The Canadian oil sands industry under carbon constraints

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HIGHLIGHTS

- We investigate the impact of climate policies on Canada's oil sands industry.
- A computable general equilibrium model of the world economy is applied for the assessment.
- Without climate policy, Canadian bitumen production increases almost 4-fold from 2010 to 2050.
- With regional policy, bitumen output may drop by up to 68% and upgrading moves to no-policy countries.
- With global policy, bitumen production is significantly reduced since upgrading abroad is no longer viable.

ABSTRACT

We investigate the impact of climate policies on Canada's oil sands industry, the largest of its kind in the world. Deriving petroleum products such as gasoline and diesel from oils sands involves significant amounts of energy, and that contributes to a high level of CO\textsubscript{2} emissions. We apply the MIT Emissions Prediction and Policy Analysis (EPPA) model, a computable general equilibrium model of the world economy, augmented to include detail on the oil sands production processes, including the possibility of carbon capture and storage (CCS). We find: (1) without climate policy, annual Canadian bitumen production increases almost 4-fold from 2010 to 2050; (2) with climate policies implemented in developed countries, Canadian bitumen production drops by 32% to 68% from the reference 4-fold increase, depending on the viability of large-scale CCS implementation, and bitumen upgrading capacity moves to the developing countries; (3) with climate policies implemented worldwide, the Canadian bitumen production is significantly reduced even with CCS technology, which lowers CO\textsubscript{2} emissions at an added cost. This is mainly because upgrading bitumen abroad is no longer economic with the global climate policies.

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1. Introduction

In this paper, we explore the effects of implementing CO\textsubscript{2} emission reduction policies on Canada's oil sands industry. Bitumen is petroleum based substance that can be extracted from oil sands and upgraded to a synthetic crude oil. From there synthetic crude oil can then be further refined into conventional petroleum products such as gasoline and diesel. The process involves the addition of lighter hydrocarbons, and because the synthetic crude is relatively heavy the refining process generally requires the use of cracking and other advanced refinery operations to generate a product slate with substantial fractions of the higher value petroleum products. Each part of the process involves significant amounts of energy, and that contributes to a high level of CO\textsubscript{2} emissions, and hence the industry would be affected by CO\textsubscript{2} control policies. Addition of carbon capture and storage (CCS) to the process is one strategy that could reduce the CO\textsubscript{2} implications of production but would add to the cost.

Canada has the largest oil sands reserves in the world, with Venezuela the other country with significant known extra heavy oil reserves. Venezuela extra heavy oil may be less degraded then oil sands and thus easier to be extracted. But it also requires substantial upgrading into a crude equivalent. As of 2007, it was estimated that economically recoverable oil sands reserves in Alberta were just over 160 billion barrels, making up over 95% of Canada's total oil reserves of 179 billion barrels. That estimate makes Canada second in the world only to Saudi Arabia's 264 billion barrels of oil reserves. (Government of Alberta, 2009; National Energy Board, Calgary, 2008; Energy Information Administration (EIA), 2008). The oil sands industry prospered, especially as crude oil prices rose in recent years. Although the crude price drop over the last year has slowed expansion of the
industry (Healing, 2009), existing oil sands projects may continue as long as world oil prices exceed roughly $35 to $40 per barrel (Levi, 2009). In addition, the oil peak theory (Hubbert, 1956) is another ground that supports the development of Canadian oil sands industry. More pessimistic research often argues that the oil peak of conventional crude production is imminent (Deffeyes, 2001), while even based on more optimistic research, it may arrive within decades, depending on different assumptions such as the rate of exploring new crude reserves, the development of existing oil fields, economic conditions, and climate policies (Brandt et al., 2010; Cambridge Energy Research Associates (CERA), 2006; Energy Information Administration (EIA) (2004a)). Moreover, in response to increasing oil imports from politically-stressed regions, many firms and policymakers in the U.S., Canada, and elsewhere are looking to Canada’s oil sands as an answer to energy security threats.1

However, with potential CO2 control looming in Canada, the economic viability of the industry and the value of these large reserves may be at risk. Existing studies have found that currently, the GHG emissions from bitumen production and upgrading are higher than those from conventional crude (Charpentier et al., 2009; McKellar et al., 2009). As of 2008, the GHG emissions of Canada have reached 734 megatonnes of carbon dioxide equivalent (Mt CO2-e), which is already 32% above the Kyoto target Canada once proposed (Environment Canada, 2010).2 A recent estimate for 2009 has the oil sands industry alone responsible for 41.9 Mt CO2-e, equivalent to 6.5% of Canada’s total emissions and 0.1% of the global greenhouse gas (GHG) emissions (Government of Alberta, 2012).

