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Allocation of Carbon in the Production of Liquid Fuels and Electricity in the United States

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June 8, 2012

Abstract

The crude from Canadian oil sands provides enormous security and economic advantages to the United States, but the carbon dioxide emitted during its extraction and refinement is about double that of most conventional crudes. This paper proposes that the U.S. government formulate policies that foster the diversion of Canadian oil sands crude to U.S. Gulf refineries, offsetting the additional carbon dioxide they create by using gas instead of coal to generate electricity. The development of oil sands should reduce the U.S. trade deficit; it would also ease the economic pressure to accelerate the production of coal-to-liquid fuels, which would result in four times as much carbon dioxide per gallon of fuel as the Canadian oil sands.

I. Introduction

It is not our aim to rehash the science of global warming. We take it as a given that global temperatures are rising as the result of human activity—primarily carbon dioxide (CO_2) emissions resulting from the combustion of fossil fuels. Humanity has thus embarked on a colossal unplanned experiment on the world climate. The actual consequences of this experiment are the subject of continued debate. Changes in local climates may lead to massive migrations of human populations. Such a global upheaval would be destabilizing in an already unstable world.
The world economy requires energy and at our current level of technology, this requires the consumption of fossil fuel. Since fossil fuels are necessary, and carbon dioxide emissions must be controlled, the optimal allocation of carbon dioxide emissions is important.

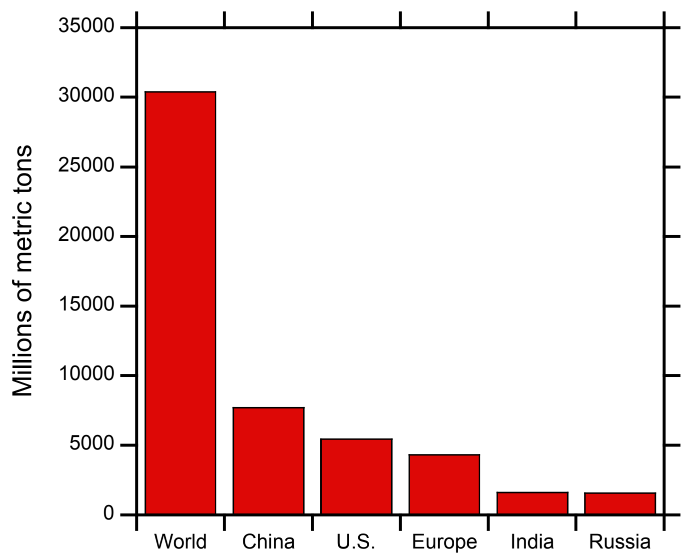
The United States contains enormous reserves of coal and natural gas. These fuels, along with nuclear and renewable energy, supply almost 63 percent our energy needs. While much of our demand for liquid fuels can be met by domestic production, the United States imports about 9.4 million barrels of fuel a day net. A reliable supply of liquid fuels is vital to our economy and national security. We must place a high priority on finding an alternative to imports that might be interrupted and that represent a significant fraction of our balance of payments deficit.

Canadian oil sands and the recent discovery of how to exploit the massive deposits of natural gas locked in shale in the United States make it possible for the United States to reduce its dependence on fuels from outside North America without increasing carbon dioxide emissions. We propose that the U.S. government develop policies that redirect our carbon usage, and thus our carbon dioxide emissions, away from the electricity generation sector toward transportation fuels by facilitating the development of Canadian oil sands, and offset the resulting additional carbon emissions by shifting the conversion of electrical generation from coal to gas. Many of the policies that may be necessary to reduce carbon dioxide emissions in the United States may result in some economic cost. However, reallocating carbon dioxide emissions from electrical generation to transportation is welfare improving. Further, Canada is the largest trading partner of the United States and experts estimate that more than 50 percent of Canadian income from the sale of oil would be spent in the United States with a substantial impact on our balance of payments.[1]

II. Carbon Dioxide Emissions

We review briefly world carbon dioxide emissions using a few figures to make the emission facts clear. The total emissions of the world's major carbon dioxide emitters as of 2009 are shown in Figure 1, below.[2] This figure shows that China has passed the United States in total carbon dioxide emissions.

Figure 1. Total CO_2 emissions and major emitters

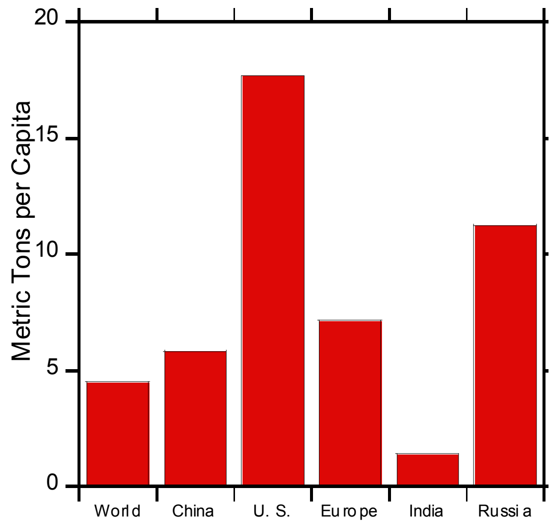


[1] Statistics from Ian F. Fergusson, "United States-Canada Trade and Economic Relationship: Prospects and Challenges," Congressional Research Service, 2008; and expert opinion from conversations with J. David Richardson, Maxwell School of Syracuse University.

[2] U.S. Energy Information Administration, "Total Carbon Dioxide Emissions from the Consumption of Energy," http://tonto.eia.doe.gov/cfapps/ipdbproject/IEDIndex3.cfm?tid=90&pid=44&aid=8.

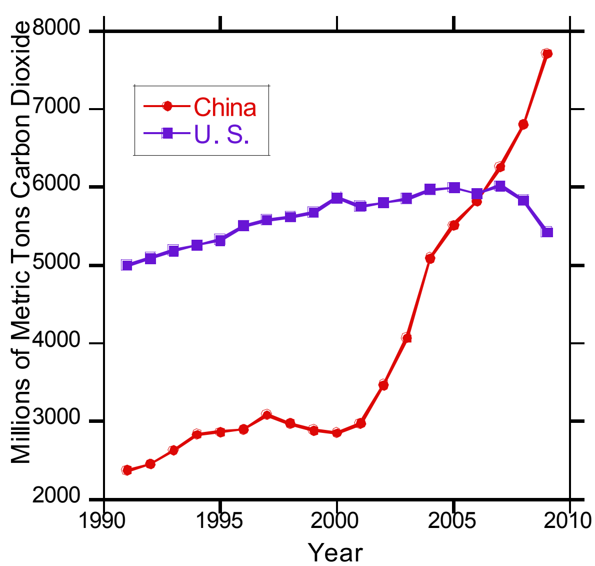
A different way to look at the situation is in terms of per capita emissions.

Figure 2. Per-person CO_2 emissions by the same countries



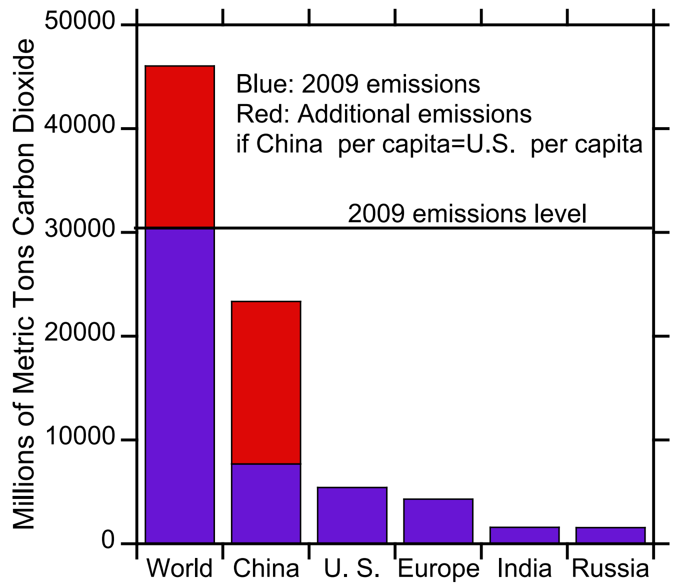
The United States is the largest emitter of carbon dioxide among large countries on a per capita basis. The worry is that China, with its much larger population, will catch up. A cause for alarm is how rapidly this is taking place, as seen in Figure 3.

