Table A2. Qualitative responses to case studies

	LiDea—Caribou Habitat Restoration	GHGSat—Measuring Greenhouse Gases	Virtual Sensors—OTSG Steam*	Tailings Management Through CO_2 Addition and Capture	Gas-Turbine OTSG
Year of start-up	Cenovus initially experimented with various reforestation techniques in 2008. The LiDea project (for "Linear Deactivation") was initiated between 2013 and 2015. In 2016, the company announced the use of LiDea technology for its caribou habitat restoration project (2016-2026).	GHGSat was founded in 2011. The project with COSIA started in 2015.	The project began in 2015 with the development of "soft sensors" in collaboration with the University of Alberta. This novel solution was developed and tested internally at Canadian Natural between 2016 and 2018; it is easier to implement and use.	Injection of CO_2 into the non-segregating tailings (NST) process began in late 2015. CO_2 capture from the upgrader started in 2017.	The technology has been around since at least 2009, but it has recently been implemented in the oil sands context.
Short description	Boreal forest habitats have been fragmented by oil and gas exploration activities. The project is based on proven restoration methods typically used in the forestry industry. They include the creation of mounds, the dispersion of wood debris, and the planting of trees. Tests have been conducted with amphibious vehicles to restore caribou habitat, allowing for year-round field work.	Oil sands mine operators must annually measure emissions from tailing ponds and mines, known as fugitive emissions. These emissions represent a significant portion of total mine emissions. All emissions are reported annually to the provincial government for compliance purposes. This project will develop modelling to enable COSIA members to use GHGSat technology to measure emissions above tailing ponds and above the surface of a mine. The technology tested could	The majority of OTSGs (steam injectors in bitumen) operate with 75-80% quality steam (= percent of water that is converted to steam). It is very important to optimize the vapour quality around 80%, because, if the ratio is too high, there is a risk of scaling and fouling the generator tubes, reducing their efficiency. A mathematical model predicting the vapour quality of an OTSG has been developed by virtual sensor technology, which uses existing	Tailings are a mixture of water, sand, and clay that naturally occurs in the oil sands and remains after the extraction process. The majority of solid residues is deposited at the bottom of the tailing ponds and the remainder are liquid tailings. The NST process allows tailings to be drained through centrifugation before being sent to the waste pond. The CO_2 from the Horizon capture facility is injected and sequestered into the tailings. Adding CO_2 to the treated waste further	The OTSG gas turbine (GT-OTSG) operates on the same principle as traditional OTSGs, in addition to generating electricity that can be used to supply power to facilities. GT-OTSGs are the key to generating electricity at the same time as steam. This technology was piloted in Surmont. The GT-OTSG allows units to operate with greater flexibility and efficiency. In addition, it reduces the reliance of generating facilities on

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	As well, forest stand modification is done by modulating tree trunks to create a physical barrier along seismic lines.	replace the current method used to estimate emissions by improving the accuracy of estimates and increasing the frequency of measurements. The project could also avoid safety risks for employees conducting ground measurements and reduce costs associated with measurement operations.	measurements to calculate the unknown values of a quantity of interest using advanced algorithms. Virtual sensors are used where conditions make physical sensors inappropriate or too expensive. Canadian Natural is also conducting research on monitoring and forecasting parameters for fouling and scaling. The objective is to reduce OTSG downtime and optimize maintenance operations.	improves the capture of fine particles and accelerates their dehydration. The water removed is already heated and can be used for production. Also at Horizon, Canadian Natural built the Applied Process Innovation Centre (APIC), a centre designed to accelerate the development and commercial-scale implementation of promising new technologies. This centre also facilitates direct collaboration between industry, academic and government peers.	Alberta-generated electricity (the majority of which is produced by coal-fired plants), thereby reducing net GHG emissions.
Origin: oil sands or other industry?	The LiDea project is based on proven reforestation methods commonly used in the forestry industry. However, its two innovative aspects (amphibious vehicles, tree barriers along seismic lines) have been developed for the specific context of the oil sands.	Innovation originates in the oil sands and electricity generation (specifically hydroelectricity).	Innovation comes from the oil sands, because OTSGs are primarily used in that industry.	Applied research in the oil sands is the main source of innovation. After establishing the current NST plant, tests were conducted to better understand the limits of segregation, CO_2 addition rates, the thickener and geotechnical properties of NST waste produced with CO_2.	This pilot project was developed specifically to fit the context of ConocoPhillips's and Total E&P Canada's oil sands operations.

