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Life Cycle Assessment of Oil Sands Technologies

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ABOUT ISEEE

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PREFACE

The energy sector has been a dominant factor in Alberta's development and growth over the last half-century. The large capital investments and operating expenditures associated with finding and producing oil and gas have directly provided a major stimulus to the economy. But the indirect and induced impacts have been equally important. The development of many other industries supplying inputs to the energy sector, the generation of substantial export and government revenues, and the stimulus for large inflows of people have resulted in large 'multiplier' effects. In combination, these have also played a major role in shaping Alberta's 'character' which is generally distinguished by its highly educated, adjustable and entrepreneurial labour force, low unemployment and high labour force participation rates, strong work ethic and sense of self reliance, and its optimistic outlook.

In recent years the energy sector has become even more dominant and has increasingly made Alberta a key driver of the national economy. In a world with a rapidly growing demand for energy, having one of the largest concentrations of energy resources in the world might seem to translate into an assured, prosperous future. There is clearly huge potential associated with unconventional oil and gas, coal, remaining conventional resources and with alternative and renewable energy. However, translating this potential into reality will be daunting. Increasing constraints related to resource access, environmental impacts, infrastructure requirements, and availability of highly qualified people need to be addressed. Other challenges include the massive long-term investments in developing and implementing new technologies and making the right changes in the policy and regulatory framework. Indeed, the fact that relatively few nations have managed to convert resource wealth into high standards of societal welfare is a useful reminder of the magnitude of the challenges.

Alberta is in many respects at a crossroads. On the one hand complacency will almost certainly mean a dimming of the province's long-term prosperity. Declines in the conventional oil and gas sector will significantly dampen growth and prosperity. There are no other sectors of the province's economic base that could realistically expand sufficiently to offset significant declines in the dominant energy sector. On the other hand, visionary, strategic investments today can unlock non-conventional and other energy resources critical to securing a strong and prosperous long-term, sustainable future for the province.

It is in this context that ISEEE has undertaken a series of papers focused on Alberta's energy futures. The intent is to take a longer term look at the challenges, opportunities and choices and what they mean for Alberta's future.

Life Cycle Assessment of Oil Sands Technologies

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1.0 Introduction

A wide variety of new technologies are being developed to produce bitumen and other products (refined fuels, electricity, etc.) using surface and in situ techniques for accessing the oil sands bitumen resource. In addition to new technologies, current oil sands technologies are becoming more deeply integrated into Canada's energy system through imports of natural gas, exports of electricity and integration of upgrading into refinery operations. Construction, operation, and eventual retirement of these facilities will have large and complex impacts on Canada's economy and environment.

Quantities such as CO_2 emissions and inputs of capital, energy and water required per unit of final product cannot be simply estimated from operational data supplied by oil sands operators because such data does not include the indirect impacts stemming from procurement of necessary inputs such as steel and natural gas.

A life cycle framework is required to understand the full impact of developing oil sands bitumen (i.e. from extraction of resources to disposal of unwanted residuals). The indirect emissions associated with the construction and operation phases of the life cycle are largely neglected in energy LCA studies as they are often an order of magnitude lower than the emissions associated with the use phase. This is not the case in oil sands operations due to the capital and energy intensive nature of the production phase. Life cycle assessment (LCA) methods allow for systematic assessments of the life cycle implications of important oil sands technologies as an aid to public and private choices about major investments in these technologies and research. A hybrid LCA model is proposed that combines process-based and economic-input-output (EIO) approaches. This effort will combine three elements; an EIO-LCA model of the Canadian economy, a region- and sector-specific process model, and data specific to oil sands technologies.

This report summarizes the literature that currently exists that pertains to oil sands and LCA research. The purpose of this report is first, to assess previous work and available data sources, and second, to identify and assess specific questions of particular public policy or methodological interest which might be usefully addressed by the application of LCA tools to oil sands technologies.

This report begins with a summary of current oil sands operations, projections on how this industry is expected to grow and the impact that this will have on the province, country and the global community. LCAs that are relevant to a life cycle study of oil sands technologies are then reviewed. The available data that could improve the economic and environmental components of the Canadian EIO-LCA model are then discussed. Available research and data that could be used for the process level component of the analysis are then summarized and discussed. Finally, potential applications of the model are discussed including the data requirements associated with each application.

2.0 The Challenges of Managing Oil Sands Growth

Current estimates suggest 1.7 trillion barrels of crude bitumen resources are available in Alberta and that 180 billion barrels could be economically recovered using currently available technologies[1]. These reserves are second only to Saudi Arabia in quantity and represent 14% of global reserves. In 2003, 1.1 million barrels per day of this resource was produced[2]. This production level contributed 64% of the total crude oil and equivalent produced in Alberta, 42% of that produced in Canada[3] and 1.3% of global production[4]. Assuming no technological advancements, production levels of 5 million barrels day could be sustained for roughly 100 years[5].

Oil Sands production is increasing rapidly. Several projections suggest that production could reach 4-5 million barrels per day (MBPD) by 2025 to 2030 [6,7,8]. Assuming, for the moment, that production were to reach 5 MBPD in 2025, production from oil sands will be 15 % of North American and 4.2% of global oil demand[9].

The development of the oil sands resource also has impacts on the economies of Alberta and Canada. A recent report from the Canadian Energy Research Institute projected the economic and labour impacts of development to 2020[10]. In 2000, the oil sands industry represented 9.0 % of Alberta's GDP. This is projected to increase to 20% by 2020. In 2000, the industry represented 1.5% of Canada's GDP and this is expected to increase to 3.0% by 2020 (assuming 4.2 million barrels per day production). Oil sands activities are expected to generate almost as much employment outside Alberta as inside Alberta for a total of 6.6 million person years. This development will also have an impact on the materials required to build and maintain this capital intensive industry. The area in Northern Alberta is currently constrained by infrastructure including pipeline, transmission, housing, etc., as well as labour.

The environmental impacts from these operations are significant. They include the direct impacts of land, water and energy consumption for production and upgrading as well as indirect impacts arising from supplying the capital and energy infrastructure. The full life cycle environmental impacts of oil sands production are complex and poorly understood.