Figure 3. Total CO_2 emissions between 1991 and 2009 for the United States and China



In spite of rapidly overtaking the United States in total emissions, the per capita emissions from China are still far smaller. The obvious danger is that China will continue its rapid growth in carbon dioxide emissions. Figure 4 shows total emissions if China's per capita emissions rose to the United States' 2009 level.

Figure 4. Total emissions if China's per capita emissions equaled those of the United States



Parity of Chinese per capita emissions with U.S. emissions would increase the rate at which carbon dioxide is entering the atmosphere worldwide by about 50 percent.

China has few tools at its disposal for maintaining the growth of its economy without continued rapid growth of its carbon dioxide emissions. The principal energy resource of China is coal, which is by far the biggest emitter of CO_2 per unit of energy obtained. It will be hard, perhaps almost impossible, for the Chinese government to slow, much less stop, the growth of Chinese carbon dioxide emissions.

The Chinese government is powerful. However, asking the Chinese population to make sacrifices in order to avoid climate change while Chinese per capita emissions remain far below those of the United States would be difficult. We believe it is necessary for the United

States to control its own carbon dioxide emissions if there is going to be any possibility of control worldwide.

III. Substitutes for Conventional Petroleum

There are only three ways to address the shortage of liquid fuels: first, expand domestic production of oil; second, improve the energy efficiency of the vehicle fleet; and third, develop alternative sources of liquid fuels. All three approaches must be pursued. We propose, as many have done before, that the United States facilitate the development of alternative sources of liquid fuels, specifically the development of oil sands, in a manner that mitigates carbon dioxide emissions. At the present time, there are three potential alternative sources of liquid fuels that are economically viable: oil sands, the conversion of coal into synthetic liquid fuels, and the conversion of natural gas into synthetic liquid fuels. (We will not consider oil shale, as it is not economically viable at current prices.) Some of these alternative sources are more carbon dioxide-intensive than conventional fuels. This has created opposition to their development, as illustrated by 2007 legislation prohibiting the U.S. Department of Defense from purchasing fuels with high carbon intensity;[3] the California Low Carbon Fuel Standards Regulation;[4] and recent protests against the Keystone XL pipeline, which—among other environmental concerns—transports oil that results in higher greenhouse gas emissions than conventional oil.[5]

We argue in this paper that recent concern about the additional carbon dioxide that might result from approval of the Keystone project is misplaced. While it is true that Canadian oil sands fuel production creates more carbon dioxide than some other crude oils, this additional carbon dioxide is small compared with the carbon dioxide emissions that result from our current use of coal to produce electrical power. We will show that shifting some electricity generation from

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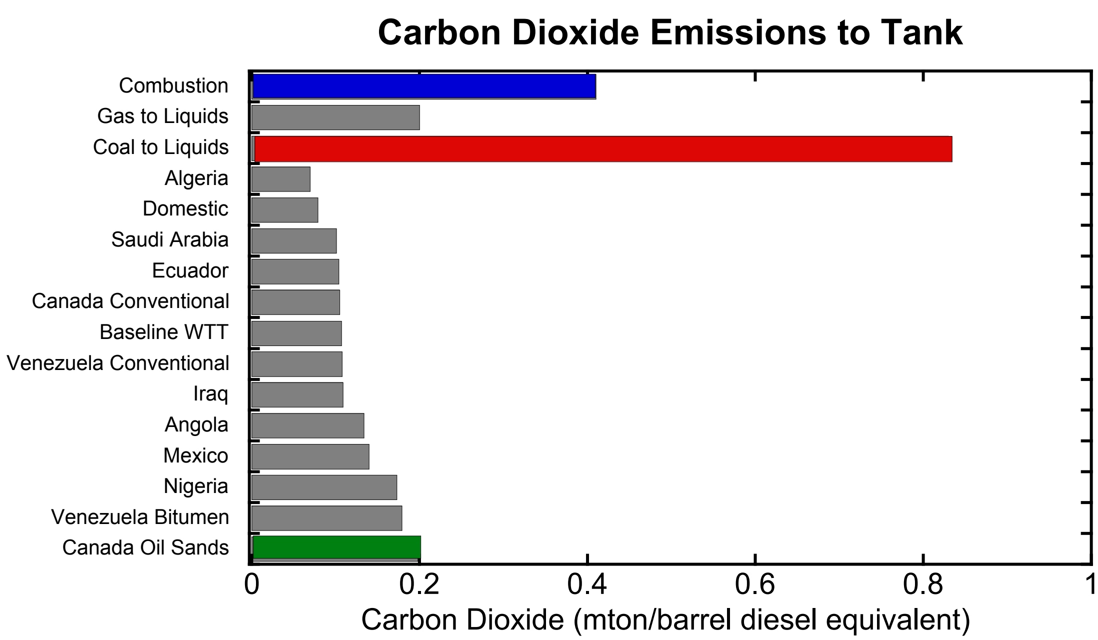
[3] See the Energy Independence and Security Act of 2007, Section 526:
"No Federal agency shall enter into a contract for procurement of an alternative or synthetic fuel, including a fuel produced from nonconventional petroleum sources, for any mobility-related use, other than for research or testing, unless the contract specifies that the lifecycle greenhouse gas emissions associated with the production and combustion of the fuel supplied under the contract must, on an ongoing basis, be less than or equal to such emissions from the equivalent conventional fuel produced from conventional petroleum sources."
[4] See California Governor Executive Order S-01-07, issued January 18, 2007.
[5] *New York Times*, "Tar Sands and the Carbon Numbers," Editorial, August 21, 2011.

coal to natural gas could easily compensate for all additional carbon dioxide emissions from Canadian oil sands.

However, such a shift requires the reallocation of resources within the economy that we believe may not be accomplished solely by market forces. Government emissions regulations already encourage displacement of coal with gas, but further action will be required to offset carbon dioxide from alternative fuel sources.

If no regulatory mechanism is developed to mitigate carbon dioxide from alternative fuel sources, a coal-to-liquids fuel industry could rapidly expand, resulting in greatly increased emissions. Figure 5 below helps provide perspective on these issues.

Figure 5. Comparison of relevant carbon dioxide emissions. Combustion refers to the carbon dioxide emitted when the fuel is used.[6]



[6] Gerdes, Kristin J. and Timothy J. Skone. 2009. *Consideration of Crude Oil Source in Evaluating Transportation Fuel GHG Emissions*. National Energy Technology Laboratory. DOE/NETL- 2009/1360, March 20. For information on gas-to-liquids and coal-to-liquids quantities see the Appendix at the end of this paper.

The development of a coal-to-liquids fuel industry is not merely speculative. Our calculations show that it is economically feasible and should be quite profitable if there are no constraints on carbon dioxide emissions. In fact, Energy Information Administration (EIA) projections show coal-to-liquids fuel coming online starting in 2020.[7] We fear the demonstration of an economically profitable coal-to-liquids technology would lead to its rapid expansion unless some mechanism is developed to regulate greenhouse gases from the production of oil. Additional crude from the Canadian oil sands could help stave off this undesirable development by reducing the price of crude oil. If our suggestion for mitigating the emissions from Canadian oil sands is followed, it could create a precedent for regulation of carbon dioxide from alternative sources of liquid fuels and deter the development of a coal-to-liquids industry.

However, the Chinese have already started production of liquid fuels on a large scale. In its first year of operation, the coal-to-liquids fuels plant of Shenhua Energy Company produced approximately 3.7 million barrels of liquid fuel. The company is proposing to capture the carbon dioxide emissions using an algae scheme[8] by 2020. Production from this plant will eventually scale up to about 8 million barrels per year.[9, 10]

There are three ways of allocating carbon dioxide in a carbon dioxide-constrained economy: first, a carbon tax that would require emitters of carbon dioxide to internalize the externality from carbon dioxide; second, a market in carbon dioxide emission permits serving the same function; third, direct control of carbon dioxide emissions by regulation. The carbon tax results in transfer payments from the consumer to the government. Regulation shuts down inefficient producers without compensation. The distributional effects of cap-and-trade are complicated and depend on how it is structured. They differ in details as to the information required to implement

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[7] If there are no constraints on the production of greenhouse gas Energy Information Administration projects, the production of coal-based synthetic liquids rises to 1.3 million barrels per day in 2035. U.S. Energy Information Administration, *Annual Energy Outlook 2011*, page 87 and Table A11, page 137.

