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Canada's Bitumen Industry Under CO_2 Constraints

Gabriel Chan, John M. Reilly, Sergey Paltsev, and Y.-H. Henry Chen

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To inform processes of policy development and implementation, climate change research needs to focus on improving the prediction of those variables that are most relevant to economic, social, and environmental effects. In turn, the greenhouse gas and atmospheric aerosol assumptions underlying climate analysis need to be related to the economic, technological, and political forces that drive emissions, and to the results of international agreements and mitigation. Further, assessments of possible societal and ecosystem impacts, and analysis of mitigation strategies, need to be based on realistic evaluation of the uncertainties of climate science.

This report is one of a series intended to communicate research results and improve public understanding of climate issues, thereby contributing to informed debate about the climate issue, the uncertainties, and the economic and social implications of policy alternatives. Titles in the Report Series to date are listed on the inside back cover.

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Gabriel Chan*, John M. Reilly*, Sergey Paltsev*, and Y.-H. Henry Chen*

Abstract

We investigate the effects of implementing CO_2 emissions reduction policies on Canada's oil sands industry, the largest of its kind in the world. The production of petroleum products from oils sands involves extraction of bitumen from the oil sands, upgrading it to a synthetic crude oil by adding lighter hydrocarbons, and then use of more conventional petroleum refining processes to create products such as gasoline and diesel. The relatively heavy crude 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 such as diesel and gasoline. Each part of the process involves significant amounts of energy, and that contributes to a high level of CO_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 over 6-fold from 2005 to 2050; (2) with CO_2 emissions caps implemented in developed countries, Canadian bitumen production drops by nearly 65% from the reference 6-fold increase and bitumen upgrading capacity moves to the developing countries; (3) with CO_2 emissions caps implemented worldwide, the Canadian bitumen production becomes essentially non-viable even with CCS technology, at least through our 2050 horizon. The main reason for the demise of the oil sands industry with global CO_2 policy is that the demand for oil worldwide drops substantially. CCS takes care of emissions from the oil sands production, upgrading, and refining processes, at a cost, but there is so little demand for petroleum products which still emit CO_2 when used that it can be met with conventional oil resources that entail less CO_2 emissions in the production process.

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1. INTRODUCTION

In this paper we investigate the effects of implementing CO_2 emission reduction policies on Canada's bitumen industry. Bitumen is petroleum based substance that can be extracted from oil sands and upgraded to a synthetic crude oil. Venezuela extra heavy oil is a similar resource, slightly less degraded then oil sands and thus easier to extract by conventional technology. But they also require substantial upgrading into a crude equivalent. 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_2 emissions, and hence the industry would be affected by CO_2 control policies. Addition of carbon capture and storage (CCS) to the process is one strategy that could reduce the CO_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 oil sands and heavy oil reserves. 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, 2009a; OPEC, 2008; EIA, 2008). The bitumen industry prospered, especially as crude oil prices rose in recent years. The crude price drop over the last year has slowed expansion of the industry and with CO_2 control looming in Canada the economic viability of the industry and the value of these large reserves are at risk. As of 2006, the GHG emissions of Canada have reached 721 megatonnes of carbon dioxide equivalent (Mt CO_2 eq, or Mt), which is already 29% above its Kyoto target (Environment Canada, 2008b). A recent estimate has the bitumen industry alone responsible for 29.5 megatonnes, about 5% of Canada's total emissions (Canada's Oil Sands, 2009).

Bitumen can be produced with surface mining techniques when deposits are near the surface or through in situ techniques for deposits that are located deeper in the earth. There are varying approaches, in either case, that lead to varying CO_2 emissions per barrel produced. Adding CCS technology increases the cost of production, and would affect the competitiveness of the industry. Canadian CO_2 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 CO_2 control policies, creating a source of "CO_2 leakage." CO_2 leakage refers to an increase in emissions outside of a regulating jurisdiction in response to its CO_2 limits. CO_2 regulation (domestically or abroad) may also affect the overall demand for petroleum products and thus affect the bitumen industry indirectly through the price paid for crude and petroleum products. While the addition of CCS would greatly reduce emissions from mining and processing of the bitumen, the petroleum products that are produced would still release CO_2 when finally used as fuel. Production of products from oil sands would be disadvantaged compared with conventional 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 CO_2 emissions per barrel to approach that emitted from conventional crude production.

We investigate the viability of the bitumen industry in the face of Canadian and global CO_2 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 bitumen 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 answer 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 bitumen industry, with separate production and upgrading activities. We also consider scenarios that include carbon capture and storage (CCS) technology on either or both production and upgrading.

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 current version, EPPA4, is built on the GTAP 5 dataset (Hertel, 1997; Dimaranan and McDougall, 2002). The GTAP data are 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).

The EPPA model belongs to the class of computable general equilibrium (CGE) models with two main components: households and producers. Households provide primary factors (such as labor and capital, etc.) to producers and receive income in the form of factor payments (capital and resource rents and wages) from them. 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 in other sectors (intermediate goods) 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 5 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 vintaged, non-malleable portion, and a malleable portion. The vintaged 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 (Cobb-Douglas and Leontief specifications, special cases of the CES function, are also used). 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 (IEA 2005a; IEA 2005b). IEA price data (IEA 2005b) and the data from Energy Information Administration (EIA 2004) 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 weak 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. 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 oil reserves, and exogenously specifies a changing weight of conventional crude in 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 oil resources, and deplete them as production occurs. Only Canada and Latin America (Venezuela) are specified as having oil sands/extra heavy oil endowments.

These elaborations of the petroleum sector facilitate improved CO_2 accounting to (1) consider the large amount of CO_2 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 CO_2. We apply a CO_2 coefficient to these products in their final consumption that reflects only that share of carbon emitted in the feedstock that is finally emitted as CO_2.