Consider CO_2 emissions. In 2000, the oil sands industry emitted 23 mega tonnes of CO_2 equivalent. That is approximately 3% of Canada's and 11% of Alberta's total emissions that year. Assuming that emissions in Alberta and Canada remain at 2000 emissions levels and the production of bitumen from the oil sands is increased to 5 million barrels/day without any further reduction in emission intensity, the oil sands operations would contribute approximately 15% of Canada's and 55% of Alberta's GHG emissions.

Figure 1 shows the CO_2 eq emissions from each phase of the life cycle in the production of petroleum from oil sands bitumen and from conventional methods. In the case of CO_2 emissions, the majority of lifecycle emissions (60-85%) come from combustion of the final product (liquid transportation fuels). This phase has been carefully studied and is well understood. Of the upstream emissions, most arise from the energy consumption associated with extraction, upgrading and refining of the bitumen. The portion of the life cycle that will take place in Alberta and is therefore a concern to policy makers and those that will be impacted by a potential carbon tax includes the production (direct and indirect) and refining phases. The indirect production emissions are those emissions that are incurred during the construction and maintenance of the production site. For example, the emissions associated with the manufacture of heavy duty vehicles that are required to construct and operate the extraction facility would be included in indirect production emissions. Due to the fact that this industry is extremely capital intensive, these upstream emissions are significant, and preliminary estimates show that they can represent 20-25% of the direct production emissions. These estimates are considered conservative since they are based on U.S. data, the capital costs are going up (which should translate in some additional indirect impacts), and operational emissions are being targeted for reduction (which will increase the proportional contribution of the indirect production).

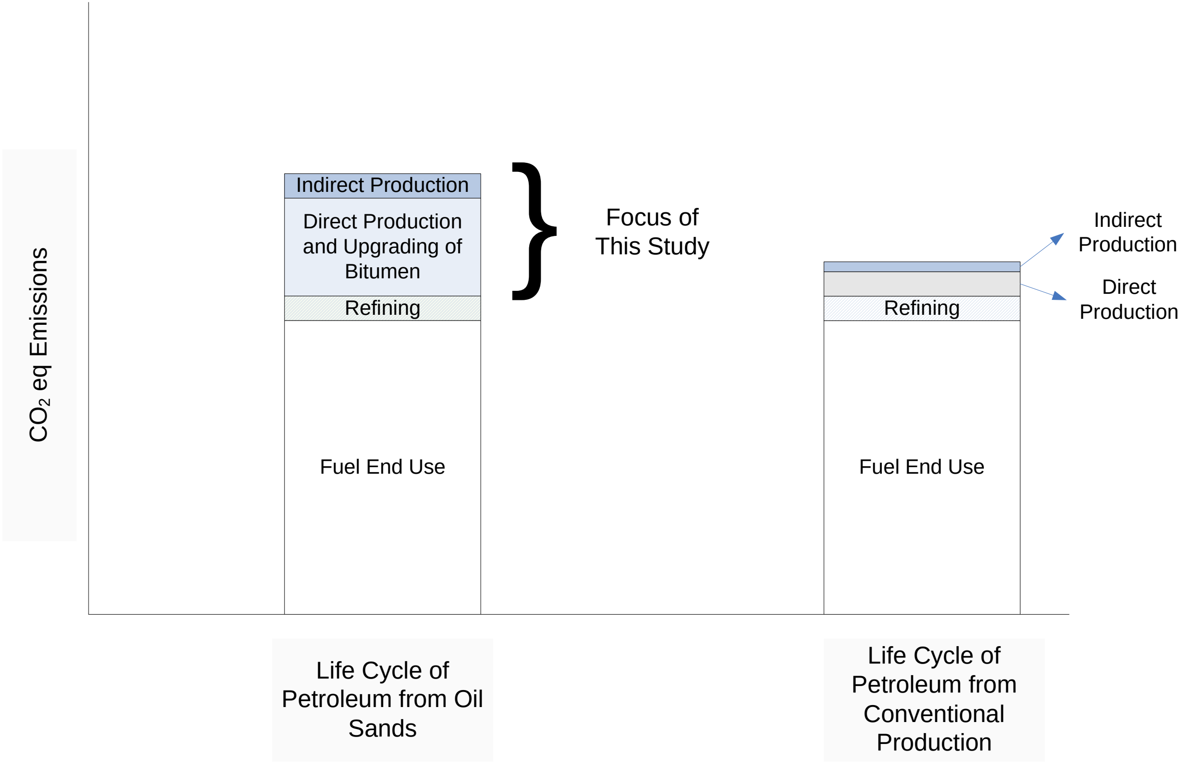

Figure 1. Life Cycle CO_2 Emissions for the Production of Petroleum from Oil Sands Operations and from Conventional Methods.

Other air emissions are important to consider when assessing the impacts of the oil sands industry. Examples of these are NOx and SO_2 emissions that are released during operations. Each of these emissions are more than double those from conventional oil production (~ 0.095 kg/barrel for conventional and ~ 0.23 kg/barrel of bitumen from oil sands)[11]. In 2000, NOx emissions from oil sands operations represented 6% of Alberta's and 2% of Canada's NOx emissions. If oil sands production increases to 5 million barrels/day without any further reductions in NOx emission intensity, the contribution from oil sands operations will increase to 31% of Alberta and 8% of Canada's emissions (assuming total emissions from all other sources of NOx remain constant). The contribution from oil sands operations to SO_2 emissions in 2000 was 18% of Alberta and 4% of Canada's total emissions. If production is increased to 5 million barrels per day this contribution would increase to 92% and 20% respectively.[12]

Other environmental impacts to consider in assessing the overall impacts of this industry include land and water impacts. The land for the operation site itself, as well as the disruption caused by the infrastructure required to support the operation (e.g. roads, pipelines etc.). The water impacts include both the removal of water from nearby water bodies, as well as the impacts of contamination of water bodies due to the operations.

Oil Sands development is an example of a more general phenomenon: the transition to produce hydrocarbon transportation fuels from heavier/dirtier feedstocks[13]. As oil prices remain unstable and high, interest in Canadian oil sands, Venezuela's extra-heavy oil, oil shale, as well as gas-to-liquids, coal-to-liquids[14], and gasification of other petroleum products (e.g. coke, asphaltene) continues to increase. The transition to increased use of these options will result in a different set of environmental concerns as well an increase in emissions in many cases[15]. Lessons learned from a more detailed life cycle assessment of the oil sands industry will provide valuable insight into the issues that are common among these alternative transportation fuels.