[8] Global CCS Institute, "China coal-to-liquid plant will use algae-based CO_2 capture," October 20, 2011, http://www.globalccsinstitute.com/institute/news/china-coal-liquid-plant-will-use-algae-based-co2-capture *(Accessed May 20, 2012)*

[9] *Reuters*, "China Shenhua coal-to-liquids project profitable—exec," September 7, 2011, http://www.reuters.com/article/2011/09/08/shenhua-oil-coal-idUSL3E7K732020110908.

[10] This year, China hosted a World CTL Conference, April 17-20, 2012.

the policies and the cost associated with errors in information about the slopes of the demand and supply curves.

If either of the first two methods were in place, the issue of nonconventional sources of liquid fuels would be relatively easy to address. The question would be simply whether the production of these fuels was economically viable if producers were forced to internalize the cost of the carbon dioxide emissions. Unfortunately, the current political climate has made cap-and-trade, originally a conservative idea with bipartisan support, politically unviable at this time.

At present, gas prices are low compared with a few years ago because of the development of unconventional gas. In March 2012, the price of gas dropped to below $2.50 per thousand cubic feet (tcf). An estimate by the Massachusetts Institute of Technology (MIT) for gas resources in the United States is 2,100 trillion cubic feet (Tcf). The low case estimate (with a 90 percent probability of being met or exceeded) is 1,500 Tcf, and the high case estimate is 2,850 Tcf (with a 90 percent probability of not being exceeded).[11] As a point of reference, gas consumption in 2010 was 24.13 Tcf.[12] The price of gas is relatively volatile and hard to predict. The MIT study projects the price of gas based on various technological and policy scenarios. These projections have the price of gas in the $5 to $10 range in the 2020 to 2040 time period.[13] The EIA projections are $4.47 to $7.23 in the 2015 to 2035 time period.[14]

How should the new gas be used? One possibility is to use it directly as the fuel for internal combustion engines. It is much cheaper per-unit energy than gasoline or diesel fuel. This is already beginning to happen with bus and taxi fleets. However, because the energy density per-unit volume is much smaller for methane than for gasoline or diesel fuel, gas vehicles for long distance travel seem to be faced with the chicken-and-egg problem of no demand for vehicles without a wide distribution of gas service stations and no wide distribution of gas service stations without many vehicles to supply. Thus, it appears to us, there are two main choices. The new gas

[11] Ernest J. Moniz, *The Future of Natural Gas: An Interdisciplinary MIT Study*, June 2011, page 30.
[12] U.S. Energy Information Administration, *Annual Energy Outlook 2012 Early Release*, Table A13, page 27.
[13] Moniz, *The Future of Natural Gas*, page 60.
[14] U.S. Energy Information Administration, *Annual Energy Outlook 2012 Early Release*, Table A13, page 27.

can either be used to move electricity production from coal to gas, or it can be used to manufacture synthetic liquid fuels, most likely by the Fischer-Tropsch process.

There is new interest in the conversion of stranded natural gas to liquid fuels. Shell has made an investment of more than $20 billion in the Pearl natural gas Fischer-Tropsch liquid fuels project in Qatar with the encouragement of the Qatar government.[15] Chevron has made a smaller, but still substantial, investment in a similar project in Nigeria, which is not yet operational and might be abandoned. Could similar projects be initiated in the United States? We believe this is unlikely because domestic natural gas is not stranded, and competing uses will make its cost too high to use as feedstock for gas-to-liquids fuel conversion.

An analysis of the economics, and carbon dioxide emissions, of the synthesis of liquid fuels by the Fischer-Tropsch process is given in an appendix to this paper. The major conclusions of this analysis are:

- The capital costs of constructing a Fischer-Tropsch plant are quite high.
- Whether such a plant is economically feasible depends upon the price of conventional fuels and the price of the input fuel to the plant.
- Synthetic fuels produced from coal, which can have prices as low as $12 per short ton at the mine, are competitive with conventional petroleum at petroleum prices as low as $56 per barrel. At a natural gas price of $5 per thousand cubic feet (tcf), Fischer-Tropsch liquid fuel from natural gas is competitive at a petroleum price of $79 per barrel.
- The production of liquid fuel from coal produces 0.82 to 0.92 metric tons (mton) of CO_2 emissions per barrel, while production of liquid fuel from natural gas produces 0.2 mton of CO_2 per barrel, on a par with Canadian oils sands crude.

Natural gas has a history of wide swings in price. It has not been long since natural gas was $12 per million BTUs (MMBTU). Petroleum also has a history of wide swings in price. When the high capital cost of construction of a Fischer-Tropsch plant is considered, it is unlikely that gas

[15] Julia Werdigier, "Royal Dutch Shell Profit Nearly Doubles," *New York Times*, July 28, 2011, http://www.nytimes.com/2011/07/29/business/global/royal-dutch-shell-profit-nearly-doubles.html?scp=1&sq=Pearl "natural gas" Shell&st=cse.

Fischer-Tropsch production will occur, simply because of the fear that price swings might make production uneconomical, resulting in loss of the capital used in building the plant. Further, given the low carbon intensity of this process, there is not a strong need for a policy to regulate it.

If there is no constraint on the production of carbon dioxide, coal Fischer-Tropsch is profitable for oil prices above $65 a barrel. If oil prices stabilize above $100 a barrel, the development of coal Fischer-Tropsch is a very real possibility from an economic point of view. This would result in a very substantial increase in carbon dioxide emissions. We calculate that coal Fischer-Tropsch production of one million barrels a day would result in 300 to 336 million tons of carbon dioxide a year. This is 13 to 18 percent of the 1,828 million tons of carbon dioxide produced by coal generators in 2010.[16] We think that government policies should aim to discourage this development.

Canada has proven oil sands reserves of 170 billion barrels. This is enough to supply five million barrels a day for more than 90 years. Canadian oil sands produce more carbon dioxide than conventional oil (0.2 vs. 0.11 mton/barrel well-to-tank [WTT]), but this is about on a par with Venezuelan bitumen and far less than the 0.82 to 0.92 mtons in production for coal Fischer-Tropsch.

The market for petroleum is global so it very unlikely that any U.S. policy can keep Canadian oil sands off the global market. Canada will produce oil from the sands regardless of any U.S. policies. Thus, we argue that it is feasible to mitigate the carbon dioxide externality from the oil sands. The Keystone project can increase U.S. energy security without increasing net emissions of carbon dioxide. Such an arrangement has net benefits to both parties. It is less expensive for Canada to use U.S. Gulf ports to market their oil. Canadian oil sands crude would typically be refined in the United States and shipped overseas in the form of gasoline and diesel fuel. This oil would create jobs in the U.S. petrochemical industry and be a secure source of oil for the United States if world oil markets were disrupted. Finally, Canada is the United States' largest trading partner; importing oil from Canada rather than other countries is likely to be less detrimental to the U.S. balance of payments. Income to Canada from whatever source is going to result in

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[16] U.S. Energy Information Administration, *Annual Energy Outlook 2012 Early Release*, Table A18, page 36.

higher exports from the United States to Canada; thus no matter how the oil is marketed, exploitation of the Canadian oil sands is good for the U.S. balance of payments.

The most efficient and environmentally responsible way to use natural gas to augment our supply of transportation fuels is to displace coal in the generation of electricity, and use the savings in the carbon dioxide emissions to mitigate the additional carbon dioxide from the Canadian oil sands. There are several reasons why this is feasible. The capital cost of natural gas electricity generators is low, making replacement of existing coal generators with gas generators economically possible. Because natural gas combined-cycle generators are more efficient than coal generators, and natural gas produces much less carbon dioxide per BTU than coal, replacing coal with gas will reduce carbon dioxide emissions.