A key new addition to the model in our application here is the CO_2 capture and sequestration (CCS) option for the bitumen production technologies. Adding CCS increases the production cost but with a policy that limits CO_2 emissions such an option could be competitive and allow the oil sands industry to continue to operate. We base our estimates of the CCS cost on a study that looked at scrubbing CO_2 from the flue gas of pulverized coal electric power plants (Ansolabehere *et al*. 2007). We adapt these costs for the bitumen production and upgrading technology by assuming the same flue gas capture ratio of about 89% and cost per ton of CO_2-captured. We then add the extra labor, capital and energy costs to the base costs for the bitumen production technologies, to create the alternative version of these processes with the CCS option. A summary of these costs and comparison to the original pulverized coal cost estimates is shown in **Table 2**. Per ton of CO_2 captured, the cost is by construction the $40.36 estimated by Ansolabehere *et al*. (2007) for all three processes as shown in the final column of the Table. The CCS options increases the electricity production cost by just over 60%. It increases the cost of bitumen by about 19% and of upgrading by about 23%. If CCS were added to both processes, it would increase production costs of the upgraded products by about 22%. This works in the model by passing the higher cost of CCS in the first production stage on the bitumen which then is more expensive input in the upgrading process. In EPPA, we represent these additional costs as "mark-up" over the cost of an existing technology. Based on the specific capital, labor and energy costs for the CCS and the input costs for these two production process, the percentage mark-up for each process is as shown in Table 2. Because of the different amount of CO_2 in the emissions stream and of the share of each input the "mark-up" for labor, capital, and fuel differs greatly among the processes even though the costs per ton captured are identical.

Table 1. Sectors in EPPA4 and EPPA-ROIL.

Sectors in EPPA4	***Sectors in EPPA-ROIL***
Energy Supply & Conversion	***Energy Supply & Conversion***
Electricity Generation	Electricity Generation
Conventional Fossil	Conventional Fossil
Hydro	Hydro
Nuclear	Nuclear
Wind and Solar	Wind and Solar
Biomass	Biomass
Advanced Gas	Advanced Gas
Advanced Gas with CCS	Advanced Gas with CCS
Advanced Coal with CCS	Advanced Coal with CCS
	Advanced Heavy fuel with CCS
	Advanced Coke with CCS
Fuels	Fuels
Coal	Coal
Crude Oil	Conventional Crude Oil
	Extra-heavy Crude Oil [a]
	Extra-heavy Crude Oil with CCS [a]
Refining	Refining; Upgrading; Upgrading with CCS [b]
	Refinery Gas
	Gasoline
	Diesel
	Heavy Fuel Oil
	Petroleum Coke
	Other Petroleum Products
Natural Gas	Natural Gas
Shale Oil	Shale Oil
Gas from Coal	Gas from Coal
Liquids from Biomass	Liquids from Biomass
Other Sectors	***Other Sectors***
Agriculture	Agriculture
Energy Intensive Products	Energy Intensive Products
Other Industries Products	Other Industries Products
Industrial Transportation	Industrial Transportation
Services	Services
Household	Household

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.

Table 2. Cost of CCS for Pulverized Coal Power Plants, Bitumen Production and Upgrading.

Technology	Total Cost		CO_2 Emissions		Cost Ratio of CCS to Conventional Technology				Carbon Entry Price for CCS
	w/o CCS	w/ CCS	w/o CCS	w/ CCS	Capital	Labor	Fuel	**Total**	
	(*¢/kWh*)		(*g-CO_2/kWh*)		(*Mark-up*)				(*\$/t-CO_2*)
Pulverized Coal for Electric Power	4.78	7.69	830	109	1.61	2.13	1.32	**1.61**	40.36
	(*\$/boe*)		(kg-*CO_2/boe*)		(*Mark-up*)				(*\$/t-CO_2*)
Bitumen Production	10.00	11.93	55	7	1.38	1.27	1.13	**1.19**	40.36
Bitumen Upgrading	12.78	15.76	85	11	1.26	1.80	1.12	**1.23**	40.36

Table 3 provides the detailed cost share parameters for all inputs as specified in the EPPA model. Data are in 1997 prices, the base year of the model. The GDP deflator index is up about 15% since 1997 and so at current (2003) prices the cost would be closer to \$25 per barrel without CCS for the upgraded product. The costs in the Table are "break through" costs absent adjustment cost pressures that result from rapid expansion with limited fixed factor input specified in the model.

Table 3. Bitumen CCS Input Shares for Canada.

	Canada (w/o CCS)		Canada (w/ CCS)	
Input	**Bitumen Production**	**Bitumen Upgrading**	**Bitumen Production**	**Bitumen Upgrading**
GAS	0.216	0.127	0.204	0.126
RGAS	0.018	0.008	0.015	0.007
HFOL	0.005	0.029	0.005	0.029
ELEC	0.014	0.007	0.012	0.006
K	0.286	0.287	0.331	0.319
L	0.209	0.048	0.222	0.076
EINT	0.035	0.033	0.029	0.029
SERV	0.015	0.004	0.013	0.004
TRAN	0.092	0.018	0.077	0.016
Non-conventional Resource	0.100	-	0.084	-
Bitumen	-	0.439	-	0.388
Fixed Factor	0.010	-	0.008	-
Resulting CO2 emissions (kg/boe produced)	**55.00**	**85.00**	**7.15**	**11.05**
Production Cost (\$/boe produced)	**10.00**	**22.78**	**11.93**	**25.76**

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,

2) Canada produces large quantities of bitumen, but a majority of upgrading moves abroad,
3) Canada produces reduced quantities of bitumen and nearly all upgrading moves abroad,
4) 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 4** with the details of each alternative policy assumption described below.

Table 4. Assumptions of the Policy Scenarios.

Scenario Name	Annex I Policy*	Canadian Policy**	Developing Country Policy***	Biofuels Restricted	Bitumen CCS Available
No Climate Policy					
Annex I	✓	Conservative Plan			
Annex I + CCS	✓	Conservative Plan			✓
NoBio	✓	Conservative Plan		✓	
NoBio + CCS	✓	Conservative Plan		✓	✓
World Policy	✓	Conservative Plan	✓		
World Policy + CCS	✓	Conservative Plan	✓		✓
Strict CAN	✓	Liberal Plan			
Strict CAN + CCS	✓	Liberal Plan			✓

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 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 CO_2 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 CO_2 implications, biofuels may make a limited contribution to fuel supplies.