Bitumen can be produced with surface mining technique when deposits are near the surface or through in situ technique for deposits that are located deeper in the earth. There are varying approaches, in either case, that lead to varying CO2 emissions per barrel produced.3 Adding CCS technology increases the cost of production, and would affect the competitiveness of the industry. Canadian CO2 policy obviously could affect the industry, but policies abroad are also likely to affect the economics of the oil sands resource. Bitumen extraction itself would need to remain near the site of reserves but upgrading could occur abroad. Pressure to move upgrading abroad could result from differential CO2 control policies, creating a source of “CO2 leakage.” CO2 leakage refers to an increase in emissions outside of a regulating jurisdiction in response to its CO2 limits. CO2 regulation (domestically or abroad) may also affect the overall demand for petroleum products and thus affect the oil sands industry indirectly through the price paid for crude and petroleum products. While the addition of CCS would greatly reduce emissions from energy used in extracting and upgrading bitumen, the petroleum products that are produced would still release CO2 when finally used as fuel. Production of products from oil sands would be disadvantaged compared with conventional crude oil; as bitumen production is generally a more expensive production process than crude oil extraction, and the addition of CCS would add further to the cost and only get CO2 emissions per barrel to approach that emitted from conventional crude production.

We investigate the viability of the oil sands industry in the face of Canadian and global CO2 policies with or without CCS technology. Will it remain profitable to extract these resources? Will there be a demand for the product? Can CCS make the oil sands industry viable and under what conditions? And finally, what is the overall economic impact of climate policy on the Canadian economy, given that it may limit this large and growing industry?

To provide insights in answering these questions, we use a version of the MIT Emissions Prediction and Policy Analysis (EPPA) model, EPPA-ROIL, that includes an elaborated representation of the oil production and refining sectors (Choumert et al., 2006). Like the standard EPPA model, EPPA-ROIL is a recursive dynamic multi-regional general equilibrium model of the world economy. The elaborated treatment of oil production and refining sectors of EPPA-ROIL includes a specific representation of the oil sands industry, with separate production and upgrading activities. While in the original EPPA-ROIL, there is only a single representative bitumen production technology, in our analysis, we modify this representation so that bitumen production from surface mining and in situ projects is now disaggregated into two separate technologies. This extension allows us to take into account the various carbon footprints of different bitumen production projects. In addition to climate policy, we also consider scenarios that include CCS technology on bitumen production and upgrading, and consider cases where biofuels may or may not be the liquid fuels substitutes with low life-cycle carbon emissions. This paper is organized as follows: Section 2 presents the EPPA-ROIL model, Section 3 provides the policy scenarios and simulations, Section 4 analyzes the simulation results, and Section 5 provides the conclusion.

2. Model description

The EPPA-ROIL provides greater disaggregation of the petroleum, refining, and liquid fuels sectors compared to the standard model. As with the standard model, the world economy is simulated through time to produce scenarios of GHG, aerosols, other air pollutants emissions from human activities. The EPPA model is built on the GTAP dataset (Center for Global Trade Analysis, 2012), and is supplemented with additional data for the GHG and urban gas emissions and on technologies not separately identified in the basic economic data (Paltsev et al., 2005, Babiker et al., 2001).

The EPPA model belongs to the class of computable general equilibrium (CGE) models (Dervis et al., 1982; Shoven and Whalley, 1984; Bovenberg and Goulder, 1996; Böhringer and Rutherford, 2009) with two main components in the model: households and producers. Households provide primary factors (such as labor and capital, etc.) to producers and receive factor payments (capital and resource rents and wages) in return. Production sectors are characterized by production functions that represent the technologies in each sector. Production functions transform inputs, including primary factors (labor, capital, natural resources) and intermediate inputs (i.e., outputs of other sectors) into goods and services that are used either as intermediate goods (those used by industrial sectors as inputs) or as final goods (those used by households, government, for capital goods or exports). Imported goods compete with domestically produced goods to supply intermediate and domestic final demands.

The model aggregates the GTAP dataset into 16 regions including the United States (USA), Canada (CAN), Mexico (MEX), Japan (JPN), Australia and New Zealand (ANZ), Europe (EUR), Eastern Europe (EET), Russia Plus (FSU), East Asia (ASI), China (CHN), India (IND), Indonesia (IDZ), Africa (AFR), Middle East (MES), Latin America (LAM), and a Rest of the World (ROW) region. The economy grows as a result of exogenously specified growth in population (and therefore labor) and in labor, energy, and land productivity and through endogenously determined savings and investment. Savings is determined in a Leontief aggregation of consumption and savings in the welfare
function. All savings is used as investment, which is the source of demand for capital goods that replace depreciated capital or add to the capital stock. The capital is divided into a vanguard, non-malleable portion, and a malleable portion. The vanguard portion is sector-specific and operates with a Leontief (fixed coefficient) production function, where input shares are fixed at the time of installation based on relative factor prices at the time. Factor substitution is possible for the malleable portion, allowing implicitly for retrofit of existing capital. All new investment is initially malleable.