At current gas prices, the price of electricity would be virtually unaffected by shifting electricity generation from coal to gas. However, gas may have an anomalously low cost at present. We content ourselves here with calculating the cost to the consumer of a forced shift of enough electricity generation from coal to gas to compensate for the increased use of Canadian oil sands fuel. In this, we will use projected higher prices of natural gas.

IV. The Simple Feasibility of Compensating Oil Sands Emissions with an Electricity Shift

Suitable government polices can offset the additional carbon dioxide from the Canadian oil sands through a mechanism that replaces coal with gas in electricity generation. We calculate the cost of doing so below.

In 2011, we calculated a marginal cost of carbon dioxide.[17] The calculation is repeated below in Section V. This price of carbon dioxide is not a measure of the cost of carbon dioxide as an externality—i.e., this carbon dioxide price is not a measure of the cost of carbon dioxide emissions to the world, or even to the United States. It is simply the marginal carbon price needed to shut down that plant (and all less efficient plants) and thus reduce carbon dioxide by

[17] Dagobert L. Brito and Robert F. Curl, "Economics of Pricing the Cost of Carbon Dioxide Restrictions in the Production of Electricity," *The Energy Journal* 32, no. 4 (2011).

switching the generation of electricity from coal to gas. This carbon price can be in the form of a carbon tax or a tradable entitlement. Shifting electricity generation from coal to gas can also be accomplished by regulation.

The price of carbon dioxide that will shut down a marginal coal generator is a function of the price of coal, the price of gas, and the heat rate of the marginal coal generator.[18] In order to calculate the carbon dioxide price needed to remove a total of *Z* tons of carbon dioxide emissions by conversion of a portion of the electricity generation industry from coal to gas, we consult a table produced by the Energy Information Administration that lists the total amount of fuel used, Q_k in MMBTU, and the total amount of electricity produced, E_k in MWh, by every generator in the country over a particular year.[19] From this list, the heat rate of each generator is calculated as

(4.1) $$R_{1k} = \frac{Q_k}{E_k}$$

Then the list is sorted by decreasing heat rate in order to list the coal generators by increasing efficiency. The offset is determined by subtracting the amount of carbon dioxide emitted by the gas-fired generators that offset the electricity from the amount of carbon dioxide emitted from the coal-fired generators that will be shut down. This is the amount of carbon dioxide reduced while keeping the amount of electricity generated constant. Thus if we list the coal-fired generators from the least efficient to the most efficient, we must sum the carbon dioxide emission savings as we go down the list until we have replaced enough generators to reach our carbon dioxide target. We express this by

(4.2) $$A\sum_{j=1}^{k} Q_j - B\sum_{j=1}^{k} E_j \geq Z$$

where Z is the target amount of carbon dioxide reduction and *k* is the index of the last plant shut down. The first sum in equation (4.2) is the amount of carbon dioxide not emitted by shutting down the coal-fired generators. *A* (=0.0946) is the metric tons of carbon dioxide emitted upon

[18] The heat rate is the amount of energy a generator needs to produce electricity. It is a measure of the efficiency of a generator. Heat rates are usually stated as BTU/kwh. In our calculations it is more convenient to use MMBTU/MWh. MMBTU stands for one million BTU.
[19] U.S. Energy Information Administration, "2010: EIA-923 January-December Final, Nonutility Energy Balance and Annual Environmental Information Data," http://www.eia.gov/cneaf/electricity/page/eia906_920.html.

burning enough coal to produce one MMBTU. Q_j is the total fuel used by generator *j* to generate the amount of electricity E_j for a year. The second term is the amount of carbon dioxide global warming equivalent emitted by the gas-fueled generators required to replace the coal-fueled generators shut down. All replacing gas generators are assumed to have the same efficiency. *B* is the mton of CO_2 equivalent when enough natural gas is burned to replace the electricity of generator *j*.

(4.3) $$B = GWP \times Cv / Eff$$

Cv is the factor converting MWh (here thought of as unit of heat) into mton carbon dioxide assuming that one mole of carbon dioxide is produced for each mole of methane burned, and *Eff* is the (fractional) efficiency of the replacing gas generators in converting heat into electricity. If there were no leaks of methane in its production and distribution, *GWP* would be 1 because by definition the global warming potential of carbon dioxide is 1. Unfortunately, there is significant leakage of methane before it reaches the electricity generator, and methane is a powerful global warming gas. The quantity *GWP*>1 is thus introduced to correct for this. It will shortly be considered in more detail.

(4.4) $$Cv = \frac{mtonCO_2}{moleCO_2}\left(\frac{moleCH_4}{Joules}\right)\frac{Joules}{MWh} = 44.\times 10^{-6}\frac{1}{.890\times 10^{6}}3600\times 10^{6} = 0.178\frac{mtonCO_2}{MWh}$$

The appropriate number for *GWP* involves much uncertainty about quantitative information and complex, even philosophical, considerations. The complexity is introduced because the production of natural gas results in significant leakage of methane into the atmosphere. The fraction of methane leaked in its production and distribution is uncertain over wide range because reliable quantitative information about the magnitude of this leakage[20] is difficult to obtain. Methane is a powerful,[21] but relatively short-lived (~12 years), global warming gas. When the global warming power of methane is combined with significant leakage (of the order

[20] Robert W. Howarth, Renee Santoro, and Anthony Ingraffea, "Methane and the greenhouse-gas footprint of natural gas from shale formations," *Climate Change* 106 (2011): 679.
[21] D.T. Shindell and G. Faluvegi et al., "Improved Attribution of Climate Forcing to Emissions," *Science* 326, no. 5953 (2009): 716.

of 3 percent to 8 percent), the contribution of leaked natural gas to the GWP of the use of gas, in our case for electricity generation, cannot be ignored.

Because methane is short-lived, the choice of global warming time horizon makes a significant difference. The global warming potential of methane over a 20-year time scale is about three times larger than over 100 year scale. The global warming effect of carbon dioxide also depends upon time, but after an initial rapid decrease its global warming effect lingers for hundreds of years. In deference to future generations, we argue that at least the 100-year average global warming effect of methane should be used. This GWP ranges from 25 to 34.[21] We thus write

(4.5) $$GWP_{100} = 1 + \frac{16}{44} LEAK \times GWP_{100}^{methane}$$

The global warming potentials of greenhouse gases are defined per kilogram relative to carbon dioxide. The 1 in the first term represents one kilogram of carbon dioxide and takes into account the carbon dioxide produced when the gas is burned in electricity generation. The second term takes into account gas leakage in the production and distribution of natural gas that never reaches the generator. The factor $\frac{16}{44}$ in the second term is the number of kg of methane needed to produce the one kg of carbon dioxide on combustion. The total kg of methane leaked per kg carbon dioxide burned in the generator is $\frac{16}{44} LEAK$. The global warming potential of methane $GWP_{100}^{methane}$ is relative to carbon dioxide, i.e., $GWP_{CO_2} \equiv 1$ at any time. We use *LEAK*=5% as an average of conventional and shale gas, $GWP_{100}^{methane}$ = 30 as a guess between the 2007 IGCC value of 25 and a revision[21] involving very complex considerations of the effects of methane atmospheric chemistry upon aerosol formation. In equation 4.3 for *Eff,* we use 0.5 (i.e., 50 percent) as the heat efficiency of a combined-cycle gas generator. [22]

[22] John Deutch et al., *2009 Update of the 2003 MIT Report: The Future of Nuclear Power*, Massachusetts Institute of Technology. Available at http://web.mit.edu/nuclearpower/pdf/nuclearpower-update2009.pdf. A footnote to Table 1 in this update cites the heat rate of a combined cycle gas generator as 6800 kWh/MMBTU, which translates to an efficiency of approximately 50 percent.

The information about coal-fired generators needed to calculate the running sums is taken from the Energy Information Administration 2010 report[19] on the electricity generation sector. Table 1 below summarizes the results of putting the information and assumptions described above into equations 4.5, 4.3, and 4.2.