The upstream impacts discussed in this section have received little attention to date and ignoring them could be a source of potential liabilities for the oil sands industry and the province of Alberta. For example, since the costs incurred by companies within the supply chain will eventually be passed on to the oil sands operators, they may wish to design processes that minimize the potential for increased costs under an economy wide carbon tax. The potential research projects discussed in following sections of this report will focus on opportunities to reduce impacts from the indirect and direct production phases of the oil sands life cycle.

3.0 Life Cycle Assessment Methods

The LCA framework allows for the examination of the environmental impacts associated with products and processes from extraction of materials to disposal of residuals. LCA is particularly appropriate for complex systems, and for systems where the impacts of capital construction and supply chain activities are significant compared to those that arise during operations.

The conventional method for LCA is based on process models. The U.S. Environmental Protection Agency and the Society of Environmental Toxicologists and Chemists developed and formalized process-based LCA methods in the 1990's[16,17]. The central challenge for process-based LCA is to define the boundaries of the analysis. If a given process requires some input (e.g. cement), one must expand the process analysis to compute upstream mass and energy balances for cement manufacture. Thus, the analyses tend to be time consuming and expensive. The boundary for the analysis is often drawn tightly, excluding potentially important activities with significant life cycle impacts. Results may therefore be strongly dependent on the choice of analysis boundaries.

Recently, an alternative approach to LCA has been derived from economic input-output (EIO) models. Economic Input-Output Life Cycle Assessment (EIO-LCA) is based on an augmented EIO framework originally proposed by Leontief[18], and implemented (for the US economy) by researchers at Carnegie Mellon University[19,20]. EIO-LCA is based on detailed economic and environmental data. The method combines standard EIO table data gathered by governments (industry by industry matrices which represent the inputs from all sectors of the economy into all other sectors as well as the distribution of each sector's output throughout the economy) and a matrix of sector level environmental coefficients. The EIO-LCA models enable the estimation of economy-wide economic and environmental impacts (e.g. total CO_2 emissions across the supply chain) of a production decision. EIO-LCA has two principal advantages over the conventional process-LCA. First, the use of a consistent boundary (the entire economy of the relevant region) and second, the use of publicly available data, which respectively lead to a larger proportion of indirect effects being considered in the LCA and to rapidly-reproducible results.

EIO-LCA models solve the system boundary issues that plague process-based LCA, but their application is limited by the resolution of the sectoral data. In the case of the Canadian EIO-LCA model described in section 3.2, only 117 sectors are used to represent the entire Canadian economy making it impossible to apply the method to directly estimate life cycle impacts of specific and prospective oil sands technologies.

3.1 Previous LCA Work that is relevant to the study of Oil Sands Technologies

Very few studies have actually produced life cycle analysis of emissions from Oil Sands operations. In 1999, McCann et al., produced a greenhouse gas life cycle analysis for Suncor and Syncrude and compared the emissions to other methods of petroleum production[21]. Oil sands operations (typical production blended for the two companies) were estimated to produce life cycle emissions in 1995 of 4.0 metric tons of CO_2 eq/cubic metre of transport fuel used in central North America. This is roughly 16% greater than Canadian light crude, 11% greater than Saudi light crude and roughly the same as very heavy, partly upgraded product from Venezuela. They found that 66% of the emissions come from the transport fuel combustion phase. Of the remaining 34%, 57% comes from the production phase. The byproduct equivalent, refining emissions, and transportation emissions produce 9%, 4%, and 1% respectively of the total emissions. Table 1 shows a summary of emission estimates from several previous studies.

Researchers at Argonne National Laboratory conducted an analysis which compares the energy use and GHG emissions of nuclear, coal and natural gas to supply the energy and hydrogen to the oil sands industry using the GREET model (discussed later in this report)[22].

Furmisky, 2003 estimated carbon dioxide emissions from literature values for oil sands operations using two different coking processes[23]. The total life cycle emissions range from 3.1 to 4.1 metric tons of CO_2 per cubic metre of synthetic crude oil. The fluid coking process was found to have lower CO_2 emissions than the delayed coking process. The transport fuel combustion phase was found to be 70-80% of the life cycle emissions.

Some oil sands companies are currently reporting their annual emissions including the upstream emissions[24]. However, the definition of "upstream" is unclear. It appears that it is simply the emissions from the energy used in the extraction and upgrading processes.

Table 1 shows a summary of the GHG emissions calculated from LCAs conducted on oil sands operations to date. The table shows that the boundaries for analysis vary as do the emissions estimated in the production phase (0.38-1.4 metric tons of CO_2 eq/m^3) for oil sands operations. There is much less variation in the transport phase (2.5-2.7 metric tons of CO_2 eq/m^3).

A follow up to the Oil Sands Technology Roadmap was a study that reviewed the long-term R&D opportunities for bitumen recovery technology[25]. This study outlines and prioritizes research and development areas in terms of GHG emissions reduction potential and project costs versus potential payback. This study also summarizes several stages of the oil sands extraction process and is the only study found to date that does this for in-situ versus mining operations.

The boundaries of these studies are not clearly outlined. It does not appear that any of these studies take into consideration the economy wide impacts that are possible to assess using the EIO-LCA tool. A dissertation from the University of Alberta developed a method for boundary selection in LCA[26]. Another chapter of the dissertation deals with uncertainty and the method is demonstrated using the oil sands operations as an example[27].

Several LCA studies have investigated alternatives to oil for transportation. One such study looked at biomass as a potential fuel source and made a comparison as to whether the biomass should be transported either by trains or trucks in addition to the optimum transportation distance based on minimizing emissions[28]. This research might be helpful for comparisons of overall life cycle emissions for alternative fuels. In addition, the location considered in the analysis is Alberta, so some of the transport distances and emissions could be applied to the Oil Sands analysis.