Natural resource capital assets in agriculture (arable land), oil, coal, and natural gas industries (fossil fuel resources), and in electricity production (water, wind/solar, nuclear) are owned by households, and their returns accrue to households as income, with the rental value/price determined by their scarcity (Paltsev et al., 2005). Land, water for hydropower, and solar/wind are renewable resources, and fossil resources are depletable. Physical quantities of energy and land resources are tracked with supplemental accounts to facilitate the analysis of GHG emissions, depletion, and allocation of resources among competing. The supplemental physical accounts further facilitate parameterization of advanced technologies, those not represented in the base economic data, because the costs, physical production, and conversion efficiencies can be compared more directly to engineering cost and agronomic studies. Advanced technologies also require an initially limited, technology specific, fixed factor representing the limited initial capacity to expand the industry. The endowment is owned by the representative household, and expands with expansion of the industry. It represents gradual expansion of engineering capacity in the early phases of a new industry, creating adjustment costs and rents (i.e., profits) that accrue to the representative household when demand growth for the industry output is rapid.

The production sectors and final consumption are modeled as nested constant elasticity of substitution (CES) production functions (Solow, 1956; Arrow et al., 1961; Klump et al., 2007). These are constant return to scale (CRTS) functions, required to solve the model, as a mixed complementarity problem (MCP) (Mathiesen 1985; Rutherford, 1995) using the MPSGE modeling language (Rutherford 1999). The CRTS implies an income elasticity of one. To overcome this limit the elasticity and share parameters are a made function of income between periods, but not within a period.

The energy commodities in GTAP include crude oil, natural gas, coal, electricity, and a single refined oil commodity encompassing all the different petroleum products from crude oil refining. To better analyze how supply and demand for the refined oil products could be affected by climate policy, the EPPA-ROIL model disaggregates both the downstream and upstream oil industries as shown in Table 1 (Choumert et al., 2006).

The downstream refining sector includes six product categories: (a) refinery gases (b) gasoline (c) diesel (d) heavy fuel oil (e) petroleum coke and (f) other petroleum products. The physical flows of the refined product are disaggregated using the International Energy Agency Databases (International Energy Agency, 2005a; International Energy Agency, 2005b). IEA price data (International Energy Agency, 2005b) and the data from Energy Information Administration (Energy Information Administration (EIA), 2004b) are used to estimate regional and sectoral prices for these refined products, and subsequently, the value flows are disaggregated. Final calibration is needed to fully reconcile trade flows.

The new refining sector is specified as a multi-output production technology characterized by constant elasticity of transformation (CET) on the output side, and constant elasticity of substitution (CES) on the input side. The specification is appropriate for a production technology where multiple products are produced jointly from a single process, as in oil refineries. The CET allows some shift in the product mix in response to changing relative output prices, but an important issue for the refinery sector is the stronger increases in demand for some products (gasoline, diesel) with weaker demand growth for others (e.g., heavy oil, petroleum coke). The relative over-supply of heavier products is exacerbated by the fact that the crude slate is becoming heavier as production from reserves of lighter conventional crudes fall off and heavier conventional crudes or synthetic from oil sands fill in. This phenomenon is especially the case from the long-term perspective. To better capture this feature of refining, explicit upgrading technology was added that converts these heavy refinery products into more other products. A residue upgrading technology further processes heavy fuel oil into the five categories of refined products, and a gasification technology can turn the heavy oil and petroleum coke into synthetic gas. Heavy products are also allowed as an input for electricity generation. These additions offer more options for the use of these products if other conventional demands for them do not keep up with supply. In that case the price gap between heavy products and gasoline and diesel will widen, making upgrading economic and/or the falling price relative to gas or coal would favor use of the heavy products in gasification or use for electricity production. The biofuel technology in the standard EPPA is also further elaborated as CES-CET multi-product technology that produces diesel and gasoline substitutes via a Fischer–Tropsch process.

To capture the changing crude oil slate, the upstream oil industry separates non-conventional oil reserves, such as oil sands in Canada and Latin America, from the conventional crude oil reserves, and exogenously specifies a changing weight of conventional crude

<table>
<thead>
<tr>
<th>Table 1</th>
<th>Sectors in EPPA4 and EPPA-ROIL</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Energy supply and conversion</strong></td>
<td><strong>Energy supply and conversion</strong></td>
</tr>
<tr>
<td>Electricity generation</td>
<td>Electricity generation</td>
</tr>
<tr>
<td>Conventional fossil</td>
<td>Conventional fossil</td>
</tr>
<tr>
<td>Hydro</td>
<td>Hydro</td>
</tr>
<tr>
<td>Nuclear</td>
<td>Nuclear</td>
</tr>
<tr>
<td>Wind and solar</td>
<td>Wind and solar</td>
</tr>
<tr>
<td>Biomass</td>
<td>Biomass</td>
</tr>
<tr>
<td>Advanced gas</td>
<td>Advanced gas</td>
</tr>
<tr>
<td>Advanced gas with CCS</td>
<td>Advanced gas with CCS</td>
</tr>
<tr>
<td>Advanced coal with CCS</td>
<td>Advanced coal with CCS</td>
</tr>
<tr>
<td>Advanced heavy fuel with CCS</td>
<td>Advanced heavy fuel with CCS</td>
</tr>
<tr>
<td>Advanced coke with CCS</td>
<td>Advanced coke with CCS</td>
</tr>
<tr>
<td>Fuels</td>
<td>Fuels</td>
</tr>
<tr>
<td>Coal</td>
<td>Coal</td>
</tr>
<tr>
<td>Crude oil</td>
<td>Conventional crude oil</td>
</tr>
<tr>
<td>Extra-heavy crude oil</td>
<td>Extra-heavy crude oil with CCS</td>
</tr>
<tr>
<td>Refining</td>
<td>Refining; upgrading; upgrading with CCS</td>
</tr>
<tr>
<td>Gas from coal</td>
<td>Gas from coal</td>
</tr>
<tr>
<td>Liquids from biomass</td>
<td>Liquids from biomass</td>
</tr>
<tr>
<td><strong>Other sectors</strong></td>
<td><strong>Other sectors</strong></td>
</tr>
<tr>
<td>Agriculture</td>
<td>Agriculture</td>
</tr>
<tr>
<td>Energy intensive products</td>
<td>Energy intensive products</td>
</tr>
<tr>
<td>Other industries products</td>
<td>Other industries products</td>
</tr>
<tr>
<td>Industrial transportation</td>
<td>Industrial transportation</td>
</tr>
<tr>
<td>Services</td>
<td>Services</td>
</tr>
<tr>
<td>Household</td>
<td>Household</td>
</tr>
</tbody>
</table>

