Energies **2013**, *6*, 5940-5959; doi:10.3390/en6115940

OPEN ACCESS

energies

ISSN 1996-1073

www.mdpi.com/journal/energies

Article

Time Series EROI for Canadian Oil and Gas

Alexandre Poisson and Charles A. S. Hall *

Program in Environmental Science, College of Environmental Science and Forestry, State University of New York, Syracuse, NY 13210, USA; E-Mail: apoisson@syr.edu

* Author to whom correspondence should be addressed; E-Mail: chall@esf.edu; Tel.: +1-315-470-6870; Fax: +1-315-470-6934.

Received: 24 August 2013; in revised form: 31 October 2013 / Accepted: 4 November 2013 / Published: 15 November 2013

Abstract: Modern economies are dependent on fossil energy, yet as conventional resources are depleted, an increasing fraction of that energy is coming from unconventional resources such as tar sands. These resources usually require more energy for extraction and upgrading, leaving a smaller fraction available to society, and at a higher cost. Here we present a calculation of the energy return on investment (EROI) for all Canadian oil and gas (including tar sands) over the period 1990–2008, and also for tar sands alone (1994–2008). We used energy production and energy use data from Statistics Canada's Material and Energy Flow Accounts (MEFA). We were able to quantify both direct and indirect energy use, the latter from Statistics Canada's energy input-output model. We found that since the mid-1990s, total energy used (invested) in the Canadian oil and gas sector increased about 63%, while the energy production (return) increased only 18%, resulting in a decrease in total EROI from roughly 16:1 to 11:1. We also found (although with less certainty) that the EROI for tar sands alone has fluctuated around 4:1 since 1994, with only a slight increasing trend. Finally, we analyzed underlying factors possibly influencing these trends.

Keywords: energy return on investment (EROI); input-output; net energy; tar sands; oil and gas

---

1. Introduction

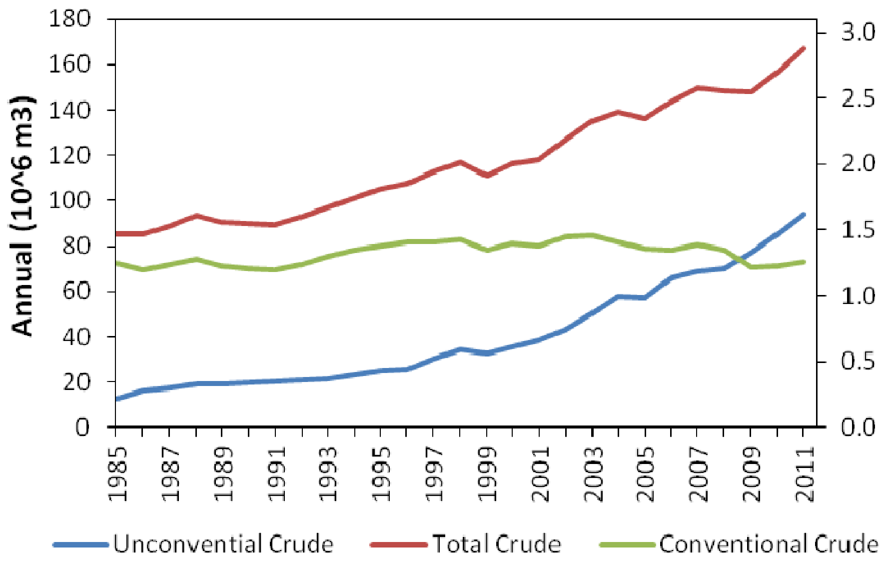
Canada is the third largest natural gas producing country in the World, and the sixth largest producer of crude oil, with a daily production of approximately 2.9 million barrels of crude per day (mbbl/d) [1].

Due to its large and newly accessible unconventional energy resources, Canada has become the country with the third largest oil reserves after Saudi Arabia and Venezuela [2].

Canadian oil production began in southern Ontario in 1856, two years before the famed Drake discovery in Pennsylvania [3]. The industry grew slowly thereafter, until 1947, with the discovery of large amounts of oil at the Leduc field, near Edmonton, Alberta. The discovery launched Canada's modern era of petroleum production and was accompanied by a major boom in oil and natural gas exploration and production in Alberta and Saskatchewan in subsequent decades [4]. Today, Western Canada remains the country's dominant hydrocarbon region, accounting for ~85% of crude oil production and 97% of natural gas production [4].

Over the last 25 years, Canada's production of conventional oil has gone from approximately steady to slightly declining (Figure 1) [5]. On the other hand, production of unconventional oil (diluted bitumen and synthetic crude from tar sands) has grown rapidly, almost tripling between 2000 and 2011, from 0.6 mbbl/d to 1.6 mbbl/d [6], and now even surpassing that of conventional oil (see Figure 1).

Figure 1. Canadian Crude Oil Production, conventional and unconventional [5].



Originally, tar sands production (which began in 1967) was restricted to surface mining and upgrading operations. Since approximately the year 2000, recovery of tar sands from deeper layers using underground (*in situ*) extraction techniques has expanded, and now represents ~50% of total tar sands production [5].

From the perspective of energy systems analysis, the shift in energy resources from conventional to unconventional oil and gas can be described as a decrease in natural resource quality [7]. It can be quantified empirically in part by using the metric of energy return on investment (EROI), the ratio of energy output (returned) over energy input (invested) in an extraction process [8,9]. EROI captures the idea that society has to divert some portion of its existing or immediately available energy resources away from production to meet final demand, and instead invest it to extract more of the same (or an equivalent) energy resource, such as a coal deposit or an oil and gas reservoir. As such it is one index of the quality of that resource. This ratio of energy output over energy input may vary over space and time, based on many geological, technical and economic factors, including: initial concentration and total size of a resource, ease of access, efficiency of further conversions (e.g., chemical refining or electricity production) and depletion of the resource. As conventional oil and gas resources are increasingly depleted around the globe, the EROI of these resources are showing declining trends [10].

How fast and consistently the EROI of oil and gas is changing in different areas of the world remains to be documented accurately. Estimates are available for the US, Norway, and China [11–15], and Gagnon [10] made a preliminary assessment for all publically traded oil companies. But such assessments are rare or incomplete for Canada [16].

Recently, Brandt *et al*. [17] published the most detailed and complete energy analysis of tar sands. It uses high quality data from the Alberta government in physical units. Their data and analysis covered both *in situ* and surface mining, was disaggregated in terms of tracking the different types of fuel used, and spanned a wide period of time (from 1970 to 2010), at high temporal resolution (per month). It included good data on the energy used directly but did not include indirect energy uses, that is energy used off site to generate materials used on site. Freise [16] calculated a preliminary time series EROI for conventional Canadian oil and gas from 1950 to 2010 using a monetary technique that we believe can be improved upon. Thus more accurate estimates of the EROI of Canadian oil and gas are needed to detect important trends in time, compare the extraction efficiency of Canadian oil and gas with that of other countries and compare the EROI of conventional with unconventional oil.

In this paper we present a calculation of the energy return on investment (EROI) for all Canadian oil and gas combined (including conventional oil, natural gas, natural gas liquids and tar sands) from 1990 to 2008, and similarly for that of tar sands alone, from 1994 to 2008. We compare these two results, detect any significant trends, and discuss possible underlying factors which may explain the temporal trends. Due to the high quality of the energy data derived from Statistics Canada's database (in energy units), our study allowed for independently testing the validity of some common methodological assumptions employed in estimating energy expenditures at the national level over time. We discuss this in more detail below, and make some suggestions for future research.