With regard to Canada, the Kyoto Protocol sets targets through 2012 but there are differences among the country's political parties on whether those will be met and on targets beyond that date. Canada's current majority party, the Conservative Party, has called for a near term (2010) intensity target (the ratio of greenhouse gas emissions to gross domestic product), and then to reduce emissions to 20% below 2006 levels by 2020. Canada's Minister of the Environment and member of the Conservative Party, called for a 50% reduction in greenhouse gas emissions by 2050, a figure consistent with the G8 global goal for 2050. We interpolate these points to produce what we refer to as the conservative plan. The Liberal party supports the Canadian Kyoto target through 2012, a 6% reduction from the 1990 emission baseline by 2012 for the three most energy-intensive sectors of the Canadian economy. We impose such an emission restriction across the entire Canadian economy in 2010. The Liberal plan calls for a 20% reduction from 1990 by 2020, 35% by 2035, and 60-80% by 2050. We again interpolate between years and use a 70% reduction target for 2050. The liberal plan is more aggressive but both plans would reduce emissions substantially below the *No Policy* case for Canada (**Figure 1**).

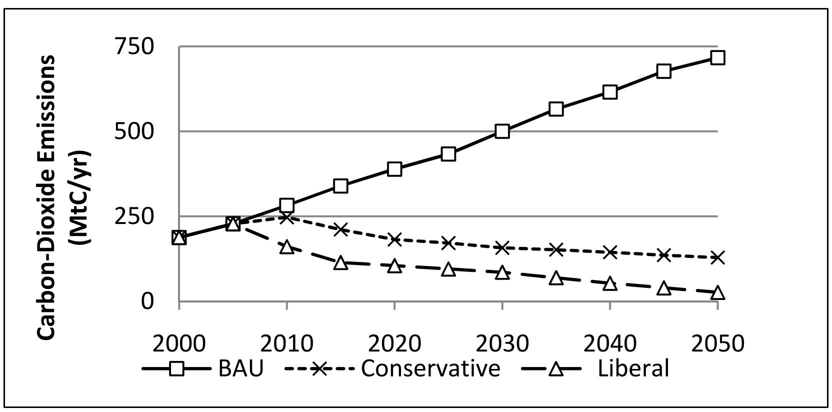

Figure 1. Canadian CO_2 Emission Target Proposals.

With regard to the Kyoto-ratifying UNFCC Annex I parties, we represent their Kyoto Protocol targets in 2010, and assume they will achieve 20% and 50% reduction below 1990 in 2020 and 2050, respectively. In the Global scenario, the developing countries are assumed to adopt emissions targets that begin in 2025, returning to their EPPA-projected 2015 emissions level in that year, and to their 2000 emissions level by 2050. The reductions are linearly interpolated between 2025 and 2050. For the United States we approximate recent Congressional cap-and-trade emission targets. While the U.S. proposals have called for reductions of as much as 83% below 2005 by 2050, they allow significant use of domestic credits for land use and from reductions in emissions and deforestation in developing countries. We approximate the resulting policy as allowing a 5% increase in emissions by 2020 relative to 2005 and a 54% reduction in carbon-dioxide emissions by 2050 relative to 2005 emissions. The *Annex I* and *Global Policy* scenarios are shown in **Figure 2**. Both have Canada at the Conservative plan level, however, the difference between the Liberal and Conservative plans are only on the order of 0.05 Gt C, an amount so small relative to global emissions that it would not be easily distinguished in Figure 2.

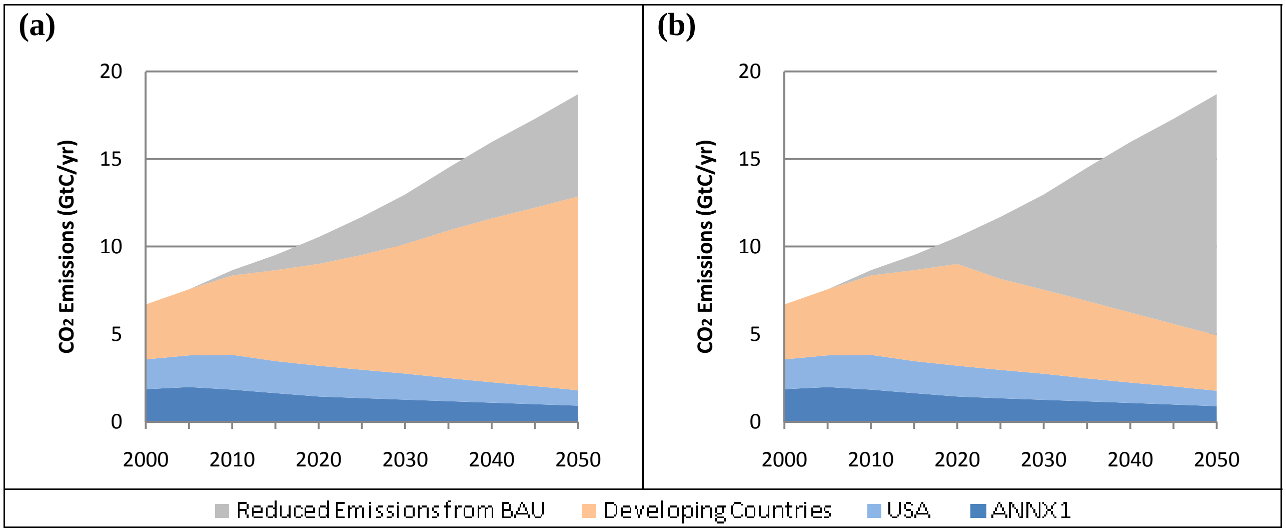

Figure 2. (a) Policy Goals in *Annex I* and (b) *Global Policy* Scenarios.

4. RESULTS OF THE SCENARIO ANALYSIS

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. **Figure 3** shows global liquid fuel supply through 2050 in the *No Policy*, *Annex I*, *No Bio*, and *World Policy* cases. It shows gradual depletion of conventional oil resources leading to a peak of conventional oil production around 2025 even as demand continues to grow. Demand growth is met from a combination of Canadian oil sands, Venezuelan extra heavy oil as well as shale oil and biofuels.

Across these cases, there is actually little change in conventional oil production. The main exception is in the *World Policy* case where reductions in the developing countries cut demand and production enough to affect conventional oil 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 largely disappear in both the *Annex I* and the *World Policy Cases*. 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 30 EJ in the *Annex I* scenario and over 50 EJ in the *World Policy* scenario. In the *Annex I No Biofuels* case liquid fuel use drops the most—over 70EJ. A role for shale oil and Venezuelan extra heavy crude oil is preserved and a small role for Canadian oil sands. Canadian oils sands is negatively affected both by the drop in world demand for liquid fuel and the CO_2 policy in Canada.