| *a* This category includes the oil sands in Canada and the heavy crude oil reserves in Venezuela.  
| *b* Both refining and upgrading yield the six listed refinery products. |
each EPPA region. Two separate production activities for oil sands are added: (1) bitumen production (possible only in Canada and Latin America where the resources are located) and (2) upgrading of the bitumen to synthetic crude oil, a process that also produces heavy oil and petroleum coke as by-products (possible outside of Canada and Latin America through importation of the bitumen). There are a variety of oil sands production and upgrading processes. We base the EPPA-ROIL bitumen upgrading sector on a process developed by Total (2009). Details of our modeling of the processes are reported in Choumert et al. (2006). Because this second activity involves the production of three products, the CES-CET modeling approach is used. The products are used in conventional refining, in the residue upgrading production sector or for other uses of heavy oil and petroleum coke described above.

The elaboration of the refining sector also requires changes in demand and in resources. The final demand for the refined products is composed of the intermediate demands from production sectors and final demand from the household. The structure also requires that we separately identify oil sands resources from conventional crude resources, and deplete them as production occurs. Only Canada and Latin America (Venezuela) are specified as having oil sands额外 heavy oil endowments.

These elaborations of the petroleum sector facilitate improved CO2 accounting to (1) consider the large amount of CO2 emissions from producing and upgrading non-conventional oil reserves, (2) accurately treat additional emissions from more intensive refining processes as crude slate and product mix changes, and (3) provide a more detailed treatment for the emissions from consumption of petroleum products. For example, “other petroleum products” consists of many refined products not destined for energy uses, and thus not oxidized to produce CO2. We apply a CO2 coefficient to these products in their final consumption that reflects only that share of associated CO2 emissions of surface mining, in situ project by about 12% and 25%, respectively, and increases the cost of bitumen upgrading by around 23%. The cost indices, cost share parameters and the associated CO2 emissions of surface mining, in situ, and upgrading processes are presented in Table 2. A sensitivity analysis with different CCS costs and CO2 reduction rates on bitumen production and upgrading in Canada is presented in the Appendix.

### 3. Scenario analysis: Factors affecting bitumen production and upgrading industries

In our application of the EPPA-ROIL model, we developed a suite of scenarios to analyze the important policy and technology dependencies of the Canadian bitumen production and upgrading industries. We find four distinct regimes for the oil sands industry:

1. Canada produces and upgrades large quantities of bitumen, and petroleum coke described above.
2. Canada produces reduced quantities of bitumen, but a majority of upgrading moves abroad.
3. Canadian bitumen production and upgrading shut down.

Which regime occurs depends on the climate policy in place in Canada and elsewhere and assumptions about the availability of competing liquid fuels. To illustrate how these factors affect the industry we construct different plausible policy and technology scenarios that show conditions that yield each of oil sands industry regimes that are possible. The scenarios are summarized in Table 3 with the details of each alternative policy assumption described below.

Briefly, the scenarios involve a case with no climate policy in any region and eight additional scenarios with varying climate policy and technology assumptions. Any scenario in EPPA involves continued growth in population and labor productivity growth, improvement in energy efficiency improvements, via an exogenous autonomous energy efficiency improvement (AEEI) coefficient, depletion of conventional fossil fuels, and the use of other new energy technologies as they become economic. The basic exogenous assumptions are identical across the scenarios

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Table 2

Input shares and cost indices for bitumen production and upgrading. Sources: Choumert et al. (2006) and National Energy Board (2004).