2. Methods

The equation for EROI is:

$$EROI = \frac{Energy\ Return\ (Outputs)}{Energy\ Invested\ (Inputs)} \tag{1}$$

Energy return (outputs, or production) data for hydrocarbons is easily available through various organizations and at different scales. However, it is usually much harder to get data on energy inputs, both direct and indirect, especially in energy units covering long periods of time [18]. In this context, direct energy is defined as the energy commodities (e.g., diesel, gas, electricity) used on sites owned by the industry for its own production [19]. In the case of oil and gas extraction, direct energy use includes the sum of energy commodities used at the site of extraction, up to the point of shipment from the producing property, during all activities in the exploration and preparation of natural gas, crude oil, natural gas liquids, and synthetic crude oil and bitumen (both surface mining and *in situ* extraction of tar sands). Indirect energy is defined as the energy used elsewhere in the economy for the production of the goods and services that are used by the industry in the production of that resource [7,20,21].

Since the introduction of net energy (and EROI) analysis in the late 1970s, there has been considerable debate as to the most appropriate method to use for estimating indirect energy costs, particularly the energy embedded in materials and services [7,9,19,22–26]. The same kinds of methodological problems arise, for example, in the life cycle analysis literature for estimating greenhouse gas emissions embodied in goods and services [27–30].

Traditionally, two methods have existed to estimate the indirect energy embodied in goods and services: process-analysis and input-output analysis [7,22]. Process analysis is a micro-level technique which involves tracking, at a very detailed level, all individual materials and energy flows needed to manufacture a unit of product of interest, through many stages of a complex production and supply chain. It carries the advantage of being quite precise and specific. But due to the complexity and interconnectedness of the industrial system, the analysis must eventually be truncated [29] resulting in a systematic underestimation of the energy costs by an unknown factor. The second method, energy input-output analysis, is a more comprehensive and macro-level approach. An input-output model is a complex matrix of all financial transactions in a society, aggregated in sector categories, and organized by government agencies into national input-output accounts [7,24,28]. It can be used to identify how much activity (e.g., energy commodity inputs) from all other sectors of the economy (coal, iron, paper, business services) were necessary to generate a commodity of interest (e.g., steel output).

Although it lacks precision because of data aggregation, it benefits from being very comprehensive as the boundary of analysis is essentially infinite, encompassing all upstream stages of production and supply [28,30]. Early on, Bullard *et al*. [23] developed a procedure to combine the advantages of both process-analysis and input-output analysis, which they termed the hybrid approach. Increasingly, a hybrid approach is being recommended to provide sufficient precision and accuracy for robust results in both net energy analyses and greenhouse gas emissions inventories [30].

Along these lines, Murphy *et al*. [18] provide guidelines for evaluating EROI (including time-series EROI), combining direct energy use data in energy units and information derived from industry expenditure or sales data and national energy input-output tables. We essentially follow their description of “standard” $EROI_{stnd}$ at the “mine-mouth”.

2.1. Energy Return: Production of Canadian Oil and Gas

We used data on production of Canadian hydrocarbons from Statistic Canada’s Socioeconomic Information Management (CANSIM) database for oil, natural gas and natural gas liquids [5,31,32]. The CANSIM production data covers the period from 1985 to 2010 (although we use only data from 1990 to 2008, to match energy use data), and provides detailed production data by province and by fuel type (in units of volume per year) (see Table 1).

We converted these annual production volumes into energy units using energy content factors (heat values) from the Alberta Government (see Table 2) [33]. These numbers differ only slightly from those from other sources, such as from Canada’s National Energy Board [34]. We chose the ones provided by the Alberta government because they were more complete, including values for synthetic crude and bitumen.

Table 1. Annual production of Canadian petroleum [31,32,35].

Year	Heavy crude	L&M crude	Syn crude	Bitum.	Cond.	Pent plus	Eth.	Prop.	But.	Nat. Gas
	10^6 m^3									10^9 m^3
1990	18.2	51.9	12.1	7.9	0.2	6.6	7.1	6.7	3.4	123.2
1991	19.4	50.0	13.2	7.1	0.2	6.9	7.5	6.9	3.8	129.6
1992	22.1	49.8	13.8	7.4	0.2	7.6	7.3	7.9	4.0	143.2
1993	22.7	52.6	14.1	7.7	0.3	8.5	8.3	8.3	4.4	155.0
1994	24.1	54.3	15.2	7.8	0.3	8.7	9.1	8.1	4.8	166.5
1995	27.0	53.0	16.3	8.6	0.3	9.0	10.0	9.4	5.3	176.4
1996	30.2	51.4	16.3	9.5	0.4	9.9	10.8	10.0	5.5	182.2
1997	32.7	49.3	16.8	13.8	0.4	10.7	10.9	9.9	5.3	184.4
1998	31.6	51.3	17.9	16.4	0.4	10.9	10.6	10.4	5.2	189.5
1999	30.6	47.5	18.8	14.2	0.5	10.8	11.9	10.3	5.5	195.8
2000	32.6	48.4	18.6	16.8	0.9	10.5	12.2	10.4	5.7	201.7
2001	33.2	46.7	20.3	18.0	1.1	9.7	11.8	10.8	6.6	204.6
2002	32.1	51.8	25.5	17.5	1.2	8.9	12.9	8.8	5.1	205.8
2003	31.8	52.9	25.0	25.0	1.2	8.9	13.7	9.1	5.5	200.9
2004	31.8	50.0	26.7	30.9	1.1	8.7	14.7	9.0	5.4	201.5
2005	30.5	48.4	21.9	35.3	1.5	8.5	14.6	9.1	5.5	203.5
2006	30.0	48.1	28.8	36.9	1.6	8.7	14.8	9.8	6.2	202.8
2007	29.0	51.5	39.9	29.2	1.7	8.3	14.5	10.2	6.4	196.7
2008	27.1	51.4	38.0	31.9	1.8	7.8	12.9	9.8	6.2	187.6

Notes: L&M = light and medium; Bitum. = bitumen; Condens. = condensate; Pent.plus = pentanes plus; Prop. = propane; But. = butane; Nat.Gas = Natural Gas.

Table 2. Energy conversion factors [33].

Energy resource	Gigajoules (per m^3)
Ethane	18.5
Propane	25.4
Butane	28.2
Pentanes plus	33.1
Crude Oil (light and medium)	38.5
Crude Oil (heavy)	41.4
Synthetic crude (from bitumen)	39.4
Bitumen	42.8
Natural gas	37.4 (per 1000 m^3)

By multiplying volumes produced annually by the heat content of each fuel we generated a times series of total energy produced in Canada from all fluid hydrocarbons covering the period 1990 to 2008 (see Table 3).

The data in the last column of Table 3 served as the energy return (ER) value in our EROI calculation of total Canadian oil and gas extraction.

Table 3. Canadian Oil and Gas Production (Return), in energy units (derived from Tables 1 and 2).

Year	Heavy crude	L&M crude	Syn crude	Bitum.	Cond.	Pent plus	Eth.	Prop.	But.	Nat. Gas	Total
						PJ (10^{15} J)					
1990	753	1,997	476	336	6	218	131	170	97	4,609	8,792
1991	802	1,924	520	304	7	228	139	175	106	4,847	9,053
1992	917	1,916	543	315	8	253	135	200	112	5,356	9,754
1993	938	2,024	556	329	10	280	153	210	124	5,798	10,423
1994	996	2,091	599	334	12	289	168	207	134	6,228	11,058
1995	1,120	2,042	643	369	12	297	185	239	149	6,596	11,653
1996	1,250	1,977	643	407	14	327	199	255	155	6,815	12,041
1997	1,355	1,899	662	591	16	355	202	253	150	6,897	12,380
1998	1,307	1,974	704	700	16	360	196	264	147	7,087	12,756
1999	1,268	1,828	739	607	18	356	220	262	156	7,322	12,776
2000	1,349	1,863	733	718	33	347	227	265	162	7,542	13,239
2001	1,375	1,799	798	768	41	320	218	275	186	7,651	13,431
2002	1,330	1,993	1,004	748	43	294	238	224	144	7,698	13,718
2003	1,315	2,038	986	1,071	42	294	254	232	154	7,514	13,901
2004	1,316	1,924	1,050	1,321	41	289	271	229	152	7,537	14,131
2005	1,263	1,864	864	1,512	54	283	270	231	154	7,609	14,104
2006	1,241	1,852	1,133	1,581	56	290	275	248	176	7,586	14,438
2007	1,202	1,985	1,570	1,248	61	274	268	259	180	7,357	14,404
2008	1,121	1,980	1,498	1,365	64	259	239	249	175	7,015	13,966

Notes: L&M = light and medium; Bitum. = bitumen; Condens. = condensate; Pent. plus = pentanes plus; Prop. = propane; But. = butane; Nat. Gas = Natural Gas.

