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Exploitation of Unconventional Fossil Fuels: Enhanced Greenhouse Gas Emissions

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1. Introduction

Carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and ozone (O_3) are the principal naturally occurring radiatively active gases in the earth's atmosphere (Ruddiman, 2001). These gases are responsible for trapping outgoing infrared radiation in the earth's atmosphere, heating it, and thus keeping the earth's average temperature at approximately 15°C. These gases act as the panes of glass in a greenhouse, trapping in heat from sunlight, and consequently are also referred to as greenhouse gases (GHG).

The concentration of greenhouse gases throughout earth's history has fluctuated naturally, with plate tectonics being the primary, first order control. However, since the Industrial Revolution rapid rises in combustion-related GHG's, principally CO_2, have resulted from related increases in the extraction and burning of the fossil fuels oil, natural gas, and coal. Concern has existed over rising GHG levels and potential climate change since the early 1970's (reviewed in Patterson and Perl, 2007). It is now the consensus of the majority of the scientific community that increases in atmospheric GHG are responsible for measured increases in global average air and sea surface temperature.

The onset of industrialization in the 18th Century was enabled by the widespread use of coal, followed by oil and natural gas in the 19th and 20th centuries. The first resources of all three fossil fuels used were those easily accessible on land. With depletion of these sources, exploration and development has expanded to offshore fields and also to those fossil carbon accumulations inaccessible by conventional means.

The increase in the annual amounts of fossil fuel combustion in terms of barrels of oil, cubic metres of natural gas, and tonnes of coal is estimated to account for an increasingly larger component of the annual flux of CO_2 to the atmosphere. While there are natural sources of CO_2 emissions to the atmosphere (e.g. volcanic eruptions, decay of vegetation), the global increase in CO_2 concentration is attributable primarily to fossil fuel burning (Intergovernmental Panel on Climate Change [IPCC], 2007). Similarly, extraction and distribution related CH_4 emissions and combustion related N_2O are increasing as well. Following the 2008-09 recession, world primary energy consumption increased 5.6% (British Petroleum [BP], 2011). In the 21st century, fossil fuels now account for 81% of the global primary energy mix (Table 1; International Energy Agency [IEA], 2011a).

Added to this now is a new component. The initially accessed oil and gas reservoirs were shallow, and of high quality (National Energy Technology Laboratory, [NETL], 2011). With the depletion of easily accessed conventional deposits of oil and natural gas, the unconventional deposits of these fuels are increasingly being exploited. However with these resources a large energy commitment, which often involves carbon combustion, is required to extract the fuel and render it viable for refining and ultimately consumable in existing equipment. Therefore, there is not just the conventional input of energy and materials to produce fuel, but there are also additional combustion and extra resources involved in the extraction and/or upgrading of the unconventional fuel before it can be treated as a conventional product. This gives the final refined product from an unconventional source a higher carbon intensity (amount of carbon per unit of fuel burned). This creates an additive greenhouse effect to every unit of unconventional oil or gas consumed.

Fuel	**Global Use %**
Oil	33
Coal	27
Natural gas	21
Nuclear	6
Renewables	
Biomass burning	10
Hydro electricity	2
Others	1

Table 1. Global Primary Energy Mix, 2008. Oil and gas values include fuel from both conventional and unconventional sources. Data from IEA (2011a).

The purpose of this paper is to review the role of extraction and processing of unconventional oil and natural gas and the impact on greenhouse gas production. The peak of production of conventional oil has not resulted in diminished use of oil; rather, it has resulted in increased production of oil from unconventional sources. Similarly, natural gas from unconventional sources is assuming an increasing role in the global gas market (IEA, 2011b). Production of fossil fuels from unconventional sources creates more greenhouse gases than from conventional sources. Previous work by Brandt and Ferrell (2007), using IPCC scenarios, found significant potential impacts on GHG's from the substitution of unconventional oil products for conventional oil. This work examines the increased reliance on unconventional oil and natural gas to meet growing energy demands, and the impact on GHG emissions if increasing demand for fuel is met by unconventional sources with higher carbon intensity.

2. Greenhouse gases in the atmosphere

Radiatively active gases are produced by many different means in the earth system. The carbon cycle is governed by complex mechanisms involving plate tectonics, the biosphere, and solid earth-atmosphere interactions (Press and Siever, 1986). Carbon dioxide (CO_2) is introduced to the atmosphere by several processes, including volcanism, combustion, decay of organic material, and respiration. CO_2 is also removed from the atmosphere by several processes, including photosynthesis, dissolution in the oceans, geological burial of organic material, and ultimately plate subduction at tectonic boundaries (Press and Siever, 1986).