Behind these results are different changes in world oil prices that, along with CO_2 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 \$80-\$90 range.

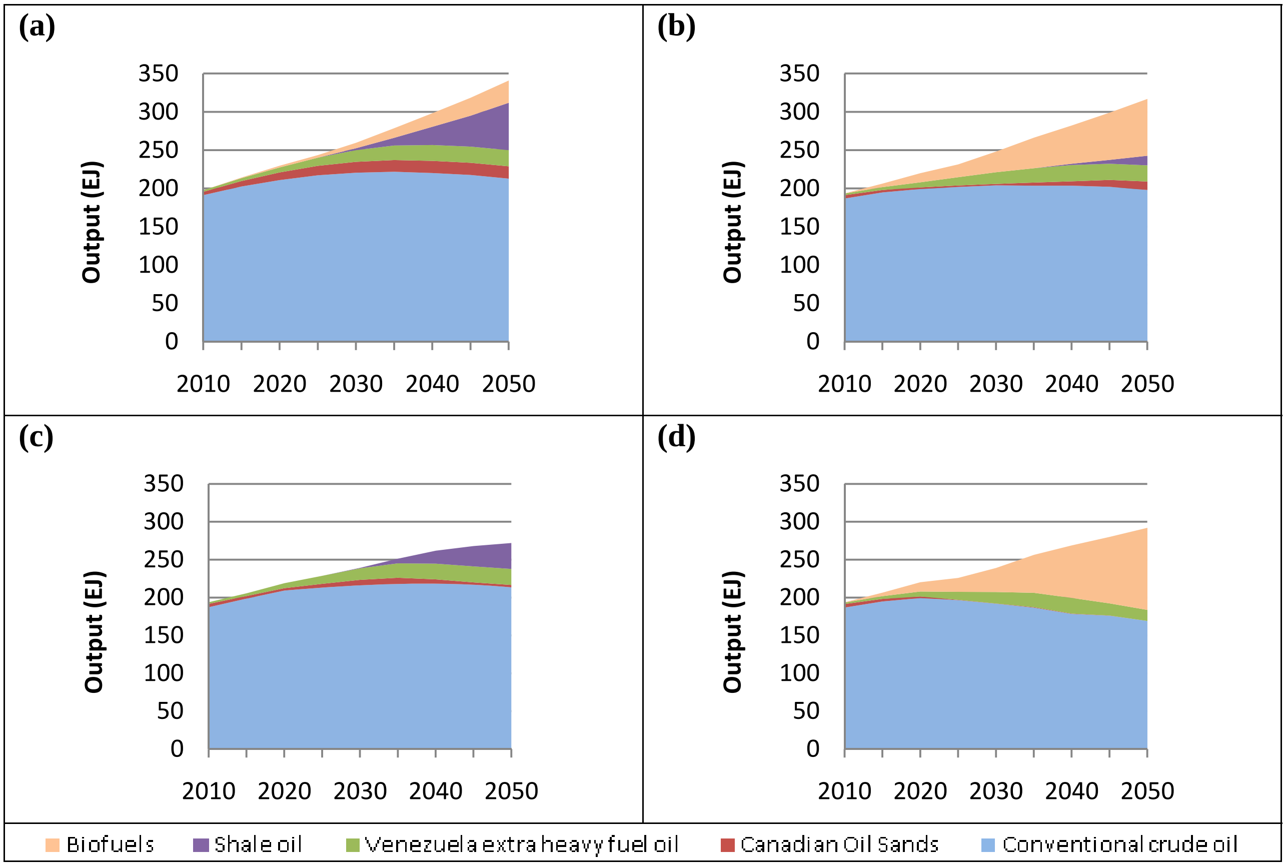

Figure 3. World Liquid Fuel Supply in the (a) *No Policy* (b) *Annex I* (c) *Annex I No Biofuels* and (d) *World Policy* cases.

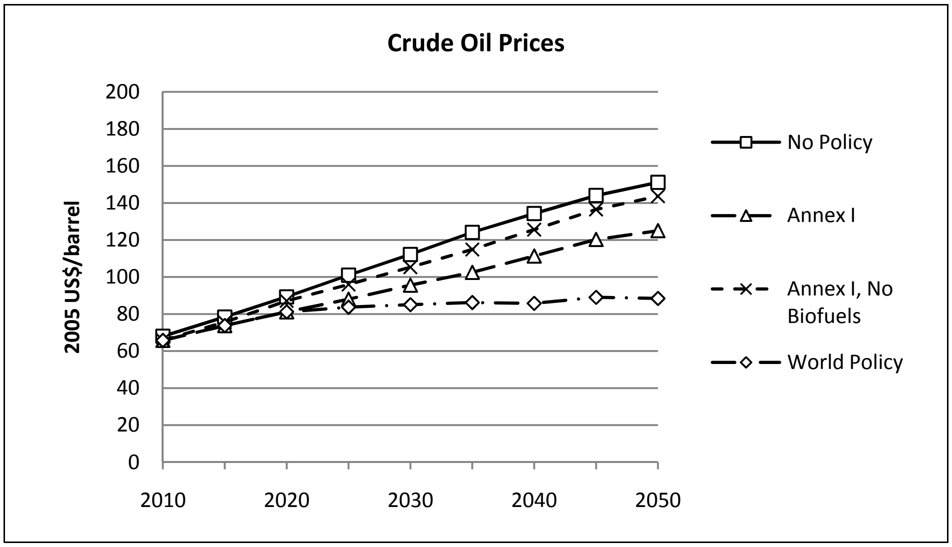

Figure 4. Crude Oil Prices in the *No Policy, Annex I, Annex I No Biofuels,* and *World Policy* cases.

This is considerably higher than the benchmark cost of the bitumen production and upgrading reported in Table 3 but several considerations explain the lack of competitiveness. First, the cost comparison in Table 3, labeled as per barrel of oil equivalent, reflect the energy content of the product not necessarily equivalent in economic value terms. 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 and upgrading processes are energy intensive and use significant amounts of natural gas. Gas prices are generally rising in the model because of resource depletion even without the CO_2 charge. Third, energy prices are higher in Canada under the CO_2 policies, and that increases the cost of gas, electricity and other energy products used in the oil sands industry.