2.2. Energy Use (Invested) in Oil and Gas Production

Statistics Canada's CANSIM database contains a record of direct energy use for each industry sector (in energy units) covering the period 1990–2008. The direct energy use data is collected from an annual energy survey managed by Natural Resources Canada which goes out to all industries across the country [36]. The energy use data is compiled as part of Canada's Materials and Energy Flow Accounts, being classified by industrial sector according to the North American Industry Classification System (e.g., NAICS code 21111 for the "oil and gas extraction industry" [35]). This energy data is then linked to the input-output accounts of the Canadian System of National Accounts, for further analysis.

The original energy survey data includes 10 different energy commodities consumed by the industrial sector: coal, natural gas, liquid petroleum gases, electricity, coke, motor gasoline, diesel fuel, aviation fuel, light fuel oil and heavy fuel oil [36]. However, Statistics Canada releases the energy use data in aggregated form (and in thermal units), having compiled the original data from the industrial survey, converted volumes of different types of energy commodities into total amounts of energy used, and summed the quantities for each industrial sector. No quality corrections are done (e.g., electricity in kWh *vs*. accounting for the natural gas used to produce that electricity) [19,37]. This will lead to a (probably small, but unquantified) underestimation of the total (primary) energy invested, and hence an overestimation of the resulting EROI. Table 4 lists the "direct energy" used in the Canadian oil and gas extraction from 1990 to 2008 (see the right column).

Table 4. Direct and indirect energy use in the oil and gas extraction sector [19,20,38].

Year	Total production value	Energy intensity (Direct + Indirect)	Energy used	
			Direct + Indirect	Direct Only
	Bill $CAN	MJ/$CAN	PJ	
1990	20,815	32.5	676	616
1991	17,860	37.1	663	605
1992	19,167	36.9	708	643
1993	21,116	33.7	712	648
1994	23,973	31.9	765	689
1995	24,136	33.4	807	710
1996	30,134	26.2	788	697
1997	30,707	25.6	787	681
1998	25,377	34.3	871	759
1999	35,227	29.9	1,055	921
2000	63,072	18.3	1,152	1,001
2001	62,790	17.9	1,125	960
2002	56,694	21.3	1,207	1,059
2003	74,810	17.5	1,311	1,138
2004	84,301	14.6	1,228	1,074
2005	106,242	11.9	1,264	1,113
2006	103,433	11.1	1,150	1,052
2007	106,868	11.3	1,212	1,104
2008	142,865	8.8	1,254	1,096

Statistics Canada databases also provide a path to estimate the indirect energy use per sector. For the period 1990–2008, they give values of energy intensity (direct and indirect combined) for each industry sector. In this context, energy intensity is defined as the energy used (direct and indirect) per current dollar value of production, in units of MJ/$CAN sold [20]. We multiplied the direct and indirect energy intensity values per monetary value of production for that year ("oil and gas extraction") [20] by the monetary value of petroleum production (provided by CAPP [38]) to create a time series of direct and indirect energy used in the extraction of fluid hydrocarbons in Canada [see Equation (2) and Table 4].

$$Energy\ use\ (D + I) = Energy\ intensity\ (D + I) \times value\ of\ production \quad (2)$$

While the direct energy use comes from the above-mentioned annual survey of all industries across Canada, the indirect portion is derived by Statistics Canada through a different method. To estimate indirect energy use per sector, Statistics Canada uses a detailed input-output model of the Canadian economy (from its System of National Accounts) connected to the direct energy use tables of Canada's system of Material and Energy Flow Accounts [19,20,39–41]. Although the method is different the indirect energy use data also originates from the same underlying energy use data collected in an annual survey. The last two columns of Table 4 served as the energy invested in our EROI calculations.

2.3. EROI of Canadian Oil and Gas

We calculated the EROI time series for Canadian oil and gas in two ways, first by dividing the annual energy production (energy return) by the annual direct (only) energy used (energy invested) and second by both direct and indirect energy used (see Section 2.2). The difference in the two EROI time series shows the sensitivity of the results to a change in the boundary of analysis; from accounting only for the direct consumption of energy commodities (e.g., diesel, gas, *etc*.), to also including the indirect energy embodied in the equipment and services used in the oil and gas extraction sector.

2.4. EROI for Tar Sands

Because of data limitations and study scope, we restricted our EROI calculation of tar sands to surface mining and upgrading operations, and to direct energy use only (thus excluding *in situ* extraction and indirect energy use). The end product of surface mining is synthethic crude oil. Bitumen from the mines is upgraded to produce a substance chemically similar to conventional crude oil (named synthetic crude, or syncrude). Our EROI analysis includes the energy required to extract the mixture of bitumen and sand from the ground, separate it, and upgrade it to syncrude oil.

Production data for tar sands (syncrude oil) was available from multiple sources, including the CANSIM database [35], as discussed above (see Tables 1 and 3), and from Natural Resources Canada [42]. On the other hand, energy use data for unconventional oil and gas was much more difficult to access, as it is currently aggregated into the entire oil and gas extraction sector of Statistics Canada industry classification system (NAICS code 21111, [35]), along with conventional oil and gas. Nonetheless, we were able to create a time series EROI of oil sands from surface mining covering the period 1994 to 2008 by combining two other datasets, as follows.

The Canadian Industrial Energy End-Use Data and Analysis Centre (CIEEDAC), based at Simon Fraser University in British Columbia, has energy use data for tar sands extraction for a limited time period: from 1994 to 2001. This is because a North American Industry Classification System category (NAICS: 211114, [35]) was reported to exist for unconventional oil alone (surface mining of tar sands) during that period; however this data collection program was discontinued in 2001 [43]. The second source is from the Natural Resources Canada's Industry Program for Energy Conservation (CIPEC), which publishes an annual report summarizing energy efficiency trends in all the main industrial sectors of the Canadian economy. Their reports include a section on energy efficiency in tar sands from surface mining. We used their 2012 report to complete the time series of energy use from 2002 to 2008 [42]. Data processing (from volumes to energy units) for CIPEC's analysis was effected by Natural Resource Canada's Office of Energy Efficiency. These data ultimately originate from Alberta's Energy Resources Conservation Board and are available only at a steep cost (but see the recently published study by Brandt *et al*. for a detailed analysis using this dataset [17]). From our point of view, the data from CIPEC are not as transparent as we would like, but at least are provided by an official government source (*i.e*., Natural Resources Canada).

For our EROI calculation, we paired the output energy data from Statistics Canada's CANSIM dataset (1994–2008) [5] to the energy input data from CIEEDAC (1994–2001) [43] and from Natural Resource Canada's CIPEC report (2002–2008) [42], as shown in Table 5. We also include the energy production data (million barrels of syncrude) provided in the CIPEC report for the year 2000–2008 (Table 5) [42] to illustrate uncertainties associated with combining these datasets. Unfortunately, these energy production values differ by as much as 60%, which is unusual for energy production data. This results in a high and low estimate for the EROI of tar sands from surface mining for the years 2002 until 2008. We use the average of these two EROI calculations for our final estimate, but also present the high and low estimates in the results section below.