Table 1. CO_2 reductions and the transfer of electricity production from coal to gas

Decrease in CO_2 (million metric tons/ year[a])	**Percent coal generation shut down**	**Marginal heat rate**	**Electrical energy moved to gas (TWh/year)**	**Natural gas required[b] Trillion cu ft**	
				Gas Leakage 5%	**Gas Leakage 0%**
40	3.39	11.53	62.	0.42	0.32
80	7.79	11.17	143.	0.98	0.69
120	12.0	11.05	220.	1.50	1.08
160	16.4	10.92	301.	2.05	1.48
200	21.2	10.78	389.	2.65	1.87

[a]Offsetting 0.1 mton per barrel at 5,000,00 barrels per day =183, million mton CO_2
[b]Total U.S. gas consumption in 2010 was 24.13 Tcf.[23] U.S. gas consumption for electricity generation in 2010 was 7.38 Tcf.[24]

Table 1 uses $GWP_{100}^{methane}$ =30; a comparison of the percentage of the coal generation shut down assuming no leakage of gas in production and distribution, demonstrating the effect of the higher global warming potential (GWP) of methane.

V. Cost Analysis of Offsetting Canadian Oil Sands Crude by Shifting Electricity from Coal to Gas

In order to determine the cost of replacing a certain number of the least efficient coal plants with gas generators, the costs of operating plants of each type must be known. The needed specific

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[23] *Energy Information Administration Annual Energy Review*, "Natural Gas Table 6.1," release date October 19, 2011, http://www.eia.gov/totalenergy/data/annual/showtext.cfm?t=ptb0601.
[24] *Energy Information Administration Annual Energy Outlook 2012 Early Release*, "Natural Gas Supply, Disposition, and Prices," release date January 23, 2012, http://www.eia.gov/oiaf/aeo/tablebrowser/ -release=EARLY2012&subject=0-EARLY2012&table=13-EARLY2012&region=0-0&cases=full2011-d020911a,early2012-d121011b.

information are the costs of coal and natural gas per MMBTU, the operating cost per MWh of each type of plant, the construction cost of gas plants, and the efficiency of gas plants. Given these, the cost of such a replacement can be calculated. The future prices of these fuels, especially natural gas, are not easy to predict. Thus much of our effort will be to present the cost of this shift in electricity generation from coal to gas using a range of assumptions for future fuel prices. The Energy Information Administration *Annual Energy Outlook 2012* predicts the prices of these fuels as listed in Table 2 below.[25]

Table 2. Fuel prices based on Energy Information Administration Annual Energy Outlook 2012 price and policy projections

	2008	**2009**	**2010**	**2015**	**2020**	**2025**	**2030**	**2035**
Price of gas dollars/MMBTU[26]	9.02	4.85	5.14	4.54	4.91	5.70	6.13	7.08
Price of coal/MMBTU	2.07	2.22	2.25	2.36	2.46	2.56	2.70	2.83
Price of carbon dioxide emissions to shut down R=10.97	63.00	18.66	21.09	13.28	15.37	21.69	23.74	31.18

As of March 2012, the price of gas is near $2.50 per MMBTU, and the price of coal is near $2.25 per MMBTU. At these prices, electricity can be generated more cheaply by new gas generators than by running the less efficient existing coal generators with heat rates greater 10.2. The heat rates of 90 percent of the existing coal generators are greater than 10.2. However, gas is predicted to rise in price. At the price predicted for coal and gas in 2035, the marginal heat rate is 12.2, and 98 percent of existing coal generators would remain in operation if the only criterion were the cost of fuel.

Table 3 gives the operating costs of each type of plant and the capital cost of a combined cycle plant. We use the 2009 MIT study (footnote 22, above) as the base case to define these parameter

[25] As we write in May 2012, the price of gas is around $2.50 per tcf, which makes the price of CO_2 zero using the 2010 coal price of Table 2.
[26] 2009-2035 data from the U.S. Energy Information Administration *Annual Energy Outlook 2012 Early Release*, Table A8, page 20 (2010 dollars). 2008 data from the U.S. Energy Information Administration *Annual Energy Outlook 2011*, Table A3, page 121.

values.[27] There is no capital cost for the coal plant, as we assume it is marginal and the value of the future income stream is zero.

Table 3. Assumptions about the operating costs of both types of plants and construction of gas plants

Parameter	**Symbol**	**Coal i=1 $**	**Gas i=2 $**
Operating cost/MWh	d_i	8	2
Construction cost/MWh	b_i	–[a]	10

[a] Coal plant is marginal and the value of the future income stream is zero.

The total cost of the shift is given by subtracting the cost of the electricity generated by the coal generators being shut down from the cost of the electricity from the gas generators replacing them. Equation 5.1 below describes the summations required using the EIA report[19] on the electricity industry.

$$\text{(5.1)} \qquad Cost = \left[\left(Gas_{cost} Cnv / Eff + b_2 + d_2 \right) \sum_{j=1}^{k} E_j \right] - \left(Coal_{cost} \sum_{j=1}^{k} Q_j + d_1 \sum_{j=1}^{k} E_j \right)$$

where *Cnv* (=3.4) is the conversion from MMBTU to MWh. By dividing *Cost* by the total number of barrels of crude to be compensated for 0.1 mton carbon dioxide, one can obtain the cost per barrel for the offset by dividing the results of substituting costs into equation (5.1) by the number of barrels giving rise to the carbon dioxide. If we instead divide *Cost* by the total number of MWh in the U.S. electricity market, one can obtain the average cost $/MWh for the offset. No transfer payments are included in these calculated costs.

[27] The MIT study uses kilowatts and kilograms. Since our interest is in the cost of carbon dioxide emissions and the units used are dollars per metric ton, it is more convenient to use megawatts and metric tons in the paper. The cost data for the calculations is from the support paper for the MIT update by Du and Parsons (2009, 20-32), available at http://web.mit.edu/mitei/docs/spotlights/nuclear-fuel-cycle-du.pdf.

Table 4. Increased cost per barrel in offsetting 5 million barrels per day over a range of prices of coal and natural gas

Cost of coal $/MMBTU	Cost of gas $/MMBTU					
	4	**5**	**6**	**7**	**8**	**9**
1	3.83	5.14	6.45	7.76	9.07	10.40
2	1.65	2.96	4.27	5.58	6.89	8.20
3	-0.53	0.78	2.09	3.4	4.71	6.02
4	-2.71	-1.40	-0.09	1.22	2.53	3.84

Table 5. Increased cost per MWh in offsetting 5 million barrels per day over a range of prices of coal and natural gas

Cost of coal $/MMBTU	Cost of gas $/MMBTU					
	4	**5**	**6**	**7**	**8**	**9**
1	1.70	2.28	2.86	3.44	4.02	4.60
2	0.73	1.31	1.89	2.47	3.05	3.63
3	-0.24	0.34	0.93	1.51	2.09	2.67
4	-1.20	-0.62	-0.04	0.54	1.12	1.70

Note that none of the gas prices are as low as the current prices. These calculations were carried out using Mathematica, but they could almost as easily have been carried out in an Excel spreadsheet using the Energy Information Table and these fuel, capital, operating cost, efficiency, leakage, and GWP figures.

Marginal cost of offsetting one mton of carbon dioxide

In order to calculate a marginal cost, we need alter equation (5.1) to give the cost to shift one MWh from coal to gas at the margin. The cost of shifting one more MWh from coal to gas is given by equation (5.2) below.