We turn now to details of the Canadian oil sands industry. As structured in EPPA-ROIL, the industry consists of two components (1) the production of bitumen and (2) the upgrading of bitumen into synthetic crude and other by-products. **Figure 5** plots the implications of different policy and technology scenarios for these industries, with panel (a) showing Canadian bitumen production 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 oil prices are depressed, and the Canadian CO_2 policy, even the weaker Conservative plan add to the cost oil sands production (2) the availability of CCS helps in some cases, but since it adds to the cost of production, its addition makes it that much more difficult 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. The Liberal Canadian climate policy goals leave even less room for the oil sands industry, even with CCS. If biofuels are simply not available as an effective low CO_2 alternative then that provides the best chance for survival of the Canadian oil sands industry, at least in the *Annex I No Biofuels* scenario. 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.

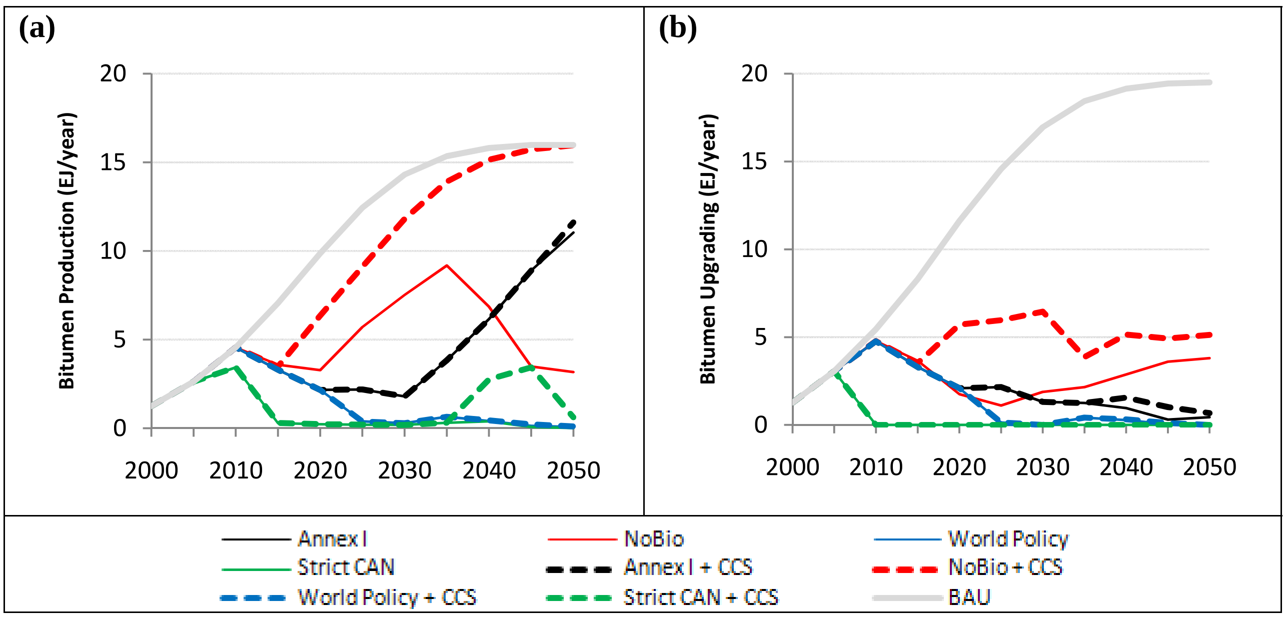

Figure 5. (a) Canadian Bitumen Production and (b) Canadian Bitumen Upgrading Under Alternative Policy Assumptions.

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 EJ of upgrading output in the No Policy scenario to the 16.5 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 CO_2 emissions in these regions—a contribution to carbon leakage. To investigate this we show in **Figure 6** the regional distribution of upgrading in four of the scenario cases that illustrate different outcomes, *Annex I*, *NoBio*, *NoBio+CCS*, and *World Policy*. 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 Figure 5 and by the shaded areas in Figure 6. The other four scenarios have either virtually no bitumen production (*StrictCAN* and *StrictCan(CCS)*) or are virtually identical to other scenarios shown in Figure 6 (*World Policy(CCS)* and *Annex I(CCS)*).

Figure 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. We find it in the Former Soviet Union region and in China and 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 2035, but with CO_2 policy in Canada upgrading moves abroad. Without the CCS option bitumen production in Canada becomes less economic in later years and the bitumen industry contracts, and what production continues is upgraded in Canada. 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 the closure of the industry—what upgrading capacity is needed in the nearer term remains in Canada.

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 leakage of CO_2 emissions related to upgrading. Thus, in the *Annex I* scenario, by 2050 all virtually all of the CO_2 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 between 57-67% of upgrading emissions are leaking abroad. In the scenarios in which the developing countries adopt a carbon policy but there is nearly no Canadian bitumen produced 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 **Figure 7**, contrasting cases with and without CCS where bitumen is produced, the Canadian policy succeeds in reducing CO_2 emissions from the bitumen production process by forcing the adoption of CCS. However, the bitumen production process only accounts for about 40% of oil sands industry emissions while the upgrading accounts for 60%.