Table 5. Energy use and production for tar sands from surface mining [5,42,43].

Year	Energy output							Energy input	
	Source #1	Thous. m^3	PJ	Source #2	Mil. Blrs	Thous. m^3	PJ	Sources	PJ
1994		15,191	599	-	-	-	-		176
1995		16,318	643	-	-	-	-		190
1996		16,318	643	-	-	-	-		184
1997		16,798	662	-	-	-	-	CIEEDAC [43]	174
1998		17,871	704	-	-	-	-		179
1999		18,767	739	-	-	-	-		182
2000		18,608	733	-	-	-	-		191
2001	Statistics Canada [5]	20,261	798	-	-	-	-		207
2002		25,495	1,004		195	30,987	1,221		290
2003		25,029	986		220	34,960	1,377		285
2004		26,662	1,050		255	40,522	1,597		320
2005		21,933	864	Natural Resource Canada (CIPEC) [42]	230	36,549	1,440	Natural Resource Canada (CIPEC) [42]	300
2006		28,764	1,133		290	46,084	1,816		380
2007		39,859	1,570		295	46,878	1,847		395
2008		38,024	1,498		280	44,495	1,753		360

2.5. Examination of Possible Underlying Factors

To compare our results with some probable underlying factors affecting the oil and gas industry, we also retrieved additional data from the Canadian Association of Petroleum Producer and the US Energy Information Administration [44]. Conceptually, our dependent variables would be energy expenditures (PJ), energy production (PJ) and EROI, and our independent variables were: drilling activity, oil prices, percentage of oil from tar sands, and monetary expenditure.

In terms of statistical analysis however, time series data have particular properties (including temporal autocorrelation, multi-colinearity, time-lag effects, stochasticity) that complicate the accurate testing of functional relations between predictor and outcome variables (through multiple linear regression, for example) [45]. There exists an abundant statistical literature on time series analysis from the econometrics field (dating back to Box and Jenkins' ARIMA models in the 1970s [46]), but our objectives for this aspect of our paper were more modest than of developing full time-series statistical models.

Thus, using SAS (the Statistical Analysis Software), we ran Pearson correlations between EROI, energy production (PJ) and energy use (PJ) on the one side, and percent of total energy production from unconventional oil (%), annual drilling activity (million meters drilled) [47], annual monetary expenditure (million Canadian dollars, corrected for inflation) [48], and average international price of oil (in 2010 Canadian dollars, for a barrel of crude oil) [49] on the other. The objective was simply to give a sense of the direction and relative magnitude of the correlations among variables.

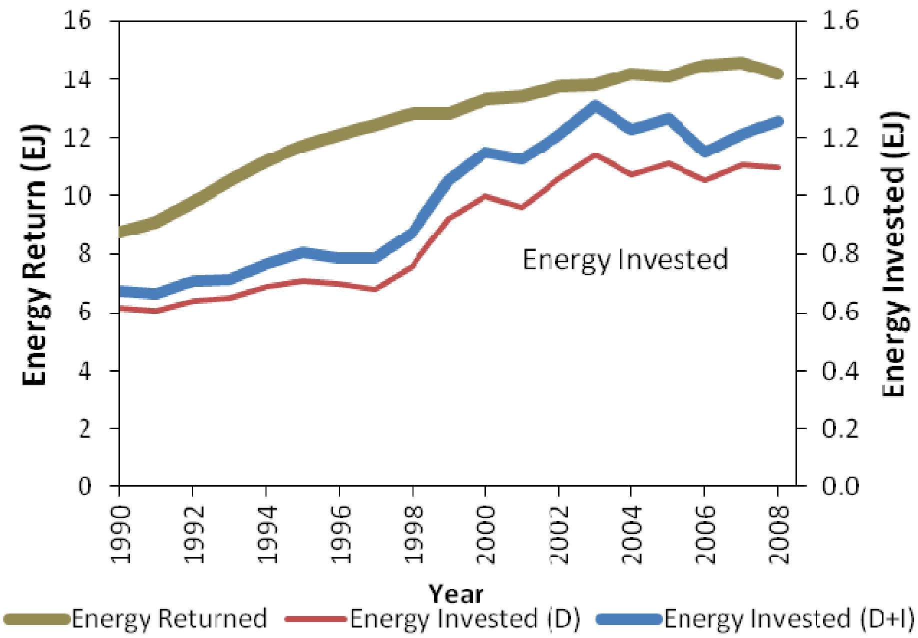
3. Results

The EROI for Canadian oil and gas combined using both direct and indirect energy, was about 16:1 in 1997 and has declined to about 11:1 in 2008, whereas when calculated using only direct energy, it was 18:1 in 1998, and decreased to about 13:1 in 2008. The EROI for tar sands alone (from surface mining only, and considering only direct energy inputs) averaged about 4:1 throughout the period analyzed, with only a slight increasing trend.

3.1. EROI of Total Canadian Petroleum

We first derived a time series of energy production (return) and energy use (investment) for the oil and gas extraction sector as a whole from 1990 to 2008 (including conventional oil, natural gas, natural gas liquids, syncrude oil from surface mining and bitumen from *in situ* tar sands extraction; see Figure 2).

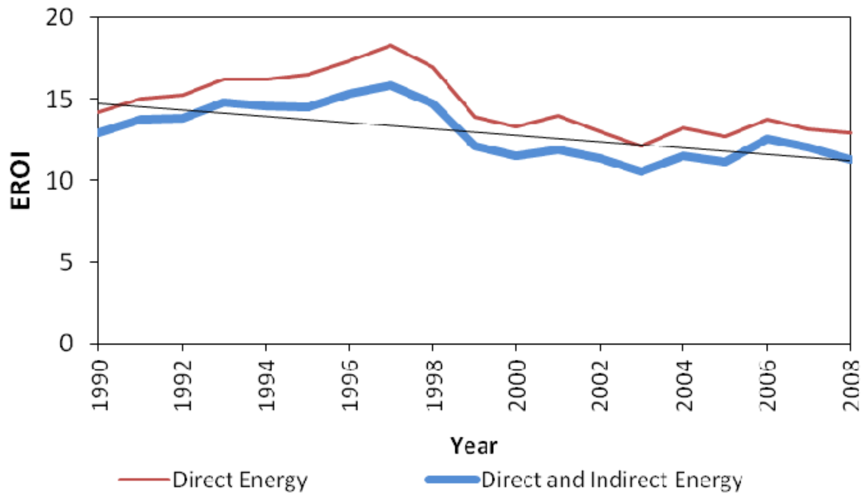
Figure 2. Energy return and energy investment: total oil and gas.



Over this period (until 2008), total annual energy production (in PJ) increased by 66 percent since 1990, and 14 percent since 1997. Meanwhile, energy use (direct and indirect) increased by 86 percent 1990–2008, and 59 percent 1997–2008. Including indirect energy in the calculation adds on average 13 percent to the total energy use; as much as 17% in 2001, and as little as 9% in 2006.

Our EROI time series (including direct and indirect energy) for total Canadian oil and gas shows a peak of about 16:1 in 1997, and a value of about 11:1 in 2008, and overall a declining trend over the entire study period (slope of −0.17, $p = 0.003$, $R^2 = 0.42$) (see Figure 3).