(5.2) $$\frac{\Delta GasCostShift}{\Delta MWh} = R_{gas} Gas_{cost} + b_2 + d_2 - \left(R_k Coal_{cost} + d_1 \right)$$

where R_{gas} is the gas heat rate (*=Cnv/Eff=3.4/Eff)* and R_k is the heat rate (MMBTU/MWh) of the coal plant at the margin, b_2 is the capital cost of the gas plant per MWh, d_2 is the cost of operating the coal plant per MWh, d_1 is the cost operating the coal plant per MWh. We now need the reduction in carbon dioxide emitted for this MWh. This is given by taking only the last index *k* in the sum in equation (4.1), i.e., the coal plant at the margin

(5.3) $$\frac{\Delta mtonCO_2}{\Delta MWhshifted} = A \times R_k - B \times R_{gas}$$

Thus the cost per mton carbon dioxide of the shift is given by

(5.4) $$\frac{\Delta\$}{\Delta mtonCO_2} = \frac{\frac{\$}{MWhshifted}}{\frac{mtonCO_2}{MWhshifted}} = \frac{R_{gas} \times Gas_{cost} + b_2 + d_2 - \left(R_k \times Coal_{cost} + d_1\right)}{A \times R_k - B \times R_{gas}}$$

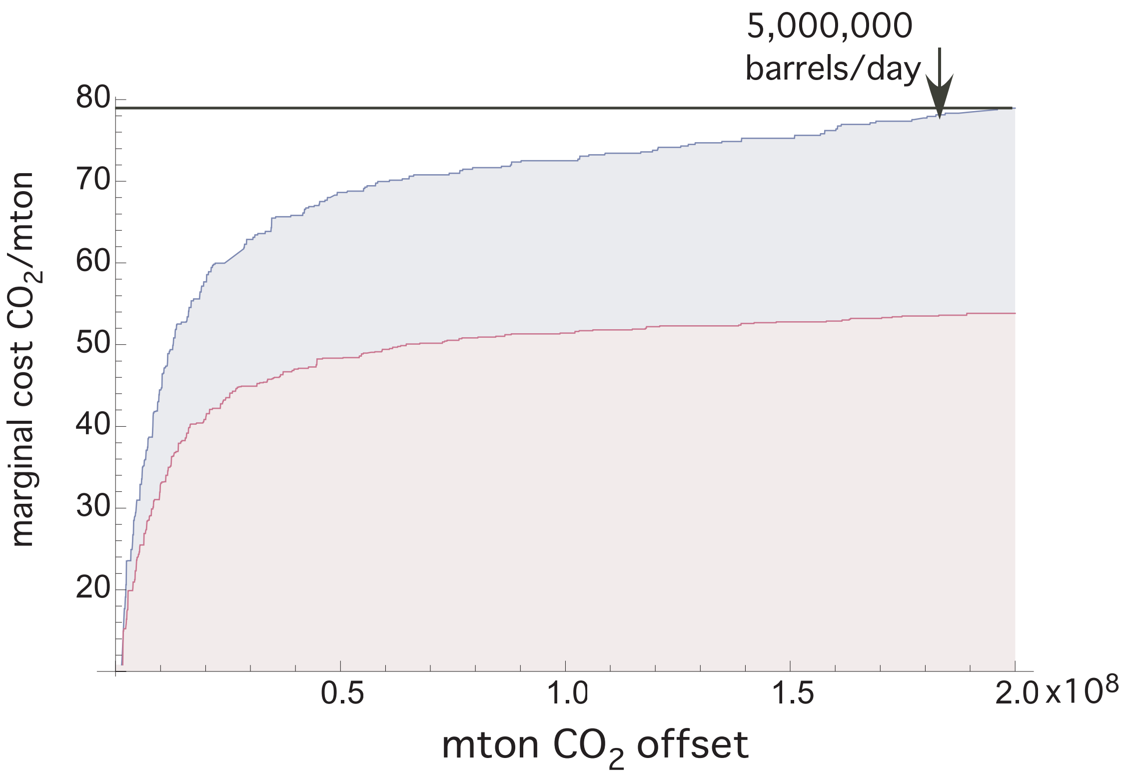
The quantity A (defined previously and =0.0946) is the mtons of carbon dioxide produced when enough coal to produce 1 MMBTU is burned, and B is given by equation 4.3, where *GWP* is the global warming potential relative to carbon dioxide including methane leakage. *Cv* is the equivalent carbon dioxide emitted per MMBTU of methane burned and *Eff* is the efficiency of the gas generator in converting heat to electricity. Substituting from Table 3, we have

(5.5) $$MarginalCost = \frac{6.8Gas_{cost} + 4 - R_k \times Coal_{cost}}{0.0946R_k - 0.55}$$

A carbon tax aimed at producing the same offset is the same as the *MarginalCost.* In our previous publication,[17] we gave this quantity the symbol π.

In Figure 6 below, *Marginal Cost* is plotted for the extreme case of $Gas_{\text{cost}} = 8$ and $Coal_{\text{cost}} = 2$.

Figure 6. Plot of *MarginalCost* for Gas_{cost}= 8 and $Coal_{cost}$ =2.



The upper curve assumes a gas leakage of 5 percent; the lower curve assumes no leakage. The integrals indicated by the shaded areas correspond to the total cost. The rectangular area defined by the axes and the maximum *MarginalCost* gives an estimate of total cost. Thus the white area below the top of the rectangle is the error incurred by approximating the upper shaded area by the rectangle.

The flattening of the marginal cost curves is caused by the fact that the distribution of the heat rates of U.S. coal electricity generators is concentrated around 9.5 to 11.5 MMBTU/MWh.

Implications for the additional costs of offsetting Canadian oil sands crude

These prices can be used to calculate the cost of the carbon dioxide from Canadian oil sands above that produced by the average barrel of oil on a well-to-tank (WTT) basis. The average barrel of oil produces 0.107 metric tons of carbon dioxide per barrel, WTT. Subtracting this from WTT carbon dioxide per barrel yields the cost of mitigating the carbon dioxide emissions of alternative sources relative to the average. The costs given in Table 6 are WTT costs in excess of

0.107 mton per barrel. The parameters used to calculate these costs are taken from the Energy Information Administration 2020 cost projections. For other cases, see Table 3.

Table 6. Offset costs for several liquid fuel sources using 2020 EIA prices of $4.91 per MMBTU for gas and $2.46 per MMBTU for coal

Cost of carbon dioxide mitigation, dollars/barrel		
Crude oil source	**Price of carbon dioxide emissions**	
	1,000,000 barrels/day	**4,000,000 barrels/day**
Canada oil sands	0.48	1.10
Venezuela bitumen	0.28	0.77
Mexico	-0.05	0.26
Canada conventional	-0.01	-0.00
Saudi Arabia	-0.01	-0.00
Domestic	-0.01	-0.00
Coal-to-liquid	9.84	impossible
Gas-to-liquid[a]	0.51	1.10

[a] This number represents the gas used in the Fischer-Tropsch production and does not include the gas converted into liquid fuel. The magnitude of emissions per crude can be found in footnote 6.

The cost of producing oil from the Canadian oil sands is on the order of $40 per barrel. Currently the market price of oil is hovering around $100 per barrel. Table 4 illustrates the prices for gas and coal projected by the Energy Information Administration.

Even for the worst case of Table 4, a gas price of $9 per MMBTU and a coal price of $1 per MMBTU, the mitigation of the *extra* carbon dioxide from the Canadian oil sands would cost less than $11 per barrel. Under any scheme allocating the production of carbon dioxide emissions in a rational manner, Canadian oil sands would be produced, because it is more efficient to allocate carbon dioxide to the production of liquid fuels from Canadian oil sands than to the generation of electricity from coal. Using this worst case, the average price electricity (see Table 5) is increased by $4.60 per MWh or 4.6 mil per kWh.

VI. Global Warming Potential of Methane

As can be seen from Figure 6, leakage in natural gas production and distribution causes a significant increase in the cost of offsetting the excess carbon dioxide emissions associated with Canadian oil sands in our proposal. At present electricity generation constitutes only about 31 percent of gas use.[28] Thus the leakage effect must be multiplied by almost three. Of course, natural gas is not the only source of methane emissions in the United States; currently it probably accounts for less than half of methane emissions. Nevertheless, our increased methane usage and the increased emissions[20] (1.9 percent) in producing gas by fracking cause us concern.

VII. Implementation

If there were some general mechanism in place for mitigating the externalities from carbon dioxide, the question of whether the Canadian oils sands should be developed would be straightforward. It would be easy to check whether it is economically efficient to offset the carbon dioxide from Canadian oil sands for the existing carbon tax or price of carbon dioxide in a cap-and-trade scheme. Economics can address the problems of externalities. However, any mechanism to do so usually involves some form of redistribution. Redistribution triggers political opposition. This is particularly true in the case of carbon dioxide. The externalities involved are global and in the future, across generations. The costs are placed on current consumers and producers of energy. This is illustrated in the history of cap-and-trade. This policy was originally a conservative idea with strong bipartisan support. It has now been politicized. As a result, most of the policies that have been implemented recently to address the problem of carbon dioxide emissions, such as the CAFE standard on automobiles or efficiency standards on electrical generators, have been administrative.