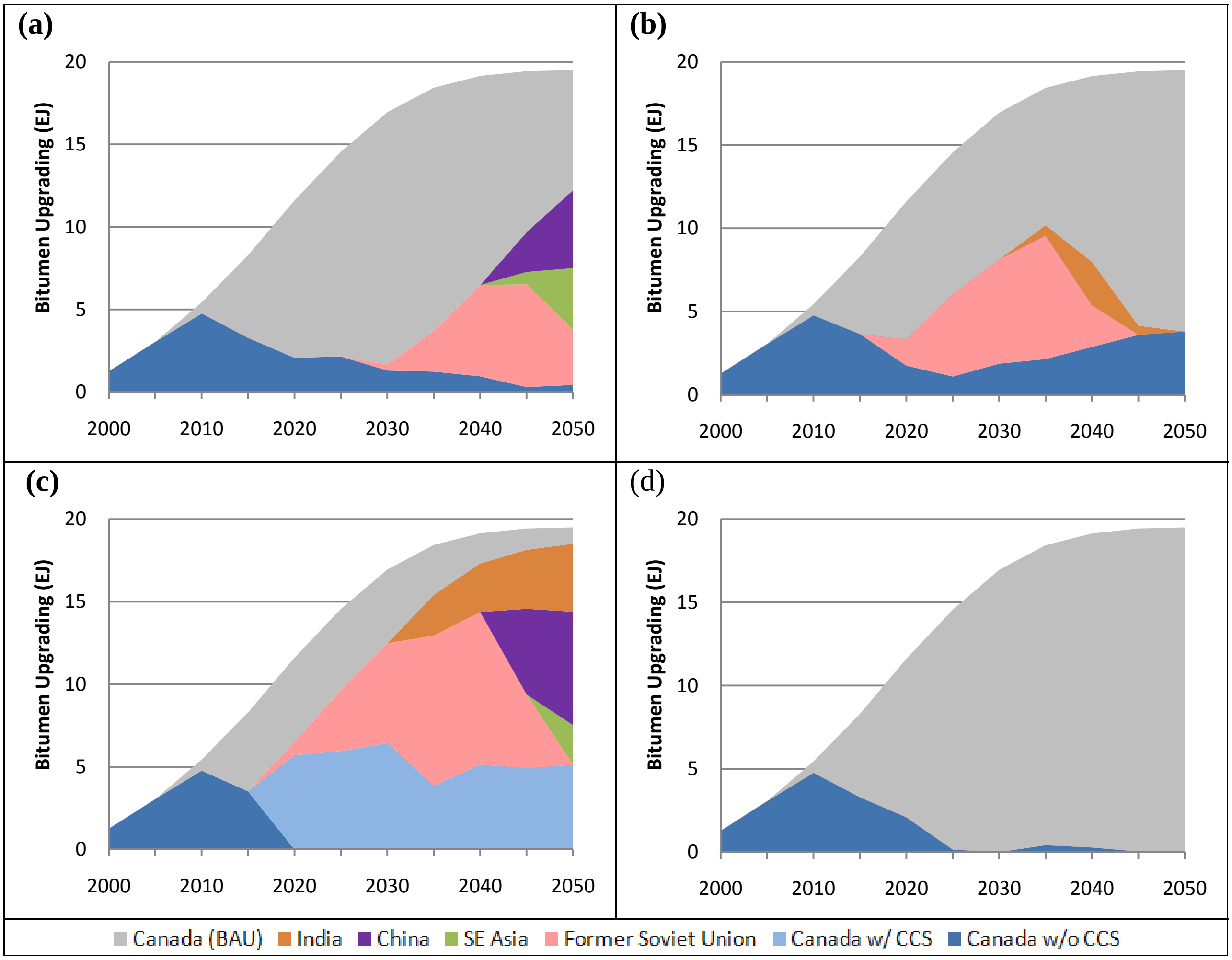

Figure 6. Relocation of Upgrading Capacity as a Result of the Climate Policy: (a) *Annex I* (b) *No Bio* (c) *NoBio + CCS* and (d) *World Policy*.

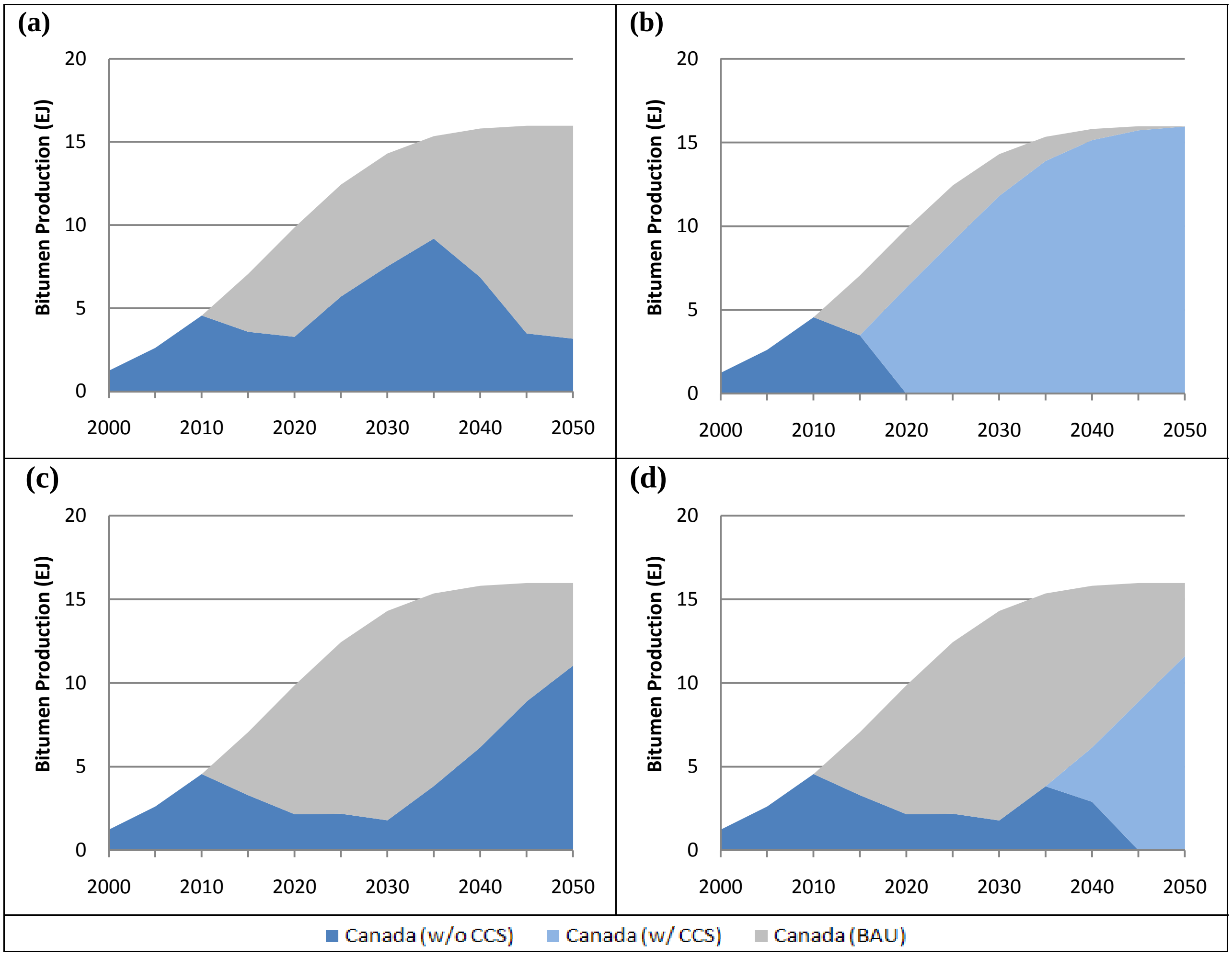

Figure 7. Use of CCS in Bitumen Production: (a) *NoBio* (b) *NoBio + CCS* (c) *Annex I* and (d) *Annex I + CCS*.