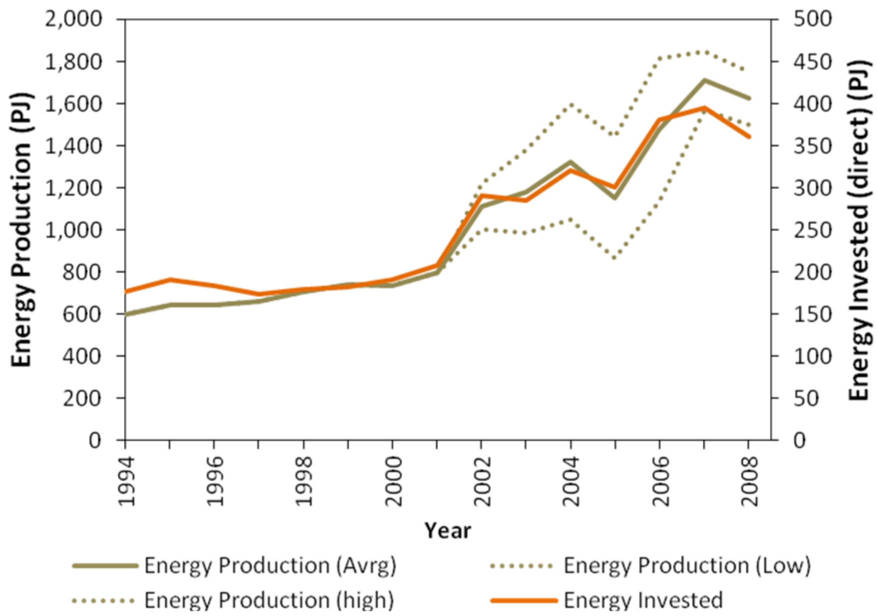
Figure 3. EROI for all Canadian Oil and Gas. The trend line is for Direct plus Indirect energy.



3.2. EROI for Tar Sands

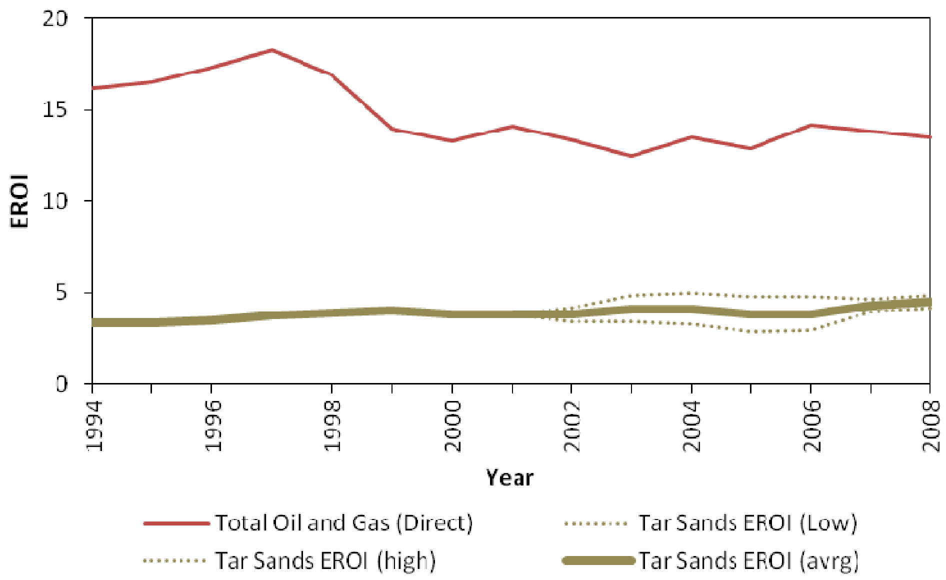
Our analysis for tar sands includes only the direct energy used in the extraction and upgrading operations from surface mining, from 1994 to 2008. We report a high, low and average estimate of production from 2002 onwards (Figure 4). Both the energy production and energy use of this sector have increased since 1994, though approximately in the same proportion (Figure 4).

Figure 4. Energy Return and Energy Invested in Tar Sands (Surface Mining). The dashed lines represent high and low estimates for production, a discrepancy due to the combination of two datasets.



Our calculation shows that the EROI of tar sands from surface mining has fluctuated around an average of 4:1 since 1994, with only a small trend upwards (slope of 0.05, $R^2 = 0.67$). In comparison, this average value of 4:1 is about 1/4 the EROI for total Canadian oil and gas (Figure 5).

Figure 5. EROI of Canadian tar sands (surface mining, direct energy), from 1994 to 2008. Also shown for comparison, the EROI of total Canadian oil and gas (1994–2008), direct energy.



3.3. Exploration of Underlying Factors

We present in Figure 5 and Table 6 the direction and strength of some correlations among predictor and predicted variables, to inform the reader about possible explanations behind the observed changes during our study period in EROI and energy use in the Canadian oil and gas extraction sector. Due to the nature of the data (time series data with autocorrelation and multi-collinearity) the independent (predictor) variables were too strongly correlated among themselves (multi-collinearity) to result in reliable model coefficient estimates in standard multiple regressions. Furthermore, some relations were more likely non-linear, requiring a statistical modeling effort beyond the needs of this preliminary paper, although possibly worth exploring in future work.

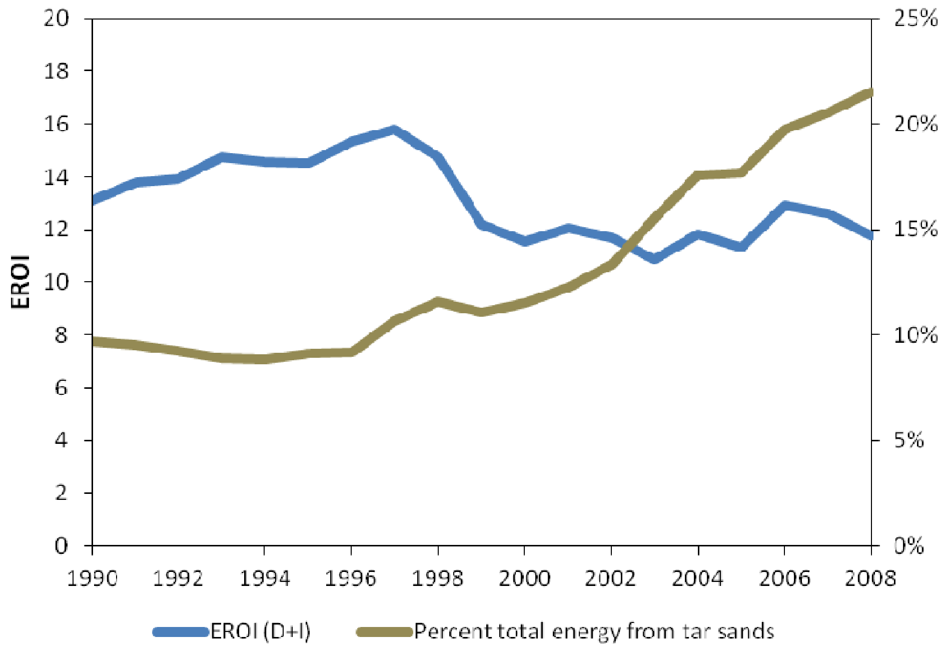
Table 6. Pearson Correlation coefficients of dependent and independent variables. EXPEND is monetary expenditure; DRILL is drilling meters; PRICE is the international price of crude oil; PERC is the percent of total energy produced from unconventional oil; PROD is the total energy produced (return) and USE the direct and indirect energy used (invested) in oil and gas extraction.

	EXPEND	DRILL	PRICE	PERC
EROI	−0.63	−0.55	−0.64	−0.69
PROD	0.82	0.9	0.61	0.77
USE	0.82	0.85	0.7	0.82

Nonetheless, we found that all four predictor variables (monetary expenditure; drilling meters; international price of crude oil and the percent of total energy from unconventional oil) were correlated in the expected direction with the three dependent variables: negatively with EROI, and positively with both the energy produced and the energy used (Table 6) In other words, the EROI is negatively correlated with money spent, drilling intensity, oil price and percentage of unconventional oil.