[28] U.S. Energy Information Administration, "Natural Gas Consumption by End Use," release date May 31, 2012, http://www.eia.gov/dnav/ng/ng_cons_sum_dcu_nus_m.htm.

As an economics problem, the question of the exploitation of Canadian oil sands is not very difficult. At the present time the price of oil is in the neighborhood of $90 a barrel while the cost of producing Canadian oil sands is in the neighborhood of $40-$50 a barrel. Producers of Canadian oil sands are earning sufficient rents to offset mitigation and taxing these rents does not create any economic distortion. Canada benefits from the production. Even if the carbon dioxide were mitigated, it would earn well over $35 a barrel from the sale of this oil on the world market and it can do so in a more economical manner if it is allowed to use U.S. Gulf ports. The United States benefits because production of oil in Canada increases U.S. energy security, shipping oil to U.S. Gulf ports will create jobs and the income to Canada from the sale of oil will result in Canadian demand for U.S. goods and services. This will help the U.S. balance of payments.

At this time there are four possibilities. First, the Canadian oil Sands could not be developed; second, Canada could construct pipelines to the Pacific and export the oil; third, the United States could permit Canada to export the oil from the Canadian oil sands to U.S. Gulf ports without any effort to mitigate the carbon dioxide; and fourth, the United States could permit Canada to export oil from U.S. Gulf ports and negotiate some arrangement for mitigating carbon dioxide.

Given the money involved, the first option is not likely. Canada will exploit that resource even if the United States is opposed. The second option is more costly to Canada and deprives the United States of the benefits of jobs and the increased oil security that would come from having access to the Canadian oil should there be some sort of emergency. Depending on the cost of building a pipeline to the Pacific and the necessary infrastructure to ship the oil to world markets, the second option is likely dominated by the third and fourth options. If the United States and Canada are both committed to mitigate global warming, then the fourth option is economically feasible.

Ideally, there should be some general policy to address a global externality. This is unlikely. It also seems unlikely that the United States will adopt some policy to rationalize the U.S. emissions of carbon dioxide. In the absence of such general guidelines, polices have to be studied individually. It is technically and economically feasible to produce oil from Canadian oil sands and mitigate the carbon dioxide. This can be done administratively. Whether it is politically feasible is another question.

The welfare implication of producing Canadian oil sands, if we include the externalities from combustion, is a more difficult question. We have shown that for prices of oil and gas in the range being forecast, it is feasible to tax the rents from the production of Canadian oil sands and use the proceeds to offset the extra carbon dioxide produced. If prices were constant and *we ignore the carbon dioxide from the combustion of these fuels*, then the production of Canadian oil sands is Pareto superior if this policy is implemented.

The difficulty comes if we consider the welfare implications of the combustion of Canadian oil sands. There is no good estimate for the marginal welfare cost of carbon dioxide.[29] The total well-to-wheel output of carbon dioxide is on the order of 0.5 to 0.6 metric tons per barrel. If Canadian oil sands cost $50 a barrel to produce and the price is $90 a barrel, then the rents associated with Canadian oil sands are approximately $40 a barrel (we are ignoring present value of the replacement cost of a barrel of oil in 2100), so if the marginal welfare cost of carbon dioxide is less than $66 a metric ton, it would be feasible to produce the Canadian oil sands and pay the Pigou tax implied by the marginal welfare cost of carbon dioxide. This suggests that it is Kaldor-Hick superior to produce the Canadian oil sands.[30] This argument applies to most conventional sources of oil. The rents being earned by the oil producers are equivalent to a Pigou tax.

The problem with this argument is that it is not feasible to offset the 14.2 million barrels a day of oil currently being consumed in transportation in the United States by shifting electrical generation from coal to gas. The most that could be offset in this manner is approximately 5 million barrels a day. Carbon taxes of such magnitude would increase the cost of electricity very substantially probably to prices where nuclear and other forms of carbon-free base load power

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[29] See N. Stern, *The Stern Review on Economics of Climate Change*,(Cambridge University Press, 2007), 318-348. Available at http://webarchive.nationalarchives.gov.uk/+/http://www.hm-treasury.gov.uk/independent_ reviews/stern_review_economics_climate_change/stern_review_report.cfm.

[30] See Feldman and Serrano pp. 195-216.

become competitive. Then it might be possible to eliminate coal generation without relying entirely upon gas.

VIII. Conclusions

Recent discoveries of natural gas in the United States and developments in technology for the exploitation of Canadian oil sands dramatically changed the liquid fuels market in North America and in the world. The amount of natural gas that can be economically recovered in the United States is on the order of 2,100 trillion cubic feet, or enough to supply the United States for about 90 years at current consumption rates. Canadian oil sands reserves are estimated to be about 170 billion barrels of oil. This is second only to Saudi Arabia and is enough to supply 5 million barrels a day for more than 90 years. At the present time, total U.S. production is 5.5 million barrels a day, and of that figure 1.7 million barrels a day are from Gulf of Mexico offshore production.[31] Bringing this Canadian oil to market would have a much larger impact on the supply of oil than all the drilling being advocated at the present time.

There is opposition to the exploitation of both gas and oil sands resources for environmental reasons. In the case of gas, the environmental objections to fracking are local, with the principal concern possible pollution of groundwater, and possible earthquakes (the latter is likely to be a minor issue). The reasons for opposition to further development of the Canadian oil sands are both local and global. The local issues involve construction and destruction in the Canadian wilderness and other environmental issues particular to Canada. There is also opposition the environmental impact of the Keystone pipeline. We have nothing to contribute to the discussion of these local issues. We address here only the global issue of the additional carbon dioxide associated with Canadian oil sand production.

Our calculations demonstrate that the replacement of coal electricity generation with gas would do much to reduce carbon dioxide emissions. Specifically, it is technically and economically feasible to offset the additional carbon dioxide resulting from oil sands production by

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[31] U.S. Energy Information Administration, "U.S. Petroleum and Other Liquid Fuels Facts 2010," http://205.254.135.7/special/gulf_of_mexico/data.cfm - petroleum_fuel_facts.

reallocating the generation of electricity from coal to gas. The required reduction in coal generation capacity to offset the carbon dioxide emissions from producing 5 million barrels a day of Canadian oil sands is slightly over 19 percent of the present coal electricity generation capacity of the United States. An upper bound to the additional cost of mitigating this carbon dioxide by shifting electricity generation from coal to gas is less than $11 a barrel. Since the cost of producing Canadian oil sands is between $40 to $50 a barrel, it is economical to produce this oil in the carbon dioxide-neutral manner for less than $60 a barrel.

The least expensive way to reduce U.S. carbon dioxide emissions is to shift from coal to gas in electricity generation. The present glut in the gas market is a golden opportunity to push this change by adding a limit in terms of mton carbon dioxide per MWh through adding carbon dioxide to the pollutant list for electricity generation plants, and gradually tightening it.

The Energy Information Administration projects that liquid fuel will be produced from coal in the United States around 2020. This makes real our serious concern that the development of Fischer-Tropsch fuels from coal will take place. Our calculations suggest that Fischer-Tropsch fuels from coal can be produced for around $60 a barrel in the United States. Unfortunately, the production of such fuels results in about 0.9 metric tons of carbon dioxide per barrel. We are concerned that if these early plants demonstrate that production of such fuels is very profitable, there will be a large increase in Fischer-Tropsch plants if there are no restrictions on carbon dioxide. At coal Fischer-Tropsch fuel production levels of several million barrels per day, we calculate that the scheme that we are proposing will not be able to offset the resulting carbon dioxide. Coal-to-liquids represents a major source of emissions and needs to be discouraged.