LCA Study Details			CO$_2$ Emissions by Life Cycle Phases (metric tons of CO$_2$ eq/cu metre of transport fuel used in central NA)				
			Production	Transportation	Refining	Transport Fuel Combustion	Total[a]
McCann, 1999[29]	Canadian Light		0.21	0.057	0.57	2.6	3.4
	Saudi Light		0.25	0.16	0.57	2.6	3.6
	Typical 1995 Synthetic Crude Oil		0.78	0.052	0.53	2.6	4.0
	Typical 2005 Synthetic Crude Oil (Projection)		0.66	0.051	0.52	2.6	3.8
	Venezuela Heavy (primary / waterflood)		0.22	0.073	0.75	2.7	3.7
	Venezuela Very Heavy, partly upgraded		0.50	0.045	0.73	2.7	4.0
Furimsky, 2003[30]	Fluid Coking	Case A	0.57	-	0.13	2.5	3.2
		Case B	0.44	-	0.13	2.5	3.1
	Delayed Coking	Case A	1.4	-	0.13	2.5	4.1
		Case B	1.0	-	0.13	2.5	3.6
		Case C	0.88	-	0.13	2.5	3.5
Performance of Current Operations and Targets	Syncrude 2004		0.74	-	-	-	-
	Syncrude Target 2007		0.53	-	-	-	-
	Suncor 2004		0.38	-	-	-	-
Flint, 2005[31]	SAGD + Upgrader	Low estimate	1.0	-	-	-	-
		High Estimate	1.1	-	-	-	-
	Mining + Upgrader	Low estimate	0.60	-	-	-	-
		High Estimate	0.80	-	-	-	-

Table 1. Summary of GHG Emissions Estimates from LCA Studies of Oil Sands Technologies

Kaul et al., 2004 argue that efficiency and cost aren't the only metrics that should be considered when investigating alternative fuels for transportation[32]. Decision parameters such as centralized versus decentralized technologies, cost evaluations, taxation, and ecological/social benefits are also important. Matos and Hall, 2006 have proposed a framework for evaluating the fitness of LCA for corporations in managing their individual research needs[33]. This framework draws on complexity theory, risk management, stakeholder theory and innovation dynamics literature. Sustainable development issues affecting a corporation are considered including economic, social and environmental.

Several other LCA studies of other industries have the potential to contribute to the current LCA oil sands work. The Pembina Institute has conducted LCA analysis for various economics sectors in the Alberta economy. An example of these studies is an LCA of the fuel supply options for fuel cell vehicles[34]. One LCA study focused on re-refining waste oil in Japan[35]. This study might also present a comparison for emissions of alternatives to oil sands operations. A life cycle analysis of an enhanced oil recovery project in Texas as a

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[a] Note: These totals do not include the indirect impacts from the production phase. For example, including the indirect GHG emissions to Syncrude operations would increase the 2004 production GHG emissions by 19% and Syncrude's 2007 production target GHG emissions by 26%.

potential method for reducing GHG emissions produced process emissions that are minimal in comparison to original life cycle and the project was shown to be feasible[36]. Another study investigated the thermodynamic efficiency and the environmental sustainability of five processes that deliver gaseous energy carriers[37]. These include natural gas, syngas from coal gasification, and hydrogen from steam reforming of natural gas and alkaline electrolysis. This is a multiscale study that resembles LCA. A study that investigates the consequences of using low-quality petroleum provides some LCA data collected from previous studies[38]. Gate-to-gate energy information from 86 chemical manufacturing processes was used to perform a comparative life cycle assessment of these processes[39]. This analysis found that half of the organic chemicals required between 0 and 4 MJ per kg. The process energy requirements are presented in terms of net energy, electricity, steam, heating fuel, potential recovered energy, heat transfer fluid, and raw materials required. A life cycle inventory was taken from the perspective of petrochemical intermediates (e.g. how much crude oil it takes to produce 1000 kg of n-parraffins)[40]. This study investigates a wide range of intermediates as well as environmental impacts (solid waste, energy consumed, water and air emissions, carbon dioxide, etc.).

Several LCA studies have been conducted to investigate the environmental impacts of electricity generation[41,42, 43]. One such study looked at the life cycle impacts of an existing gas/oil-fired generation facility in order to suggest changes to improve environmental performance[44]. Another study collected a life cycle inventory for U.S. electricity generation[45]. This study used the DOE's EGrid model and Ecobilan's DEAM LCA database to estimate the upstream emissions for each NERC region in North America. The emissions considered in this analysis were CO_2, SO_2 and NOx, and Hg.

Other Relevant Data and Analysis

There is a lot of additional data available in other studies. Depending on the requirements of the analysis being conducted, the following summary of studies could be helpful. Gray and Masliyah, professors at the University of Alberta, offer a two day intensive course on the extraction and upgrading of oil sands bitumen[46]. The notes from the course provide data on the economics and technical aspects of the oil sands industry. Statistics Canada provides valuable data in their Energy Statistics Handbook[47]. This data contains economic data by industrial sector, as well as energy production and consumption at a higher level of aggregation.

Research and Development Directives

The Alberta Chamber of Resources produced a technology roadmap for oil sands technologies in 2004[48]. This report summarizes the state of the art for technologies involved in the extraction of bitumen, as well as the potential for new technologies and challenges for the industry. The technological reality and prospects are reviewed for mining based bitumen extraction, in-situ bitumen production, upgrading, energy and hydrogen, as well as air emissions. The data presented in this report is at a high level (i.e. industry averages).

A follow up to the Oil Sands Technology Roadmap reviewed the long-term R&D opportunities for bitumen recovery technology[49]. This study outlines and prioritizes research and development areas in terms of GHG emissions reduction potential and project costs versus potential payback. The study identified 42 program areas with an estimated current investment of $25 million that can lead to new technologies associated with the upgrading process. They also estimate that the greatest potential for GHG emissions reduction within the oil sands industry is in the extraction phase of the SAGD process. They estimate that with use of solvents in the recovery stage, up to 50% of GHG emissions could be reduced. Efforts to reduce hydrogen consumption by various methods outlined in the report can result in an overall reduction of hydrogen requirements by 10%. They estimate that there are few technologies on the horizon that will significantly reduce the GHG emissions from the mining and upgrading phases.

The Alberta Energy Research Institute plays an integral role in assessing the research and development directives set for Alberta's energy supply[50]. In a recent report, AERI identified 8 research and development priorities which include geological sequestration, adaptation of integrated gasification and combined cycle systems, catalytic upgrading research and development, lower intensity oil sands production, a water resource and technology program, establishment of dedicated hydrogen production, storage, and infrastructure research and fuel cell demonstration program, utilization of solvent deasphalting process, as well as the investigation of the interaction between these technologies. All of these research areas overlap with the oil sands industry in Alberta. These priority areas suggest areas of focus for future LCA of oil sands research.