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Innovation trigger	The finding that traditional minimal disturbance techniques that are appropriate in other contexts are not appropriate for the boreal forest. The LiDea method is now applied to the company's total boreal forest reforestation effort, which is caribou habitat.	When Quebec announced its participation in the carbon market in 2010, GHSat understood that industrial emitters would be financially motivated to better understand, control and ultimately reduce their emissions. Alberta already had a carbon pricing mechanism and oil sands development poses particular challenges with existing measurement methods required for emissions reporting.	At the Primrose and Wolf Lake facilities, the OTSGs were controlled only on the basis of water supply flow and temperature. The variation in the OTSG vapour quality was not used. Improved steam quality has been achieved by creating an innovative measurement/prediction technique that is less expensive and easier to use.	The reference case for Horizon was the NST process. When the project was postponed, Canadian Natural wanted to put in place a safe and easy-to-use process that would maintain a clean water cover on the tailing pond. CO_2 was selected for its GHG reduction, as it did not affect the chemistry of water used in production, safety and usability.	The finding that some residual steam energy could be recovered by combining it with natural gas combustion, which is more efficient than normal cogeneration configurations.
Impact on activities and organizations	Through the Caribou Habitat Restoration Project, Cenovus has invested approximately $32 million between 2016 and 2026. Several staff members are working on the project. In addition, some contractors are hired for mechanical work in the field and subsequent tree planting.	The GHGSat satellite completed one year of measurements. The project was expanded to include a second satellite to collect additional data. Details on this second launch are not finalized.	This innovation has various benefits, including increased cash flow, reduced operational costs and environmental benefits. Since development and implementation were carried out internally as part of continuous improvement activities, no additional investment or personnel was required.	The impact is difficult to quantify. This tailings management strategy was included in Horizon's construction plans. Horizon produces 250 MBPD and has over 3,000 field workers, in addition to Calgary-based workers supporting operations.	Implementation of the pilot project at the Surmont facility, ongoing analyses to determine the extent of economic and environmental benefits.
Degree of implementation in 2018	The Caribou Habitat Restoration Project is expected to continue until	Research on the use of satellite technology to measure greenhouse gas	The new model is deployed for eight 8 OTSGs and the plan is to	Innovation is implemented by Canadian Natural and	Implemented in testing phase at Surmont facilities only.

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	2026. Through our contribution to COSIA, our peers have access to this technology and we remain open to working with them on large-scale restoration projects.	emissions may increase the accuracy and frequency of measurements, and offer the potential to reduce these emissions. The objective of this project is to demonstrate that this technology can be used with regular industry technologies to improve the overall quantification of fugitive GHG emissions.	deploy the remaining 23 OTSGs, in addition to a heat recovery steam generator. This innovation could lead to future innovations in predicting scaling and fouling of OTSGs. Canadian Natural collects data and compares it to the OTSG clean-up logs. This information will help optimize servicing and maintenance schedules to optimize operating time, reduce maintenance costs and the environmental footprint of maintenance.	shared with the oil sands industry through COSIA.	
Applications to other business lines	Our innovation has addressed the need to restore large areas of the boreal forest in northern Alberta, and there is now a significant opportunity in that area.	GHGSat has several active clients in various sectors. The technology has applications in several other GHG-emitting sectors.	Since this innovation is working on saline water spraying, it can certainly be useful in any other sector that uses saline water to generate steam using OTSGs.	In theory, this technology is applicable to any mining industry that has to manage tailings through tar sands-like ponds.	Possible in theory, however, to be finalized in the oil sands.
Anticipated dissemination of innovation	The company's deployment covers its operating territory. No active dissemination planned to other industries.	GHGSat accelerates efforts to commercialize innovation. New investments have been announced by members of the Oil and Gas Climate Initiative, which will be	Information on innovation is published on COSIA's site and in industry publications. The company also interacts with industry representatives from other	No active dissemination planned outside of industry.	The first release phase would be for the company's facilities.

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		used to build two new satellites and an aircraft sensor, develop analytical tools and deliver measurements to a rapidly growing number of customers around the world.	countries. Representatives from Chevron USA have expressed interest in this innovation and discussions are ongoing.		