The EROI of total Canadian oil and gas was most strongly correlated (negatively) with the percent of total energy production coming from unconventional oil (−0.69), which we also show graphically in Figure 6.

Figure 6. EROI of total Canadian Oil and Gas, and Percent total oil and gas energy coming from Tar Sands.



4. Discussion

In the last decade, we find a decrease in the EROI for total Canadian oil and gas extraction, including tar sands. Our results are consistent in terms of the broad theoretical framework whereby a gradual shift from conventional to unconventional oil and gas extraction is accompanied by a decline in the energy return on energy investment. They are also consistent with the general trends previously reported for Canada [13–16] and in other countries over the same period, although they differ in terms of absolute magnitude and rates of change. That is, our analysis suggests that the observed rate of decline in EROI in Canada in the last two decades is smaller than what was previously estimated. The latter is likely due to the higher quality and completeness of the data we employed (dampening unusually large fluctuations which were previously reported). In fact, due to the high quality of the direct and indirect energy use data derived from Statistics Canada's database (in energy units), our study allowed for independently testing the validity/accuracy of certain common methodological assumptions employed in estimating energy expenditures at the national level over time, which we discuss in more detail below.

4.1. Comparison to Previous Estimates for Canada: Implications for Researchers

Freise [16] had estimated a time series EROI for conventional oil and gas in Western Canada (1947 to 2009), as part of his study focusing on Canadian natural gas. His analysis showed large fluctuations in EROI over a 60 year timespan, and generally a large decline in EROI since a peak of about 80:1 in the early 1970s.

However, Freise's EROI estimates were derived by estimating energy use (investment) in the oil and gas extraction sector from financial data alone and using a constant energy intensity factor (24 MJ/$US, 2005) for the entire 60 year period of his study (see below for further discussion). We believe that the direct and indirect energy use data from Statistics Canada (in energy units) have allowed us to get a more accurate estimate of energy use and hence EROI. This allows us to test the accuracy of Freise's EROI estimates for the period where our studies (and reported data) directly overlap (1993–2008).

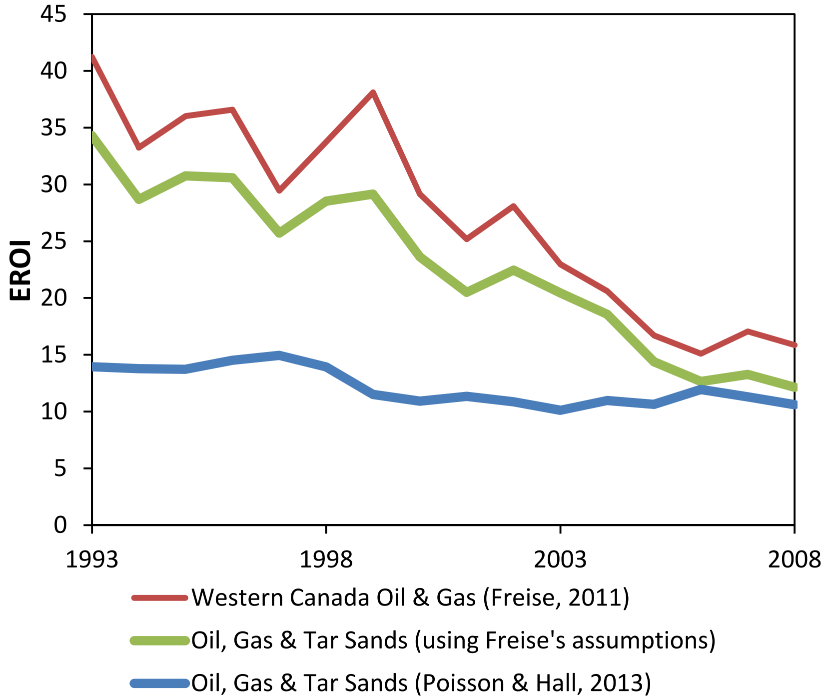
There are five approaches used by Freise that we believe can be improved upon (1) he used financial data alone to estimate both direct and indirect energy use; he also (2) multiplied the annual monetary expenditure for the industry (with some correction for inflation) by a single money-to-energy conversion factor for the entire 60-year study period. This assumes that the energy use intensity (*i.e.*, MJ per dollar of expenditure, or dollar of production) of the Canadian oil and gas industry stayed constant over more than half a century, regardless of any technology change. Furthermore, his study also (3) used a money-to-energy conversion factor (24MJ/$US 2005) from a different country than the one under study (from the US instead of Canada); (4) used a single correction factor for currency fluctuations between the US and Canada for the entire 60-year study period; and (5) used a general consumer price index for inflation correction of the monetary expenditure, instead of a sector-specific producer price index (prices of commodities in specific industry sectors vary more from year to year than the average national inflation rate, especially in the oil and gas industry).

We examined the effect of these assumptions by first recalculating the EROI of total Canadian oil and gas (including tar sands) using Freise's method (since his original study excluded tar sands and was limited to Western Canada) (see Figure 7). There is a large discrepancy between the two studies. For the year 2005 (where the two estimates should be equal), Freise's method using financial data alone and a fixed energy intensity factor (green) results in an EROI which is 35% higher than ours (blue). This overestimation of the EROI rises to ~250% for the year 1999 (~29:1 *vs*. ~12:1 in 1999). Our study, using direct energy data from Statistics Canada, finds only a small decline in the EROI over 15 years, where Freise found a steep decline, giving the false impression of a dramatic change in the industry's productivity in a short period of time (see below for further discussion).

4.2. Comparison with Other Studies: Tar Sands and Other Countries

Our EROI estimates for tar sands fall within the range of previously published studies. Brandt *et al*. provide the most detailed analysis of tar sands yet. They find EROI values for tar sands (from both surface mining and *in situ* extraction, with direct energy only) fluctuating between 2.5:1 and 4:1 during the period from 1990 to 2003, very similar to our results. After 2003, the EROI of tar sands from surface mining increases to around 6:1, showing a gain in extraction efficiency. Our results for surface mining show less fluctuation than Brandt's. We also detect a similar (but very small) upward trend in EROI during this same period. The data used by Brandt is much more detailed (disaggregated) than ours, and we believe their more precise EROI values are more accurate and rich for interpretation. For example Brandt *et al*. are able to distinguish energy investment coming from the resource itself (coke and process gas) from external purchased energy (natural gas), and with this calculate a general EROI (low, around 6:1) and an external EROI (larger, around 15:1) [17]. Thus while we find low EROI values for tar sands, Brandt *et al*. show that for surface mining, much of the energy invested is from the resource being exploited, not after being processed through society. And therefore, in this regard, the extraction may be expensive, but possible. The fact that we both have similar results gives confidence to our analysis, and the general conclusions we derive from it.

Figure 7. Comparison of our results for EROI for Canadian Oil and Gas with the results of a previous study [16].



For oil and gas extraction, Grandell *et al*. [14] found a temporal pattern quite similar to ours, in the case of Norway: an increase in EROI from 1991 to 1996, and then a decline until 2008. On the other hand the absolute values, ranged between 40:1 and 60:1, are much higher than our range of between 16:1 and 10:1. Gagnon *et al*. [10] estimated an EROI time series for global oil and gas between 1992 and 2006, and also found an increase in EROI until 1999, flowed by a decline (with a range in values between 18:1 and 35:1). Guilford *et al*. [13] examined the EROI of US oil and gas over a longer period: at five year intervals since 1972, and with more sparse estimates going back to 1919. Again, they found an increase in the EROI for oil and gas from 7:1 in 1982 to 16:1 in 1992, followed by a decline to approximately 11:1 in 2007. However, the problem in comparing and interpreting these studies directly is that the quality of the data and assumptions employed (to fill data gaps) differ, with large but generally unknown uncertainties in the EROI estimates.