<table>
<thead>
<tr>
<th>Input</th>
<th>M/E, w/o CCS</th>
<th>In situ, w/o CCS</th>
<th>Upgrading, w/o CCS</th>
<th>M/E, w/CCS</th>
<th>In situ, w/CCS</th>
<th>Upgrading, w/CCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Natural gas</td>
<td>0.096</td>
<td>0.297</td>
<td>0.127</td>
<td>0.101</td>
<td>0.310</td>
<td>0.126</td>
</tr>
<tr>
<td>Refinery gas</td>
<td>0.025</td>
<td>0.014</td>
<td>0.008</td>
<td>0.022</td>
<td>0.012</td>
<td>0.007</td>
</tr>
<tr>
<td>Heavy fuel oil</td>
<td>0.002</td>
<td>0.006</td>
<td>0.029</td>
<td>0.002</td>
<td>0.007</td>
<td>0.029</td>
</tr>
<tr>
<td>Electricity</td>
<td>0.018</td>
<td>0.010</td>
<td>0.007</td>
<td>0.016</td>
<td>0.009</td>
<td>0.006</td>
</tr>
<tr>
<td>Capital</td>
<td>0.313</td>
<td>0.269</td>
<td>0.287</td>
<td>0.329</td>
<td>0.281</td>
<td>0.319</td>
</tr>
<tr>
<td>Labor</td>
<td>0.286</td>
<td>0.158</td>
<td>0.048</td>
<td>0.301</td>
<td>0.165</td>
<td>0.076</td>
</tr>
<tr>
<td>Energy intensive goods</td>
<td>0.039</td>
<td>0.031</td>
<td>0.033</td>
<td>0.034</td>
<td>0.029</td>
<td>0.029</td>
</tr>
<tr>
<td>Services</td>
<td>0.020</td>
<td>0.011</td>
<td>0.004</td>
<td>0.018</td>
<td>0.010</td>
<td>0.004</td>
</tr>
<tr>
<td>Transportation</td>
<td>0.091</td>
<td>0.092</td>
<td>0.018</td>
<td>0.080</td>
<td>0.081</td>
<td>0.016</td>
</tr>
<tr>
<td>Oil sands resource</td>
<td>0.100</td>
<td>0.100</td>
<td>–</td>
<td>0.088</td>
<td>0.088</td>
<td>–</td>
</tr>
<tr>
<td>Bitumen</td>
<td>–</td>
<td>–</td>
<td>0.439</td>
<td>–</td>
<td>0.388</td>
<td>–</td>
</tr>
<tr>
<td>Fixed factor</td>
<td>0.010</td>
<td>0.010</td>
<td>–</td>
<td>0.009</td>
<td>0.009</td>
<td>–</td>
</tr>
<tr>
<td>CO2 emissions (kg/boe)</td>
<td>29.41</td>
<td>91.02</td>
<td>85.00</td>
<td>3.24</td>
<td>10.01</td>
<td>9.35</td>
</tr>
<tr>
<td>Cost index</td>
<td>1.00</td>
<td>1.48</td>
<td>1.28</td>
<td>1.12</td>
<td>1.86</td>
<td>1.57</td>
</tr>
</tbody>
</table>

**Note that in our analysis, CCS does not apply to emissions from the use of transportation service of the oil sands industry as it should not be. The 89% capture rate only applies to emissions associated with the non-transportation-related energy input used in extracting and upgrading bitumen.
and they are major drivers of GDP growth and energy demand. The different policy and technology assumptions affect GDP growth and energy demand, and hence supply and resource depletion. The alternative technology assumption scenarios and are run with or without the CCS options available in the bitumen production and upgrading industries and with or without biofuels. The availability of biofuels affects oil sands especially under climate policy because they are represented in EPPA as a low CO2 alternative to petroleum products. A couple of issues can lead one to question the availability of biofuels. The first is that cellulosic conversion technology, while showing promise, has yet to be demonstrated to be competitive at a large scale. The second is that recent work has shown that indirect land use emissions from deforestation induced by biofuel expansion could be substantial even when the biofuel production process results in little direct emissions. The restricted biofuels cases thus represent the possibility that because of technological feasibility/cost or CO2 implications, biofuels may make a limited contribution to fuel supplies.

With regard to Canada, although it has withdrawn from the Kyoto Protocol in late 2011, and there are differences among the country’s political parties on future carbon mitigation plans, to study the impact of a potential climate policy proposal on the oil sands industry, we consider the target once proposed by the Canadian government, which called for a near term intensity target (the ratio of greenhouse gas emissions to gross domestic product), and then to reduce emissions to 20% and 60% to 70% below 2006 levels by 2050. Thereductions are linearly interpolated to produce what we refer to as the proposed target for Canada, as shown inFig. 1.

4. Results of the scenario analysis
4.1. Global liquid fuels supply and crude oil prices

Our focus is primarily on the Canadian oil sands industry but its ultimate fate is closely linked to the global oil and liquid fuels market. Fig. 3 shows global liquid fuel supply through 2050 in the No Policy, Annex I, No Bio, World Policy, Annex I + CCS, and World Policy + CCS cases. It shows that the peak of conventional crude production is determined not only by the resource depletion, but also by the demand for petroleum products, as suggested by Cambridge Energy Research Associates (CERA) (2006); Charpentier (2002). For example, without climate policy, the oil peak of conventional crude production may arrive around 2030 to 2040, while under the World Policy scenario, it may arrive earlier due to the decline in the demand for petroleum products. In addition to petroleum products, demand for liquid fuels may also be met from a combination of Canadian oil sands, Venezuelan extra heavy oil as well as shale oil and biofuels, depending on climate policy scenarios and the availability of biofuels.