4.1 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 CO_2 prices one would observe in a cap and trade system or the CO_2 tax that would be necessary to achieve the reduction given the conditions specified in the model. To meet the constraint more of the economic 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 CO_2 prices and welfare effects in Canada. The availability of CCS makes little difference in these cases. While CCS is adopted in the *Annex I CCS* scenario, its role is limited to mostly the bitumen production process toward the end of the period. It allows Canada to produce bitumen but the extra costs reduces the rents associated with export, and so it does not create significant economic benefits in terms of a lower CO_2 price or welfare cost. CCS in the oil sands industry plays little role in the World Policy because oil sands production essentially shuts down. 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 CO_2 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. The *StrictCAN* scenarios have early welfare costs because Canada loses the oil sands industry, and higher costs in the future as it meets very tight constraints that drive the CO_2 price very high.

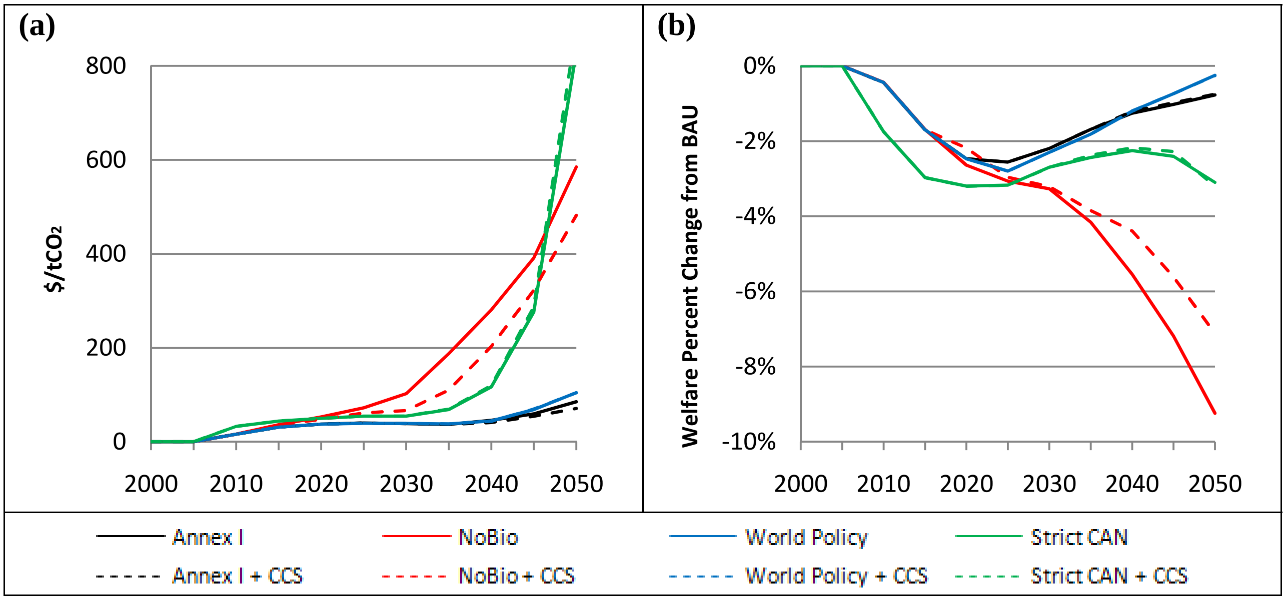

Figure 8. Economy-wide Measures of the Cost of Climate Policy in Canada: (a) Canadian CO_2 Price and (b) Welfare Change for No Policy.

5. CONCLUSIONS

The Canadian oil sands industry appears highly vulnerable to climate policy. This vulnerability stems from the fact that CO_2 emissions from the production of bitumen and upgrading are substantial and demand for petroleum products would be reduced with climate policy. With reduced demand for petroleum, crude oil and product prices are lower and higher-cost and carbon-intensive sources of oil such as oil sands, extra heavy crudes, and shale oil are most vulnerable. Adding carbon capture and storage (CCS) to bitumen production and upgrading could substantially reduce CO_2 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 relocation of upgrading of bitumen 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 is an alternative such as biofuels that can be economically competitive and produced with low life cycle CO_2 emissions, then petroleum product demand is depressed leaving much less demand for oil sands products. If such options are not available, are too costly, or are themselves CO_2 intensive because of land use change emissions, then in our simulations there continues to be a role for Canadian oil sands. 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 CO_2 targets in Canada very difficult and so the cost for country as a whole is much greater than if the oil sands industry simply shut down. We looked in particular at the biofuels option for transportation. While we did not examine them, relatively lower cost electric vehicles would be another option that would lower the cost of meeting climate policy in Canada but negatively affect the oil sands industry.

When there is substantial participation of developing countries in a 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 being that the demand for petroleum falls, and oil sands, with or without CCS, are not competitive with conventional petroleum. While production of conventional petroleum is falling off because of depletion of high grade resources, the production continues to be adequate to meet the reduced product demand. Of course if there is no developing country climate policy, it means that Canada and other Annex I countries are bearing significant economic cost to reduce emissions with relatively little climate gain because emissions continue unabated in developing countries where they are growing rapidly. The niche for the oil sands industry seems fairly narrow and mostly involves hoping that climate policy will fail. We have investigated what is now the "conventional" oil sands industry. More advanced technologies, that sought to use oil sands resources in a gasification process to produce hydrogen/electricity where carbon capture and storage captured emissions in the final product as proposed for coal, could make use of this resource. We did not investigate such a technological alternative in this paper, but it would appear to be one of the avenues by which this resource could still be used to supply energy to the world, even with CO_2 constraints.

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REFERENCES

Ansolabehere, S., J. Beer, J. Deutch, A.D. Ellerman, S.J. Friedmann and H. Herzog *et al*. (2007). *The future of coal: An interdisciplinary MIT study*, Massachusetts Institute of Technology, Cambridge, MA.