The Cleaner Hydrocarbon Technology Futures Group (a collection of public sector government officials from Alberta, British Columbia, Saskatchewan and Canada) suggest that the following areas be developed as strategic areas for addressing climate change obligations in Canada[51]: sustainable conventional oil and gas production; unconventional natural gas; oil sands and heavy oil resource development; coal bed methane; enhanced oil recovery using CO_2; integration of hydrocarbon resource development to produce petrochemicals; oil; gas; electricity and hydrogen as by-products, and investigation of environmental issues affecting the air, land and water ecosystems. They found that initiatives started now to reduce GHG emissions in Alberta will have modest but significant results by 2020.

Alternatives

Several studies investigate alternatives to various aspects of oil sands operations. For example, the development and deployment of hydrogen technology will influence the economic and environmental impacts of oil sands operations[52]. A recent study in *Energy* highlights the steps that are required to realize a hydrogen economy[53].

Renewable energy studies have also overlapped with oil sands research. Some argue that renewable energy should be developed as a replacement for oil sands extraction (and other fossil fuels in Canada)[54,55], while others argue that they could compliment each other[56,57].

A recent survey conducted by the Athabasca Regional Issues Working Group of the oil sands industry determined that there could be 30 co-generation plants located within 25 oil sands projects in Alberta by 2014[58]. However, the installed capacity of co-generation per barrel produced has decreased over the period surveys of the past 5 years. It was concluded that this indicates the move towards matching co-generation to electrical requirements as compared to the installation of excess co-generation for export potential. High gas prices and low pool prices have driven companies to build co-generation capacity closer to the site needs with minimum export capacity. Reliability of supply is still one of the driving factors for building co-generation plants.

A study in 1986 compared the costs and technical challenges associated with producing hydrogen for oil sands upgrading from natural gas reforming, coal gasification and water electrolysis[59]. This study found that the hydrogen demand for synthetic crude upgrading is higher if the synthetic crude is produced from coal instead of bitumen. This study recommends coke gasification and water electrolysis for hydrogen production. However, since this study was conducted in 1986, the assumptions of the model might not apply to current technologies and economic environment.

Forecasts and Future Scenarios

Forecasts have been used to assess the impacts that oil sands development will have on the Canadian and Global economies[60,61,62,63]. Natural Resources Canada forecasts that by 2020 the oil sands will supply 53% of Canada's oil production (from 22% in 1995)[64]. A shorter term forecast highlights the need for pipeline infrastructure to support the fast paced growth within the oil sands industry[65]. This forecast expects that production from mining operations will be close to 725 million barrels per day and in situ processes to 484 million barrels per day by the end of 2006.

The Canadian Association of Petroleum Producers produce a supply forecast for Canadian crude oil production[66]. This forecast from 2005-2015 highlights the need for new oil pipeline capacity and focuses primarily on western Canada.

A study of global energy scenarios for the transportation sector provides life cycle costs for various alternatives to gasoline vehicles and shows the costs in terms of drive train, infrastructure and fuel costs[67]. This study also provides personal transport activity by transport mode. This data might be a good comparison for a study of life cycle economic impacts of oil sands development.

Future energy scenarios that make the transition away from fossil fuels are identified and the technical/policy challenges associated with making this transition are highlighted in a recent Energy Policy study[68]. This study lists the future challenges to global energy supply as growing oil scarcity, security of supply, environmental degradation and energy and the poor.

Horn, 2004 argues that production of unconventional oil based on oil sands or coal will help to regulate price of crude oil which means that crude oil prices above $30/barrel will not be sustainable for a long period[69].

3.2 LCA Framework Components

In order to address the relevant policy questions in the oil sands industry, a hybrid LCA framework should be developed and employed in order to combine process-based and EIO approaches. This should combine three elements:

a. An EIO-LCA model of the Canadian economy.
b. A region- and sector-specific process model.
c. Data specific to oil sands technologies.

The process model takes as input Canadian average data from the EIO-LCA model (e.g. GHG emissions per dollar spent on non-residential construction), and combines it with region specific data (e.g. transportation requirements specific to Fort McMurray and associated emissions) to produce estimates of the life cycle emissions for important oil sands inputs (e.g. life cycle GHG emissions per unit of industrial construction expenditure at Fort McMurray). Finally, estimates of the inputs required for specific oil sands processes derived from data supplied by participating companies are used to estimate emissions per unit production (e.g. per barrel of synthetic crude oil) from the entire life cycle.

a. EIO-LCA model of the Canadian Economy

EIO-LCA methods were implemented for the U.S. by researchers (including H. MacLean, a current proposal applicant) within the Green Design Initiative at Carnegie Mellon University. At the University of Toronto, Professor MacLean's research group has implemented a national Canadian EIO-LCA model[70,71]. The current model has 117 industrial sectors and includes economic and environmental data for the year 1997 (the most recent available benchmark year). The model has been implemented in MATLAB for computational flexibility. The environmental metrics included in the current model are GHG (CO_2, nitrous oxide and methane) emissions and energy use. The data is from Statistics Canada. The EIO table was obtained from the Canadian Input-Output accounts, and the environmental outputs for each industry was obtained from the Canadian System of National Environmental Accounts.

Improved representations of Canada-US trade in the EIO-LCA model (previous analysis, Norman and MacLean 2005[72], has shown that trade is a critical component for Canadian LCA studies); and, improved regional and sectoral resolution of the model using provincial electricity data and/or 'L' 500-sector Canadian economic data are planned additions to the model.

The current Canadian model includes economic, energy use and greenhouse gas emissions data. However, this analysis would benefit from additional data that will either be added to the model or combined with model output. This additional data includes conventional air pollutants, water, toxic releases, etc.

The following discussion outlines the data and analysis that might be useful for building the Canadian EIO-LCA model. The economic data are discussed first, followed by the environmental data.

Economic

The economic input-output tables have already been built for the Canadian EIO-LCA model (using Statistics Canada data). However, other data exists that could improve some aspects. For example, a recent CERI report presents data for economic sectors at a provincial level[73]. Much of the data in this report comes from the Canadian Association of Petroleum Producers (CAPP) 2004 Statistical Handbook. If possible, this data could be obtained from CERI and either be incorporated into the existing Canadian model or built into a separate Alberta and Oil Sands specific model. In addition to this data, this report attempts to evaluate the labour impacts from the oil sands development at a provincial, national and international level.