Across these cases, there is actually little change in conventional crude production. The main exception is in the World Policy case where reductions in the developing countries cut demand and production enough to affect conventional crude production. Otherwise, reduced use of conventional crude-based products in developed countries is mostly offset by increased use in developing countries. The main effect of the policy cases is what happens to the unconventional sources of liquid fuels. Canadian oil sands production is largely restricted in the case of Annex I policy, and in the World Policy case, it essentially disappears in later years. Venezuela heavy oil retains some production because the policies in developing countries start later, but production there starts to drop after 2035 as policies tighten. Shale oil production is also affected by climate policy. In the No Policy case, shale oil is produced in USA, ANZ, FSU, and AFR. With the Annex I Policy, shale oil production ceases in the USA and ANZ, and in the World Policy case shale oil is not produced anywhere. Biofuels production increases based on the assumption that land use emissions are neutral. Overall production of liquid fuels is lower by about 16 EJ in the Annex I scenario and over 47 EJ in the World Policy scenario. In the Annex I No Biofuels case liquid fuel use drops the most—over 52 EJ. A role for shale oil, Venezuelan extra heavy crude, as well as Canadian oil sands is preserved. In these scenarios, Canadian oil sands is negatively affected both by the drop in world demand for liquid fuel and the CO2 policy in Canada.

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Table 3
Assumptions of the policy scenarios.

<table>
<thead>
<tr>
<th>Scenario name</th>
<th>Annex I Policy</th>
<th>Proposed Policy for Canada</th>
<th>Developing Country Policy</th>
<th>Biofuels restricted</th>
<th>CCS available</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Climate Policy</td>
<td>NoBio</td>
<td>NoBio + CCS</td>
<td>World Policy</td>
<td>World Policy + CCS</td>
<td></td>
</tr>
</tbody>
</table>

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Fig. 1. Canadian CO2 emission target proposals.
Behind these results are different changes in world oil prices that, along with CO₂ policies where they exist, affect the profitability of alternative liquid fuel technologies. As shown, crude oil prices are projected to rise substantially in the no policy case. The policy cases, generally slow the rate of increase, and in the World Policy case the price remains in the $100–$110 range (in 2010 price). Lastly, we find that with the Annex I scenario, the CCS option is crucial in the oil sands industry since it allows much higher bitumen production level to continue. In the scenario of World Policy, however, Canadian oil sands will no longer play a significant role in the global liquid fuels supply in later years, even with the presence of the CCS option.

Several considerations explain the negative impact on oil sands industry under climate policy scenarios. First, the upgrading process is a multi-product process that produces heavy synthetic crude that requires more expensive refinery upgrading process, heavy oil and...
petroleum coke. We represent explicitly these extra refinery processes and uses for heavy oil and coke, and the extra-processing required to produce high valued products such as gasoline and diesel make the oil sands industry less competitive compared with conventional crude. Second, the bitumen production and upgrading processes are energy intensive and use significant amounts of natural gas. This is especially the case for in situ projects. Note that in the long run, gas prices are generally rising in the model because of resource depletion even without the CO2 charge. Third, energy prices (in terms of user's prices) are higher in Canada under the CO2 policies, and that increases the cost of gas, electricity and other energy products used in the oil sands industry.

4.2. Impacts on the Canadian oil sands industry

We turn now to details of the Canadian oil sands industry. As structured in our revised version of EPPA-ROIL, the industry consists of three components (1) bitumen from surface mining project, (2) bitumen production from in situ project, and (3) the upgrading of bitumen into synthetic crude and other by-products. Fig. 5 plots the implications of different policy and technology scenarios for these industries, with panel (a) showing Canadian bitumen production from both surface mining and in situ and panel (b) upgrading. The solid colored lines represent scenarios without CCS technology available while the dashed colored lines represent the corresponding scenario of the same color with CCS available. The broad story in these figures is that (1) climate policy significantly dampens the prospects for Canadian oil sands development because global demand and the producer prices of oil are depressed, and the Canadian CO2 policy add to the cost oil sands production; (2) the availability of CCS allows the continued extraction of oil sands resource in some cases, but since it adds to the cost of production, its addition makes it harder for Canadian oil sands to compete against other liquid fuels alternatives, especially if there are areas of the world with no or weaker climate policy; and (3) bitumen production can survive if there is not a world climate policy but much of the upgrading of the bitumen would be done abroad in areas without climate policy.

These key results are somewhat modified by other assumptions about policy and technology. If biofuels are simply not available as an effective low carbon alternative then that provides better prospects for the operation of the Canadian oil sands industry. We have not exhausted all possible policy and technology combinations in our scenarios, and there are obviously many other possible levels of policy and participation among different countries but the scenarios we portray demonstrate some of the more likely ways in which policy could evolve.