Canadian Natural Resources, Limited (2009). *Thermal: In-Situ Thermal.* Alberta, Canada. (http://www.cnrl.com/assets/north_american_crude_oil_and_liquids/thermal/)

Canada's Oil Sands, 2009. See http://www.canadasoilsands.ca/en/issues/greenhouse_gas_emissions.aspx

Choumert, F., S. Paltsev, and J. Reilly (2006). *Improving the Refining Sector in EPPA.* MIT Joint Program on the Science and Policy of Global Change, *Technical Note 9*, Cambridge, MA. (http://globalchange.mit.edu/files/document/MITJPSPGC_TechNote9.pdf)

Direction des Affaires Economiques et Internationales/Service Economique et Statistiques – Institut National de la Statistique et des Etudes Economiques (2004). *Les comptes des transports en 2003*. Partie II. (http://www.statistiques.equipement.gouv.fr/rubrique.php3?id_rubrique=239)

Dimaranan, B., and R. McDougall (2002). *Global Trade, Assistance, and Production: The GTAP 5 Data Base*. Center for Global Trade Analysis, Purdue University, West Lafayette, Indiana.

Energy Resources and Conservation Board (ERCB), 2009. *Frequently Asked Questions on the Development of Alberta's Energy Resources*. Calgary, Alberta. (http://www.ercb.ca/docs/public/EnerFAQs/PDF/EnerFAQs12-OilSands.pdf)

Energy Information Administration (EIA) (2004). *Annual Energy Review*. Washington, DC. (http://www.eia.doe.gov/emeu/aer/)

Energy Information Administration (EIA) (2008). *Country Analysis Briefs: Canada: Oil*. Washington, DC. (http://www.eia.doe.gov/emeu/cabs/Canada/Oil.html)

Environment Canada (2008a). *Canada's Greenhouse Emissions: Understanding the Trends, 1990-2006*. Gatineau, Quebec.

Environment Canada (2008b). *National Inventory Report 1990-2006: Greenhouse gas sources and sinks in Canada*. Gatineau, Quebec. (http://www.ec.gc.ca/pdb/ghg/inventory_report/2008_trends/2008_trends_eng.pdf)

Government of Alberta (2009a). *Oil Sands*. Alberta, Canada. (http://www.energy.alberta.ca/OurBusiness/oilsands.asp)

Government of Alberta (2009b). *About the Oil Sands*. Alberta, Canada. (http://oilsands.alberta.ca/1.cfm)

Government of Canada (2007). *Action on Climate Change and Air Pollution*. Canada. (http://www.ecoaction.gc.ca/news-nouvelles/pdf/20060426-2-eng.pdf)

Hertel, T. (1997). *Global Trade Analysis: Modeling and Applications*. Cambridge University Press. Cambridge, UK.

International Energy Agency (2005a). *Extended Energy Statistics*. Paris, France.

International Energy Agency (2005b). *Oil Information*. Paris, France.

Lieberman, J., B. Cardin, R. Casey, N. Coleman, S. Collins, E. Dole, T. Harkin, A. Klobuchar, B. Nelson, C. Schumer, J. Warner, R. Wyden (2007). *S. 2191, America's Climate Security*

Act of 2007. U.S. Library of Congress. (http://thomas.loc.gov/cgi-bin/bdquery/z?d110:S.2191:)

Mathiesen, L. (1985). Computation of Economic Equilibrium by a Sequence of Linear Complementarity Problems. *Mathematical Programming Study*, 23: 144-162.

Organization of the Petroleum Exporting Countries (OPEC) (2008). *Annual Statistical Bulletin 2007*. Vienna, Austria.

Paltsev, S., J. Reilly, H.D. Jacoby, R.S. Eckaus, J. McFarland, M. Sarofim, M. Asadoorian, and M. Babiker (2005). *The MIT Emissions Prediction and Policy Analysis (EPPA) Model: Version 4*. MIT Joint Program on the Science and Policy of Global Change, *Report 125*, Cambridge, MA. (http://globalchange.mit.edu/files/document/MITJPSPGC_Rpt125.pdf)

Rutherford, T. (1995). Extension of GAMS for Complementarity Problems Arising in Applied Economic Analysis. *Journal of Economic Dynamics and Control*, 19(8): 1299-1324.

Rutherford, T. (1999). Applied General Equilibrium Modeling with MPSGE as a GAMS Subsystem: An Overview of the Modeling Framework and Syntax. *Computational Economics*, 14: 1-46.

The Economist (2008). *The Politics of Sand*. The Economist Newspaper Limited. London. Aug. 25, 2008. (http://www.economist.com/world/international/displaystory.cfm?story_id=11995791)

The Liberal Party of Canada (2007). *Balancing Our Carbon Budget*. Ontario, Canada. March, 2007. (http://ontario.liberal.ca/pdf/docs/whitepaper_EN.pdf)

The New York Times (2008). *Richest Nations Pledge to Halve Greenhouse Gas*. New York. July 9, 2008. (http://www.nytimes.com/2008/07/09/science/earth/09climate.html)

TOTAL (2009). *Total Upgrader: Overview*. Calgary, AB T2P 4H4, Canada. (http://www.total-ep-canada.com/upgrader/upgrading.html)

United Nations Framework Convention on Climate Change (UNFCCC) (2008). *Kyoto Protocol Reference Manual on Accounting of Emissions and Assigned Amount*. Bonn, Germany. (http://unfccc.int/resource/docs/publications/08_unfccc_kp_ref_manual.pdf)

United Nations (2000). *Long-Run World Population Projections: Based on the 1998 Revision*. United Nations, New York.

United Nations (2001). *World Population Prospects: The 2000 Revision, Data in digital form*. Population Division, Department of Economic and Social Affairs, United Nations, New York.

United States Environmental Protection Agency (US EPA, 2001, 2002, 2004). *US Greenhouse Gas Inventory Archive*. Washington, DC. (http://www.epa.gov/climatechange/emissions/usgginv_archive.html)

World Business Council for Sustainable Development (2005). *Mobility 2030: Meeting the Challenges to Sustainability*. Sustainable Mobility Project. (http://www.wbcsd.org/plugins/DocSearch/details.asp?type=DocDet&ObjectId=NjA5NA)

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