Another recent CERI report[74] assesses the potential supply and costs of crude bitumen and synthetic crude oil in Canada. This data could be used in the disaggregation of the oil and gas sector within the EIO-LCA model. However, the data in this report might be better suited to the process model development and is discussed in the following section.

The Production Exchange Consumption Allocation System (PECAS) land use modelling system was developed at the University of Calgary[75],[76]. This spatial input-output model incorporates temporal aspects of the market as a time series simulation with agent based computational economics. Supply-demand interaction are also incorporated and the system is run as a short run equilibrium. The Canadian EIO-LCA model evaluates a snapshot in time and is a linear model that does not allow for more geographic area to be evaluated at a time. If a more complex model is desired (for example, a system that interacts spatially or temporally), the PECAS model framework would be helpful.

Environmental

Natural Resources Council of Canada published the Energy Use Data Handbook in 2005[77]. This report summarizes total energy used and greenhouse gases emitted for 37 sectors in the Canadian Economy from 1990 to 2003.

Environment Canada's GHG Inventory provides flexibility to represent the data by greenhouse gas and by province[78]. This data could be used to disaggregate the GHG emissions in the existing Canadian EIO-LCA model. The provincial data could be used for a provincial EIO-LCA model.

Nyboer, et. al developed both energy intensity and greenhouse gas intensity indicators for Canadian industry[79,80]. In an effort to promote energy conservation throughout industries in Canada, NRCan tracks energy consumption, production and intensity (energy consumption per unit of production). The data presented in the report are disaggregated into 26 major industrial sectors (2 or 3 digit NAICS categories) and 101 smaller industry groups (3,4 or 5 digit NAICS categories). This data can be used (and already is) to represent energy intensity factors for the sectors in the Canadian EIO-LCA model. The data for the GHG emissions is broken down by GHG type. Therefore, this data should be used to disaggregate the GHGs in the Canadian EIO-LCA model.

Environment Canada produces criteria air contaminant emission summaries for Canada (disaggregated into 65 sectors). The criteria air pollutants are represented for the year 2000 and include particulates, PM10, PM2.5, SOx, NOx, VOC and CO. The sectors listed do not map directly to those considered in the Canadian EIO-LCA model, but some mapping should be possible[81].

Environment Canada also conducts a water use survey for industries in Canada every five years and publishes a report summarizing the survey[82]. The data presented in this report includes employment, intake, recycle rate, gross water use, discharge, consumption, treatment, water source, purpose, and acquisition cost. The data is also disaggregated by province/region and is available by month.

Two transportation LCA models have recently included oil sands operations data and overlap in design and application with the Canadian EIO-LCA model.

Natural Resources Canada has incorporated oil sands parameters into their LCA model – the GHGenius model. This model considers the life cycle costs (of GHG reduction options only), energy consumption and GHG emissions. However, it appears that the data used to represent the oil sands component are average values for the entire industry (i.e. you can't specify if the bitumen or synthetic crude is produced from mining or in-situ operations). The EIO-LCA model can inform the GHGenius model of the full life cycle costs (the economy wide upstream costs). In addition, if the EIO-LCA model incorporates the disaggregation of the oil and gas sector to separate mining and in-situ operations, this data could be helpful to the GHGenius model. The GHGenius model is also limited to GHG emissions. If the EIO-LCA model is expanded to include other environmental impacts, the results could be helpful for the GHGenius model as well. Conversely, the GHGenius model could help to provide data specific to the oil sands operations. In addition, it could be used to calibrate the EIO-LCA model.

The Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation (GREET) model was developed at Argonne National Laboratory and is very similar to the GHGenius model in terms of the parameters considered and focus on end use fuels of the transportation sector. In addition to GHG emissions, this model also includes regulated emissions (VOC, CO, NOx, PM_{10} and SOx). The current model appears to present average data for the industry but allows the user to input whether the operations are 100% mining or 100% in-situ operations. Upstream emissions (i.e. construction of facilities, materials in extraction machinery, etc.) do not appear to be included in either of these models.

b. Region and Sector Specific Process Model

The region and sector specific process model will serve to integrate the national average data from the EIO-LCA model with the data collected from companies within the oil sands industry. This model will be process based and will provide the regional and sectoral specificity required for the proposed analysis.

For example, the economic sector that oil sands production falls into is “oil and gas extraction”. Not only do we want to be specific about the difference between conventional oil extraction and oil sands operations, we also want to be able to distinguish between in situ and mining of oil sands in Alberta. This deeper level of granularity can only be achieved by applying the process-based LCA framework. A possible method of overcoming this issue is the integration of the input-output models that have been built by the Canadian Energy Research Institute (CERI). The models have been built for “Alberta”, “Ontario”, “Quebec” and the “Rest of Canada”. Each model is comprised of 19 sectors and 19 commodities and segments the upstream energy industry as follows: coal mining, natural gas and crude oil and oil sands. The historical data used in these models derive from Statistics Canada and the Canadian Association of Petroleum Producer’s Statistical handbook. The forecasts of investment and production in the oil sands industry are from CERI’s Oil Sands Supply Outlook.

There will be several research questions that are geographically specific to the Alberta area. Since the current Canadian EIO-LCA model is at an aggregated national level, more specific data will be used to supplement the results from the model. As noted in the previous section, this can either be done by modifying the EIO-LCA model or by using data specific to the oil sands area outside of the model.

Finally, EIO-LCA is a cradle-to-gate model. Therefore, model results will need to be supplemented with use and end-of-life data (as applicable) in order to have a complete LCA.

c. Data Specific to Oil Sands Technologies in Alberta

Industry interaction is essential to providing decision support tools that are relevant and timely for the industry. We will work with our research partners to understand the technologies that are used today and those that are being developed for future deployment. The data collected from companies in Alberta will be used to supplement the output from the two models discussed above, as well to determine which applications would be most relevant.