One thing of note, the EJ of output from upgrading of Canadian bitumen is somewhat greater than the EJ of bitumen production which can be seen by comparing, for example, the 19.9 EJ of upgrading output in the No Policy scenario to the 17.4 EJ of bitumen output. The reason for this is that other energy is used in the upgrading process for process energy and lighter petroleum products—e.g., natural gas liquids are combined with the bitumen. These energy flows and balances are accounted for in the EPPA-ROIL structure.

An implication of continued production of bitumen in Canada with reduced upgrading is that the upgrading capacity moves abroad to areas without climate policy and that results in CO2 emissions in these regions—a contribution to carbon leakage. To investigate this, we show in Fig. 6 the regional distribution of upgrading in four of the scenario cases that illustrate different outcomes, Annex I, NoBio, NoBio+CCS, and World Policy+CCS. In the No Policy scenario, all Canadian Bitumen is upgraded in Canada because that eliminates the need to transport the bitumen, as is shown in Fig. 5 and by the shaded curves in Fig. 6.

Fig. 6(a) shows results for the Annex I scenario. In this case, the strong policy in developed countries reduces the demand for oil products, leading to retrenchment of Canadian oil sands industry. Developing country demand for petroleum eventually leads to a resuscitation of the industry, but with the carbon constraints in Canada, the upgrading takes place abroad. For later years, we find it in the Former Soviet Union region and in Southeast Asia. In the NoBio case the lack of biofuels as an option keeps demand for petroleum products up enough so that bitumen production expands somewhat from 2020 to 2045, but with CO2 policy in Canada upgrading moves abroad. Without the CCS option, the expansion of bitumen production in Canada is limited, and even less upgrading is done domestically. The NoBio+CCS case is one of the more interesting—the lack of biofuels keeps up demand for petroleum products, the availability of CCS allows bitumen to be produced, but the added cost of CCS on upgrading needed to meet Canada's climate policy limits the upgrading capacity in Canada, and so significant amounts occur abroad in areas without climate policy. Finally, the World Policy decreases demand for petroleum products enough to lead to a significant contraction of the industry in later years even with the CCS option—upgrading capacity remains in Canada since no cheaper alternatives exist elsewhere.

Since we specify upgrading technology uniformly for all regions, the emissions from upgrading will be very similar regardless of the region. Thus, the leakage of upgrading abroad is a similar proportion of CO2 emissions leakage related to upgrading. Thus, in the Annex I scenario, by 2050 virtually all of the CO2 related to upgrading is leaking from Canada. The Canadian policy is eliminating these emissions on Canadian soil, but they show up abroad. In the NoBio+CCS scenario, from 2035 through 2050 over 70% of upgrading emissions are leaking abroad. In the scenarios in which the developing countries adopt a climate policy, bitumen upgrading remains within Canada and so there is nothing to leak.

The role of Canadian climate policy in upgrading leakage is not the full story on Canadian climate policy impacts on the oil sands industry emissions. As shown in Fig. 7, contrasting cases with and without CCS where bitumen is produced, the Canadian policy succeeds in reducing CO2 emissions from the bitumen production process by encouraging the adoption of CCS. We also find that CO2 reduction policy would discourage bitumen production from in situ projects more than that from surface mining ones. The reason is that in situ bitumen production is over three times more carbon intensive than bitumen production from surface mining.
The story is unchanged even when the CCS option is available. This is because under a given CO2 reduction rate, for in situ projects, higher level CO2 is captured and stored per unit of bitumen output, which suggests more capital, labor, and energy inputs are needed for carbon reduction purpose, and this makes in situ projects even more expensive to operate. 

**4.3. Carbon price and economic welfare**

The EPPA model achieves climate policy goals by setting regional emission targets which create a shadow value on the constraint which can be interpreted as the CO2 prices one would observe in a cap and trade system or the CO2 tax that would be necessary to achieve the reduction given the conditions specified in the model. To meet the constraint, more of the output of the economy must be allocated to abatement, such as adding CCS in the oil sands industry, and fossil fuel resources like oil sands are less valuable and so resource rents to the economy from fuel export are reduced. The change in economic welfare is a macroeconomic measure of these costs to the economy. The Annex I and World Policy scenarios have very similar CO2 prices and welfare effects in Canada. CCS is adopted in the Annex I + CCS scenario, and while its role is restricted to mostly the bitumen production process toward the end of the period, since it allows Canada to produce and export bitumen (although at a higher cost), it creates economic benefits and so reduces the welfare cost of carbon mitigation. Under the World Policy + CCS scenario, CCS in the oil sands industry plays smaller roles in lowering welfare cost because oil sands production retrenches further due to the lack of foreign upgrading opportunities. The NoBio cases create extremely high costs for Canada even though they preserve a greater role for oil sands. The reason is that, lacking an effective low CO2 alternative in transportation, the emissions target requires a significant reduction in fuel use in transportation, which adds to the cost of vehicles and forces reduction in their use.
5. Conclusions

Climate policies appear to have significant impacts on the future of Canadian oil sands industry. This stems from the fact that CO₂ emissions from the production of bitumen and upgrading are substantial and demand for petroleum products would decline with climate policies. With reduced demand for petroleum, the producer prices for crude oil and other fossil fuels are lower, and higher-cost and carbon-intensive sources of oil such as oil sands, extra heavy crudes, and shale oil are put at a disadvantage. Adding CCS to bitumen production and upgrading could substantially reduce CO₂ emissions – we assumed it could capture nearly 90% of them – but it adds to the cost. If developing countries fail to adopt climate policy, the Canadian oil sands industry may be hurt in the near term by developed country climate policy but could see a resurgence as petroleum demand growth continued in regions without greenhouse gas controls. A perverse aspect of this case is that the climate policy in Canada could be undermined in part by...
leakage of emissions through the relocation of bitumen upgrading to regions without climate policy.