4.3. Interpretation and Implications

The authors of the above studies for Norway, the US, Canada and at a global scale, tend to conclude that recent declines in EROI observed globally are likely due to the depletion of the highest quality conventional oil reserves internationally, and in some cases to an increase in drilling effort not associated with an increase in output [10–16]. As easily accessible oil and gas becomes more scarce, and the international price of oil rises, investments flow to resources which are more costly to exploit, both energetically and financially. Our preliminary analysis of underlying factors in Canada seems to support this interpretation, although more in depth time-series statistical modeling is required to test the accuracy of these ideas further.

The general concern in this field is that if the EROI of our major fuels continue to decline, and if the replacement "green" energy sources (with their backups) have as low an EROI as appears to be the case at this time, there is likely to continue to be a decline in the economic surplus and economic growth that previous generations had taken for granted and that seems to be increasingly characteristic of OECD countries. Will declining EROI further stress governments increasingly unable to meet legal financial commitments such as schools and pensions? On the other hand perhaps society can increase its end use efficiency as rapidly as the EROI declines or find some other energy source, such as fourth generation nuclear or thin-film solar, which may eventually have a high EROI. It will be interesting to watch how this unfolds. For a longer discussion of the implications of declining EROI see Hall and Klitgaard [49].

5. Conclusions

We set out to quantify recent trends in Canadian oil and gas extraction productivity as measured by EROI as accurately as possible. Some of the strengths of our study include: comprehensiveness (encompassing all oil and gas extraction across Canada), good temporal breadth and resolution (just under two decades covered with annual data), energy data quality (most of it available in energy units, as opposed to monetary) and data source reliability (from a reliable government agency), and ability to track indirect energy use. Our analysis showed that the energy return on investment (EROI) of Canadian oil-gas-tar combined has been declining slightly since the mid-1990s, from roughly 16:1 to 11:1. We also found an EROI for tar sands of around 4:1, from 1994 to 2008, although only including direct energy use and from surface mining. The decline in the overall EROI (and productivity) of Canadian oil, gas and tar sands combined reflects a growing dependence on a lower quality energy source which is more expensive to produce and requires higher energy and material inputs. We find however that the slope of this decline is much less pronounced than was previously reported. We recommend further work in reviewing and improving the accuracy of time-series EROI estimates for different countries. Higher accuracy in EROI estimates will be useful to build better time-series models of factors influencing EROI trends, as well as models of the implications of changes in EROI on different sectors of the economy.

Acknowledgments

Funding for this analysis was provided by United Kingdom's Department for International Development (DFID) and by a grant from Fairbank Oil. We would also like to thank the members of the Energy Systems Lab at SUNY-ESF for constant advice and feedback, as well as comments from Profs Peter Victor, Ruth Yanai and three anonymous reviewers.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. U.S. Energy Information Administration. Country Analysis Brief Overview: Canada. Available online: http://www.eia.gov/countries/country-data.cfm?fips=ca (accessed on 1 May 2013).
2. U.S. Energy Information Administration. Country Analysis: Canada. Available online: http://www.eia.gov/countries/cab.cfm?fips=CA (accessed on 1 May 2013).
3. Six Historical Events in the First 100 Years of Canada's Petroleum Industry. Petroleum Historical Society. Available online: http://www.petroleumhistory.ca/history/wells.html (accessed on 1 June 2013).
4. Canadian Center for Energy Information (CCEI). Evolution of Canada's Oil and Gas Industry. CCEI: Calgary, Canada, 2013; p. 6. Available online: http://www.centreforenergy.com/shopping/uploads/122.pdf (accessed on 1 July 2013).
5. Statistics Canada. Table 126-0001; Supply and Disposition of Crude Oil and Equivalent. CANSIM (Database). Available online: http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=1260001&paSer=&pattern=&stByVal=1&p1=1&p2=-1&tabMode=dataTable&csid= (accessed on 29 May 2013).
6. International Energy Agency (IEA). *World Energy Outlook*; IEA: Paris, France, 2013; p. 526.
7. Hall, C.A.S.; Cleveland, C.; Kaufmann, R.K. *Energy and Resource Quality*: *The Ecology of the Economic Process*; Wiley: New York, NY, USA, 1986.
8. Hall, C.A.S.; Lavine, M.; Sloane, J. Efficiency of energy delivery systems: I. An economic and energy analysis. *Environ*. *Manag*. **1979**, *3*, 493–504.
9. Smil, V. *Energy in Nature and Society*: *General Energetics of Complex Systems*; The MIT Press: Cambridge, MA, USA, 2008; p. 480.
10. Gagnon, N.; Hall, C.A.S.; Brinker, L. A preliminary investigation of the energy return on energy invested for global oil and gas extraction. *Energies* **2009**, *2*, 490–503.
11. Cleveland, C.J. Energy quality and energy surplus in the extraction of fossil fuels in the U.S. *Ecol*. *Econ*. **1992**, *6*, 139–162.
12. Cleveland, C.J. Net energy from the extraction of oil and gas in the United States. *Energy* **2005**, *30*, 769–782.
13. Guilford, M.C.; Hall, C.A.S.; O'Connor, P.; Cleveland, C.J. A new long term assessment of energy return on investment (EROI) for U.S. oil and gas discovery and production. *Sustainability* **2011**, *3*, 1866–1887.
14. Grandell, L.; Hall, C.A.S.; Höök, M. Energy return on investment for Norwegian oil and gas from 1991 to 2008. *Sustainability* **2011**, *3*, 2050–2070.
15. Hu, Y.; Hall, C.A.S.; Wang, J.; Feng, L.; Poisson, A. Energy return on investment (EROI) of China's conventional fossil fuels: Historical and future trends. *Energy* **2013**, *54*, 352–364.
16. Freise, J. The EROI of conventional Canadian natural gas production. *Sustainability* **2011**, *3*, 2080–2104.
17. Brandt, A.R.; Englander, J.; Bharadwaj, S. The energy efficiency of oil sands extraction: Energy return ratios from 1970 to 2010. *Energy* **2013**, *55*, 693–702.