Economic

A recent report from the Canadian Energy Research Institute (CERI)[83] contains a wealth of oil sands specific economic data. This data can be used for the process specific economic data requirements. In addition, the report provides a breakdown of capital expenditures for the projects. This information can be used as input to the Canadian EIO-LCA model in order to determine the environmental impacts of infrastructure investment in Oil Sands operations. The data in this report states supply costs in the unit of “cost per barrel”. These costs include capital, operating and maintenance costs, royalties and taxes for existing Oil Sands projects as well as several proposed projects in Alberta. The costs in this study can be viewed by extraction method (i.e. in situ vs. mining), whether upgrading is included and how the economic feasibility of these projects is affected by crude oil prices. This data does not specify which sectors are involved in these expenditures. This data is required to assess the upstream impacts and therefore this data still needs to be acquired.

Environmental

Nyboer, et. al developed both energy intensity and greenhouse gas intensity indicators for Canada at a national aggregate level as well as individual industrial sectors. One such assessment is for Canadian oil sands operations and heavy oil upgrading[84].The data collected for this report are from surveys conducted within the industry. Responding facilities include Husky Oil, Shell Canada Products Ltd., Syncrude Canada Ltd. and Suncor Energy Inc. This study provides detailed data about the consumption of all forms of energy in addition to the CO_2 eq. emissions from each energy source. This data ranges from 1994 to 2001 and could be helpful in building process level data for the oil sands LCA work.

The Canadian Council of Ministers of the Environment carried out a benchmarking study of refinery emissions performance[85]. A regression analysis was conducted in order to determine the factors that affect the emissions from refinery operations. This helped to normalize the emissions in order to compare the emissions performance between the refineries in Canada and comparable refineries in the U.S. The regression factors considered include size, and plant characteristics for each emission type. The emissions considered include CO, VOC, SOx, NOx, PM, PM_{10}, $PM_{2.5}$, NH_3. This detailed level data provides information for comparison with oil sands operations.

The Climate Change Issue Table conducted a study to evaluate the aggregate emissions for the refining and consumption of fuel in the downstream sectors of the petroleum industry[86]. The data is provided by fuel type and includes the energy intensity indicator. It also summarizes the Canadian primary energy demand for refined petroleum, natural gas and refined petroleum product.

4.0 Applications of Oil Sands LCA

In this section we catalog, but do not prioritize, policy-relevant research questions which could possibly be addressed by oil sands LCA.

a. LCA of existing operations

A good starting point for assessing the impacts of oil sands operations is to conduct an LCA of current operating facilities in Alberta. This assessment would allow the comparison of mining versus in situ extraction operations. The metrics for analysis would start with a breakdown of the capital and operating costs. While high level economic data is available for most currently operating facilities[87], there is a lack of detailed financial data. In order to assess the environmental impacts of these operations, this detailed economic data is required.

In addition, the flow of material should be tracked. This should include how much material is required, the distance that the materials are shipped and by which transport method. The third step in conducting this analysis would be to assess the amount of energy required in each stage of the operation. For example, roughly 1 GJ of natural gas energy is required to produce 1 barrel of synthetic crude from the in situ extraction phase. For the mining extraction phase the energy requirement is roughly 0.25 GJ of natural gas. In addition, electricity is required (roughly 0.0083 and 0.0147 GJ respectively). However, additional upstream energy is required to produce products consumed in the construction and operation of the oil sands extraction site, as well as the energy required to transport those materials. Once the cost, energy and material flows have been accounted for, the environmental impacts can be assessed. Due to increasing concern about the impacts of climate change, the GHG emissions from all phases of the life cycle should be calculated. These emissions are very different between in situ versus mining operations, as well as for different choices made in terms of fuel choice, material selection, etc.

Other impacts also require consideration and are discussed below.

Water Impacts from Oil Sands Development

The water systems in Northern Alberta are greatly affected by Oil Sands development and operation. For mining operations, these impacts take the form of muskeg and overburden drainage, aquifer dewatering, direct withdrawal of water from the water bodies such as the Athabasca River, and the long-term water management of tailings[88]. For in situ operations, the impacts include lowering the levels of groundwater aquifers and the production of large volumes of waste associated with water treatment.

The consumption of water varies from site to site, but ranges between 2 to 5 cubic metres of water withdrawn from the Athabasca River for every cubic metre of bitumen extracted. Less than 10% of the water approved for withdrawal is returned to the river[89]. For every m^3 of bitumen produced through in situ methods, 0.2 m^3 of additional groundwater must be added to produce additional steam (of the water that is removed, 90-95% of it is de-oiled and reused). Oil sands companies are currently licensed to divert a total of 349 million cubic metres of water from the Athabasca River – enough to satisfy the needs of a city of two million people[90]. The Athabasca river has an average flow rate of roughly 1000 m^3 per second, however, it is closer to 200 m^3 per second during the driest period of the year[91]. If 349 million m^3 per year were actually removed from the river, it represents roughly 6% of total flow.

Tailings accumulated during oil sands operations are approximately 6 cubic metres for every cubic metre of bitumen produced. The tailings are comprised of 3-5 cubic metres of water and approximately 1.5 cubic metres of fluid fine tailings[92,93]. The risks associated with these tailings are the migration of pollutants into the groundwater system and leakage into the surrounding soil and surface water. For example, naturally occurring naphthenic acids in rivers in the region are generally below 1 mg/L but may be as high as 110 mg/L in tailing ponds[94]. Tailing ponds are used to settle the fluid fine tailings out of solution. This process can take a few decades to 150 years depending on the technology employed. By 2020 the volume of fluid fine tailings from Syncrude and Suncor is estimated to exceed 1 billion cubic metres[95].

The U.S. EIO-LCA model includes water use as one of the environmental parameters. Even though the data used in this module dates back to the 1980's (and does not include oil sands operations specifically), the results from the model can provide some insight into the importance of water use from the operation phase of the oil sands production life cycle. The "petroleum refining" sector shows that for every barrel of oil produced, 2.0 cubic metres of water are used, 1.6 cubic metres of this are directly from the "petroleum refining" sector. Roughly 0.2 cubic metres are used in the "industrial inorganic and organic chemicals sector" and smaller quantities are used in the "blast furnaces and steel mills", "paper and paperboard mills", and "chemicals and chemical preparations, n.e.c." sectors (these values are calculated assuming a price of oil of $60/barrel USD). This shows that roughly 78% of the water used to produce a barrel of conventional oil is in the refining phase. However, roughly 1.6 cubic metres of water are either recycled or reused in the processing of 1 cubic metre of oil in the "petroleum refining" sector.