Much of the demand for petroleum products is driven by transportation needs, and so the fate of the oil sands industry depends on the availability of transportation alternatives to petroleum (or oil sands)-based diesel and gasoline. If there are alternatives such as biofuels that can be economically competitive and produced with low life cycle CO2 emissions, then petroleum product demand is depressed leaving less demand for oil sands products. If such options are not available, are too costly, or are themselves CO2 intensive because of land use change emissions, then we find that the roles for Canadian oil sands may remain crucial. Since this is an important industry in Alberta that would likely be good news for the provincial economy. However, the lack of available transportation alternatives makes meeting CO2 targets in Canada very difficult and so the cost for the country as a whole is much greater than cases where other low carbon fuels are available. We looked in particular at the biofuels option for transportation. While we did not examine alternative vehicle technologies, relatively lower cost electric vehicles, for example, would be another option that would lower the cost of meeting climate policy in Canada but may negatively affect the oil sands industry.

When there is substantial participation of developing countries in climate policy, there appears to be little role for Canadian oil sands at least through the 2050 time horizon of our analysis. The main reason for this is that upgrading bitumen abroad is no longer economic under this scenario. Further, the demand for liquid fuels falls and so does the associated producer prices, and this puts oil sands industry in a disadvantaged position because of higher carbon charges. Although CCS may alleviate this pressure and provide more room for the operation of oil sands industry, we still find the decline of this industry in later years. While production of conventional liquid fuels will eventually fall off because of depletion of high grade resources, the production continues to be adequate to meet the reduced product demand. In these scenarios, if developing country do not adopt climate policy, Canada and other Annex I countries would bear significant economic cost to reduce their own emissions with relatively little climate gain as GHG emissions continue unabated in developing countries where the emissions growth rate is high. In contrast to the gargantuan size of the oil sands resource base, the niche for the oil sands industry becomes narrower as more countries participate in climate policy. We have investigated what is now the “conventional” oil sands industry. More advanced technologies, which seek to use the oil sands resources with a gasification process to produce hydrogen and/or electricity while applying CCS to reduce emissions as proposed for coal, could make use of this resource as well. We did not investigate such a technological alternative in this paper, but it would appear to be one of the avenues by which the oil sands resource could also be used to supply energy to the world, even with carbon constraints.

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Appendix. Sensitivity Analysis of the CCS Option on Bitumen Production and Upgrading

Due to uncertainties about site, plant design, technological improvement, etc., the current projections for CCS cost often vary a great deal. For example, Intergovernmental Panel on Climate Change (IPCC) (2006) estimates that carbon capture, CO2 transportation, and storage may range from $5/t-CO2 to $115/t-CO2, $1/t-CO2 to $8/t-CO2 (per 250 km transported) and $0.5/t-CO2 to

![Fig. A1. Canadian bitumen production and upgrading under various policy scenarios and CCS assumptions.](image-url)
$8/\text{t-CO}_2$, respectively. Herzog (2000), on the other hand, has a somewhat higher storage cost estimate ($98/\text{t-CO}_2$). Thus, in addition to the analysis based on the overall CCS cost of $40.36/\text{t-CO}_2$ and a 89% capture rate from Ansolabehere et al. (2007), we also consider several different cost and capture rate assumptions to represent other plausible scenarios.

After taking into account the costs of capture, transport, and storage, the additional CCS cost and effectiveness scenarios include: (1) $15/\text{t-CO}_2$ with a 89% capture rate (the most optimistic scenario); (2) $80/\text{t-CO}_2$ with a 89% capture rate (the scenario with a doubled CCS cost compared to that of Ansolabehere et al.); (3) $35/\text{t-CO}_2$ with a 59% capture rate; and (4) $58/\text{t-CO}_2$ with a 91% capture rate. The last two scenarios are based on the CCS designs presented in Lindsay et al. (2009).

As shown in Fig. A1, we find that in general, (1) results based on Ansolabehere et al. are around the middle projections of more extreme cases; (2) Canadian bitumen upgrading is more sensitive to different CCS assumptions, reflecting while bitumen production must be on site, bitumen may be upgraded abroad where climate policies are less stringent; and (3) results based on the CCS option with a higher unit cost (in terms of $/\text{t-CO}_2$) and a higher capture rate may turn out to be quite close to those based on the CCS option with a lower unit cost and a lower capture rate. As expected, technological advancement, which makes a cheaper yet effective CCS option available, would allow Canada to produce and upgrade more bitumen domestically when climate policy is enforced.

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