18. Murphy, D.J.; Hall, C.A.S.; Dale, M.; Cleveland, C. Order from Chaos: A preliminary protocol for determining the EROI of fuels. *Sustainability* **2011**, *3*, 1888–1907.
19. Statistics Canada. Table 153-0032; Energy Use, by Sector, Annual (Terajoules), CANSIM (Database). Available online: http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=1530032&paSer=&pattern=&stByVal=1&p1=1&p2=-1&tabMode=dataTable&csid= (accessed on 29 May 2013).
20. Statistics Canada. Table 153-0031; Direct Plus Indirect Energy Intensity, by Industry, Annual, CANSIM (Database). Available online: http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=1530031&paSer=&pattern=&stByVal=1&p1=1&p2=-1&tabMode=dataTable&csid= (accessed on 29 May 2013).
21. Cleveland, C.J. Net Energy Analysis. In *Encyclopedia of Earth*; Environmental Information Coalition, National Council for Science and the Environment: Washington, DC, USA, 2013. Available online: http://www.eoearth.org/article/Net_energy_analysis (accessed on 29 May 2013).
22. Hall, C.A.S.; Kaufman, E.; Walker, S.; Yen, D. Efficiency of energy delivery systems: II. Estimating energy costs of capital equipment. *Environ*. *Manag*. **1979**, *3*, 505–510.
23. Bullard, C.W.; Penner, P.S.; Pilati, D.A. Net energy analysis: Handbook for combining process and input-output analysis. *Resour*. *Energy* **1978**, *1*, 267–313.
24. Herendeen, R.; Cleveland, C.J. Net energy analysis: Concepts and methods. *Encycl*. *Energy* **2004**, *4*, 283–289.
25. Mulder, K.; Hagens, N.J. Energy return on investment: Toward a consistent framework. *AMBIO J. Hum*. *Environ*. **2008**, *37*, 74–79.
26. Brandt, A.R.; Dale, M. A general mathematical framework for calculating systems-scale efficiency of energy extraction and conversion: Energy return on investment (EROI) and other energy return ratios. *Energies* **2011**, *4*, 1211–1245.
27. Wiedmann, T. Editorial: Carbon footprint and input–output analysis. *Econ. Syst. Res.* **2009**, *21*, 175–186.
28. Suh, S.; Lenzen, M.; Treloar, G.J.; Hondo, H.; Horvath, A.; Huppes, G.; Jolliet, O.; Klann, U.; Krewitt, W.; Moriguchi, Y.; *et al*. System boundary selection in life-cycle inventories using hybrid approaches. *Environ*. *Sci*. *Technol*. **2004**, *38*, 657–664.
29. Lenzen, M. Errors in conventional and input-output—Based life—Cycle inventories. *J*. *Ind*. *Ecol*. **2000**, *4*, 127–148.
30. Minx, J.C.; Wiedmann, T.; Barrett, J.; Suh, S. *Methods Review to Support the PAS Process for the Calculation of the Greenhouse Gas Emissions Embodied in Good and Services*; Report to the UK Department for Environment, Food and Rural Affairs: York, UK; Stockholm Environment Institute: Stockholm, Sweden; University of Minnesota: Minneapolis, MN, USA, 2008.
31. Statistics Canada. Table 131-0001; Supply and Disposition of Natural Gas, CANSIM (Database). Available online: http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=1310001&paSer=&pattern=&stByVal=1&p1=1&p2=-1&tabMode=dataTable&csid= (accessed on 2 February 2013).

32. Statistics Canada. Table 132-0001; Supply and Demand for Natural Gas Liquids and Liquefied Petroleum Gases, CANSIM (Database). Available online: http://www5.statcan.gc.ca/cansim/a26?lang=eng&retrLang=eng&id=1320001&paSer=&pattern=&stByVal=1&p1=1&p2=-1&tabMode=dataTable&csid= (accessed on 2 February 2013).
33. Energy Resource Conservation Board (ERCB). ST98-2012. *Alberta's Energy Reserves* 2011 *and Supply/Demand Outlook* 2012–2021. *Appendix A*-12; ERCB: Calgary, Canada, 2012.
34. Energy Conversion Tables. National Energy Board. Available online: http://www.neb-one.gc.ca/clf-nsi/rnrgynfmtn/sttstc/nrgycnvrsntbl/nrgycnvrsntbl-eng.html (accessed on 2 February 2013).
35. Statistics Canada. North American Industry Classification (NAICS) 2007. Available online: http://stds.statcan.gc.ca/naics-scian/2007/cs-rc-eng.asp?criteria=21111 (accessed on 29 May 2012).
36. Statistics Canada. Canadian System of Environmental and Resource Accounts—Material and Energy Flow Accounts (MEFA). Available online: http://www23.statcan.gc.ca/imdb/p2SV.pl?Function=getSurvey&SDDS=5115&Item_Id=22716&lang=en (accessed on 2 June 2013).
37. St-Lawrence, J. Statistics Canada, Ottawa, Canada. Personal Communication, 24 May2013.
38. Canadian Association of Petroleum Producers (CAPP). Statistical Handbook. Value of Producer Sales (1986–2011). Table 04–25B. CAPP: Calgary, Canada, 2013. Available online: http://membernet.capp.ca/SHB/Sheet.asp?SectionID=4&SheetID=265 (accessed on 29 May 2013).
39. Yu, K.; Masakova, I.D.; Tatarinov, A.A. Input-Output Tables in the Canadian System of National Accounts. Available online: http://flash.lakeheadu.ca/~kyu/Papers/IOTables.pdf (accessed on 29 May 2013).
40. Statistics Canada. Canadian System of Environmental and Resource Accounts—Material and Energy Flow Accounts: Estimation. Available online: http://www23.statcan.gc.ca/imdb/pIX.pl?Function=showDirectPDF&fl=http://www23.statcan.gc.ca/imdb-bmdi/document/5115_D1_T9_V1-eng.pdf&flng=eng&a=1 (accessed 29 May 2013).
41. Statistics Canada. Concepts, Sources and Methods of the Canadian System of Environmental and Resource Accounts. Available online: http://www5.statcan.gc.ca/bsolc/olc-cel/olc-cel?catno=16-505-G&lang=eng#olcinfopanel (accessed on 29 May 2013).
42. Canadian Industry Program for Energy Conservation (CIPEC). Making Energy Visible: CIPEC Annual Report 2011. Available online: http://oee.nrcan.gc.ca/sites/oee.nrcan.gc.ca/files/fil1es/pdf/CIPEC_report_e.pdf (accessed on 29 May 2012).
43. Canadian Industrial Energy End-Use Data and Analysis Centre (CIEEDAC). Energy Consumption and Energy Intensity Indicators: 211114 Non-Conventional Oil Extraction. Available online: http://www3.cieedac.sfu.ca/CIEEDACweb/mod.php?mod=NAICSPublic&output=html&what=energyproduced&industries[]=211114_0&years[]=1990&years[]=2000&years[]=2001&fuel_types[]=coal&fuel_types[]=still_gas&fuel_types[]=elec&fuel_types[]=confidential&fuel_types[]=coal_coke&fuel_types[]=propane&fuel_types[]=wood&fuel_types[]=butane&fuel_types[]=coke_oven&fuel_types[]=mid_dis&fuel_types[]=sp_pl&fuel_types[]=ng&fuel_types[]=hfo&fuel_types[]=steam&fuel_types[]=ur&fuel_types[]=pet_coke&fuel_types[]=waste_fuel&emissions=1&baseYear=1990&pd_pu=1&int_pu=1&idx_pu=1 (accessed on 29 May 2013).
44. U.S. Energy Information Administration (EIA). Short-Term Energy and Winter Fuels Outlook—Real Prices Viewer. EIA: Washington DC, USA, 2013. Available online: http://www.eia.gov/forecasts/steo/realprices/ (accessed on 5 November 2013).

45. Wooldridge, J.M. *Introductory Econometrics*: *A Modern Approach*, 4th ed.; South-Western Cengage Learning: Stamford, CT, USA, 2009.
46. Box, G.E.P.; Jenkins, G.M.; Reinsel, G.C. *Time Series Analysis*: *Forecasting and Control*; John Wiley & Sons, Inc.: Hoboken, NJ, USA, 2008.
47. Canadian Association of Petroleum Producers (CAPP). Statistical Handbook. Wells and Metres Drilled in Canada (1981–2012). Table 01–04B. CAPP: Calgary, Canada, 2013. Available online: http://www.capp.ca/library/statistics/handbook/pages/statisticalTables.aspx?sectionNo=1 (accessed on 29 May 2013).
48. Canadian Association of Petroleum Producers (CAPP). Statistical Handbook. Net Cash Expenditure of the Petroleum Industry (1981–2011). Table 04–02B. CAPP: Calgary, Canada, 2013. Available online: http://www.capp.ca/library/statistics/handbook/pages/statisticalTables.aspx?sectionNo=4 (accessed on 29 May 2013).
49. Hall, C.A.S.; Klitgaard, K. *Energy and the Wealth of Nations*: *Understanding the Biophysical Economy*, 1st ed.; Springer: New York, NY, USA, 2012.