It is clear that the impacts of oil sands operations on water are significant. It is less clear where the application of LCA can be used to improve our understanding of these impacts. For example, the EIO-LCA tool can be adapted to include water use from every sector in the economy. If this data were used in an LCA comparison of mining versus in situ operations, a total life cycle water use quantity can be calculated for each operation. However, if these operations are taking place in two different locations, removing water from different water bodies, the comparison adds little.

Comparing environmental impacts of water use and environmental impacts of CO_2 emissions is futile. A more constructive approach is to value the mitigation effort required for both of these activities. Many studies do this for $CO_{2,}$ but it is less clear for water and would require additional investigation.

A Pembina report from 2003 outlines the use of water in the oil and gas industry in Alberta as well as the current legislature related to this use[96]. Finally, they made recommendations on how to improve the current situation. Other literature has been developed to assess the impacts of the treatment of waste and wastewater[97,98] as well as remediation of areas affected by oil sands operations[99].

Labour

A recent report from the Canadian Energy Research Institute attempts to evaluate the labour impacts from the oil sands development at a provincial, national and international level[100].

The Petroleum Human Resources Council of Canada conducted a study of the challenges and trends in the upstream petroleum industry[101]. This study highlighted a trend towards a concentration of assets in large companies, as well as the skills and identified workforce demographics, skill and competency requirements, and occupational supply and demand.

The Construction Workforce Development Forecasting Committee produced a forecast for several construction-related trades in Alberta[102]. The oil sands industry was included in this study.

Land Use Impacts

There are currently over 100,000 km of linear developments in the Al-Pac FMA[103], with an average density of 1.8 km/km^2. If forestry activity persists at current levels, and if the energy sector expands at expected rates, the average density of linear developments will increase to over 5.0 km/km^2. This trend would have negative effects on many species. For example, woodland caribou habitat quality in the study area has declined by 23% over the past several decades, with further declines expected if trends in industrial development continue.

Considering the operation site, it appears that surface mining techniques disturb much more surface area than in situ operations. However, this does not take into account the fact that 4 times as much natural gas is required per barrel of bitumen for the in situ process. This means that 4 times as much natural gas infrastructure is required as well. One of the biggest impacts of land use is the fragmentation of land. Therefore, surface area is less important than the linear distance within a given area.

A more thorough analysis that includes the impact of land fragmentation is required to provide a more robust comparison between the two options for extracting oil sands resources. This analysis could be carried out by obtaining remote sensing data images for the Alberta area. A tool such as IKONOS[104] could provide satellite data at various levels of spatial resolution. This data could be used to create land cover and land use maps. Metrics could be determined to measure the impact of fragmentation on the area of interest. Software tools such as FRAGSTATS[105] would interpret the land use/cover maps to provide such results. The Wilderness Society Study used ArcView 3.2 and RoadNET[106].

Several studies in Alberta using remote sensing for the natural gas and oil industries have been found. These include the use of remote sensing for monitoring gas pipeline right of ways[107, 108]. However, a study that looks at the fragmentation of land in Alberta due to natural gas and oil operations has not yet been found.

b. Comparing mining with in situ *production.*

In situ extraction projects are generating an increasing share of oil sands bitumen production. In situ techniques offer lower land use impacts and upfront capital costs, but require large energy inputs for steam production. In situ extraction methods are becoming more integrated with upgrading technologies (e.g. the Nexen/OPTI process) and may be integrated with mining operations at the bitumen transport and upgrading phases. Sound decision-making about development of future mining and in situ operations requires improved methods for accounting for the life cycle environmental impacts of the two methods of oil sands production.

b. Prospective Technologies

Life cycle methods have generally been applied to existing technologies, but such techniques can also be employed prospectively, to assess and compare the life cycle costs and impacts of technologies now under development. Prof. MacLean and colleagues have conducted such studies (e.g. Spatari et al. 2005[109]).

Researchers will work with scientists, engineers, and members of the business community who are developing new oil sands technologies to develop and refine techniques for prospective LCA. These techniques will enable systematic estimates of the life cycle impacts of oil sands development in the period 2020 and beyond. Perhaps more importantly, these techniques will help the prioritization of research and development activities by identifying technologies, or optimal combinations of technologies, that would provide particularly large life cycle benefits.

c. Coal as a Substitute for Natural Gas

The price and availability of natural gas in North America has forced energy intensive industries to reassess their fuel supply options. This is especially true of the in situ oil sands operations in Alberta which consume large quantities of natural gas (roughly 1000 standard cubic feet per barrel of synthetic crude)[110]. We will apply the LCA model to investigate the implications of using coal to supply heat, electricity and hydrogen to oil sands operations as an alternative to natural gas. Coal is an inherently dirty fuel and rail systems are costly to build. However, the fuel itself is relatively cheap, abundant and nearby. In addition, technologies exist today that minimize many of the environmental problems associated with this fuel. In addition to the capture and removal of conventional pollutants such as NOx and SO_2, the potential for CO_2 capture and storage exists.

Applying the life cycle analysis framework to this problem is essential as the upstream and indirect impacts of these two options are non-negligible. The comparison between these two options will include economic and environmental impacts of the entire infrastructure required to operate these facilities. This includes the impacts of extracting and shipping the fuels from their source to Northern Alberta, as well as the transport of materials, construction, and operation of energy conversion facilities close to the oil sands operations. This analysis will be similar in structure to that conducted by one of the project members in this proposal[111].

d. Hydrogen for Mining Vehicles

While much of the attention devoted to hydrogen fueled vehicles has focused on use of fuel cells in light duty passenger vehicles, use of hydrogen in centrally refueled fleets using heavy diesel engines may offer much more cost- and environmentally-effective opportunities for introducing hydrogen into transportation systems. We will investigate the possibility of using hydrogen generated as part of upgrading operations to fuel the heavy equipment (e.g. dump trucks) used in surface mining operations. Given that hydrogen can currently be produced at an energy cost similar to diesel fuel, this may represent a near-term possibility for minimizing emissions from oil sands operations.

e. Other

There are several other policy questions that could be addressed using the LCA framework discussed in this document. For example, the economic and environmental impacts of exploiting transmission and co-generation opportunities within the industry, a comparison of oil sands production to conventional oil, as well as the question of where to upgrade.

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