The market for petroleum is global. Canada will produce oil from the sands regardless of any U.S. policies. It is less expensive for Canada to use U.S. Gulf ports to market their oil. This oil will create jobs in the U.S. petrochemical industry and would be a secure source of oil for the United States were world oil markets to be disrupted. It is feasible to mitigate the carbon dioxide externality from the oil sands, and the Keystone project can increase U.S. energy security without increasing the net emissions of carbon dioxide. Such an arrangement has net benefits to both parties. Finally, Canada is the United States' largest trading partner. Income to

Canada from whatever source is going to result in higher exports from the United States to Canada—so no matter how the oil is marketed, exploiting the Canadian oil sands is good for the U.S. balance of payments.

In summary, we believe concern about additional carbon dioxide emissions from Canadian oil sands production is misplaced. The strategic advantage of access to this resource far outweighs the extra carbon dioxide from its production, as this carbon dioxide can be more economically offset elsewhere in the economy. Effective government policy could encourage the development of the Canadian oil sands and the mitigation of the carbon dioxide emissions. Development of these resources would be a substantial step toward energy independence.

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Appendix

A.1 The Production of Carbon Dioxide in the Fischer-Tropsch Synfuel Process

In the Fischer-Tropsch process, a fuel is converted into a mixture of carbon monoxide and hydrogen, and then these two compounds are reacted with each other to produce a liquid hydrocarbon and water.

(A1) $nCO + (2n+1)H_2 \rightarrow C_nH_{2n+2} + nH_2O$

This reaction is the actual Fischer-Tropsch reaction, and it does not produce carbon dioxide. All carbon dioxide production in the Fischer-Tropsch process takes place in the initial step that produces the mixture of carbon dioxide and hydrogen. The production of synthetic fuel from natural gas creates far less carbon dioxide than the corresponding coal process, as the basic chemical reaction to produce carbon dioxide and hydrogen is[32]

(A2) $CH_4 + H_2O \rightarrow CO + 3H_2$

However, the gas system does produce some carbon dioxide because in order to drive this reaction, the temperature has to be raised to about 700^{o} C. We calculate that this heating requires the burning of about 40 percent of the gas converted, or close to 30 percent of all the gas used. It takes about 11,000 cubic feet of gas to produce one barrel of Fischer-Tropsch fuels. The 3,000 cubic feet of gas that is burned to provide heat results in 0.17 metric tons of carbon dioxide. The Fischer-Tropsch products are not raw petroleum. More than half is diesel fuel ready for use and the rest is naptha, which can be converted into gasoline. Thus the carbon dioxide output in the production of equivalent amounts of liquid fuel from gas is somewhat, but not a whole lot, less than that of Canadian tar sands to the pump.

[32] We note that this reaction actually has an excess of H_2 of that needed for (A1).

With coal, the overall reaction to produce a similar[33] Fischer-Tropsch input stream is

(A3) $2C + 3H_2O \rightarrow CO + 3H_2 + CO_2$

In the coal system, this overall reaction must be divided into two steps

(A4) $2C + 2H_2O \rightarrow 2CO + 2H_2$

(A5) $CO + H_2O \rightarrow H_2 + CO_2$

where the first reaction requires about 900^{o} C, requiring even more fuel and thus more production of carbon dioxide. When based upon coal, the Fischer-Tropsch process produces about 0.85 metric tons of carbon dioxide per barrel of fuel. This is a far larger carbon dioxide byproduct than that of Canadian oil sands to the pump.

A.2 Coal Fischer-Tropsch

We calculate the cost of producing a barrel of synfuel by the Fischer-Tropsch process using the data in the RAND report[34] in Chapter 3 and Appendices A and B. The plant produces 32,500 barrels of diesel-equivalent barrels a day. Plant life is 30 years. This output is composed of 24,359 barrels of diesel (crude oil equivalent factor of 1.3) and 11,398 barrels of naphtha (crude oil equivalent factor of .92).[35]

The capital cost is c_0 (at 90 percent utilization rate) and is a function of the discount rate. The capital cost is based on the RAND estimate of 100,000 to 125,000 dollars a barrel of daily production capacity for January 2007 dollars, which we have adjusted to 2010 dollars.[36]

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[33] (A3) is stated in this way to match (A2); the extent of (A5) can be adjusted to produce the exact combination of CO and H_2 needed for (A1).

[34] James T. Bartis, Frank Camm, and David S. Ortiz, *Producing Liquid Fuels from Coal*, RAND Corporation, 2008.

[35] $\frac{24,359 + 0.92 \times 11,398}{1.3} = 32,500$

[36] Bartis et al., *Producing Liquid Fuels*, page 43 and http://www.bls.gov/data/inflation_calculator.htm.

The fuel cost is $c_1 = 21.59$ dollars per barrel. The 2020 price forecast from EIA 2012, Table A15, is 39.26 dollars per ton for coal to liquid plants and about .55 tons of coal is required per barrel of fuel.

Non-fuel cost is $c_2 = 2.70$ dollars per barrel.

Annual fixed operating cost per barrel fuel $c_3 = 7.00$ dollars per barrel [37]

The fuel mix to crude barrel equivalent factor $\sum_{i=1}^{N} \beta_i$ is 1.18

The carbon dioxide intensity in production is 0.829 to .922 metric tons per barrel.[38]

The breakeven price without any carbon dioxide cost is

$$p_0 = \frac{c_0 + c_1 + c_2 + c_3}{\sum_{i=1}^{N} \beta_i} = \frac{c_0 + 21.59 + 2.70 + 7.00}{1.18}$$

Cost per Barrel (crude oil equivalent) as a Function of Discount Rate for Coal Fischer-Tropsch

Discount Rate	Capital Cost $/barrel Low	Capital Cost $/barrel High	Total Cost $/barrel Low	Total Cost $/barrel High
8	28.1	35.2	50.4	56.3
9	30.9	38.6	52.7	59.2
10	33.7	42.1	55.1	62.2
11	36.5	45.7	57.5	65.2
12	39.5	49.3	60.0	68.3

[37] Bartis et al., *Producing Liquid Fuels*, page 43.
[38] Calculated from Tables B.1 (page 125) and B.2 (page 127) of Bartis et al., *Producing Liquid Fuels*, assuming output is ULSD 2008; and Appendix G, Annual Energy Outlook 2011 with Projections to 2031, http://www.anga.us/media/210391/annual energy outlook 2011.pdf.

Our estimate needs to be compared with the \$55 a barrel estimate in the reference case of the RAND study. We use similar data, but there are the differences in the calculations. First, we are calculating economic costs of capital rather than accounting costs so we are ignoring taxes and accelerated depreciation. Inasmuch as the purpose of this paper is to calculate the economic cost of the allocation of carbon, the appropriate cost of capital is the opportunity cost to the economy rather than the pre-tax cost to the firm. Second, we are ignoring the assumption that the utilization rate would only be 70 percent in the first year. This makes a difference of about 50 cents a barrel in the cost of capital.[39] Third, our fuel cost is higher. This reflects the EIA projection of a \$39.26 cost of coal for coal-to-liquids in 2020. This adds approximately \$4.25 a barrel. Finally, we are assuming rates of return that range from 8 percent to 12 percent return to equity.

The key difference in our calculations from the RAND report is in how we treat the cost of capital. The RAND calculations are more appropriate for decision-making by a firm; we believe our calculations are more appropriate for welfare calculations.

The looming issue is the large amount of carbon dioxide produced. Fischer-Tropsch fuels from coal produce 0.82 to 0.92 metric tons of carbon dioxide per barrel. Thus 5 million barrels per day correspond to approximately 2×10^9 metric tons of carbon dioxide a year, or approximately 83 to 92 percent of the carbon dioxide currently produced by coal generation of electricity.[40] By contrast, 5 million barrels per day of Canadian oil sands can be offset by 21 percent of coal generation of electricity. The danger with Fischer-Tropsch fuels from coal is that they are very economically attractive, and countries, including the United States, not concerned about carbon dioxide emissions could produce them.

[39] The correction factor on the cost of capital is $\frac{.9\left(1-e^{30r}\right)}{.7\left(1-e^{r}\right)+.9\left(1-e^{30r}\right)}$.

[40] 2010 carbon dioxide emissions from coal generators was 1.829×10^9 metric tons. Energy Information Adminstration, Annual Energy Outlook 2012, Early Release, Table A18