The concentration of CO_2 in the atmosphere has varied throughout geologic history. For ancient sequences, millions of years old, atmospheric concentrations are inferred by the use of proxies. However, using ice cores drilled into continental glaciers, measured gas values from air trapped in the ice have yielded the values of atmospheric CO_2 concentrations for the past 800,000 years of the Pleistocene and Holocene periods. This research on ice cores has been one of the most significant and valuable contributions made to the understanding of greenhouse gases and climate in the recent geological record. In 1958, a continuous monitoring programme of atmospheric CO_2 values was undertaken on the island of Mauna Loa in Hawaii (Keeling et al, 2001; Keeling et al, 2011).

Variations in the concentration of atmospheric CO_2 through the past 800,000 years are illustrated in Figure 1. CO_2 concentrations changed, as did temperature throughout the past eight glacial cycles, with low levels of CO_2 during globally cold intervals with ice sheet expansion and high amounts of CO_2 in warm, interglacial periods. As seen in Figure 1, CO_2 values fluctuated between fairly fixed boundaries, ranging from 170 to 290 ppmv, until the beginning of the Industrial Revolution. Minimum CO_2 values were recorded during glacial maximums, and maximum CO_2 values in interglacial periods. The last 10,000 years, known as the Holocene epoch, have been remarkably stable in temperature and CO_2 values. However, beginning with the Industrial Revolution, CO_2 levels began to increase and at the present value of 390 ppmv are now higher than at anytime in the last 800,000 years. This increase is

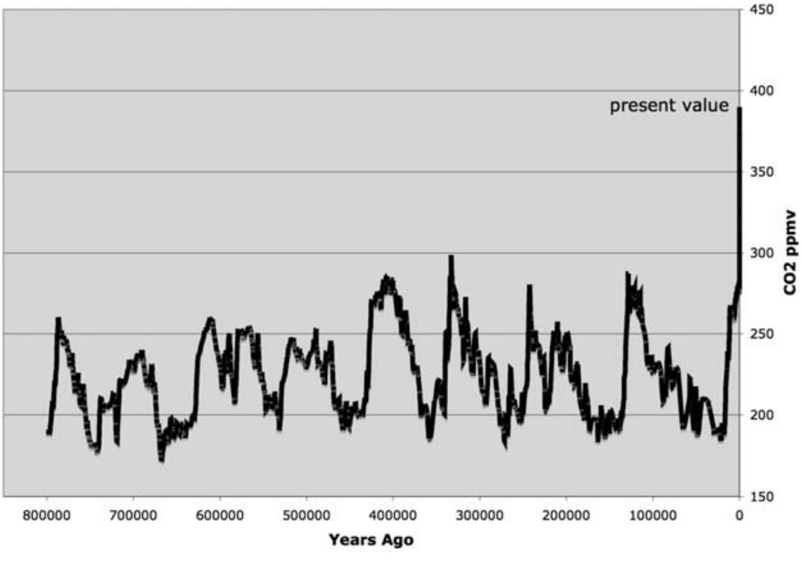

Fig. 1. Record of atmospheric CO_2 in ppmv 800,000 years ago to the present. Ice core data from Supplementary materials in Luthi et al, 2008, including Monnin et al, 2001; Pepin et al, 2001; Petit et al, 1999; Raynaud et al, 2005; Siegenthaler et al, 2005. Data from 1958 CE onwards, Keeling et al, 2001, and Keeling et al, 2011

attributed to the intensified use of fossil fuels with the onset of industrialization and, to a lesser degree, land use changes (IPCC, 2007). The earth's geological systems are unable to remove CO_2 at the same rate as it is input, and thus excess CO_2 is accumulating in the atmosphere.

Methane (CH_4) is produced due to anaerobic decay of organic material. Methane is also the principal constituent of natural gas. The cycling of methane (CH_4) is complexly tied to geological and biological activity. Research has shown that large-scale releases of methane to the atmosphere have occurred due to geological activity, including bursts from methane clathrates (e.g. Nisbet, 2002) and degassing of methane-rich sedimentary rocks following intrusion of magmas (e.g. Storey et al, 2007). Atmospheric concentrations of CH_4 in the last 800,000 years are shown in Figure 2. Ice core records show the same pattern of CH_4 as that seen with CO_2 through the glacial cycles, with low levels of CH_4 when it is cold and high levels during warm interglacial intervals. Throughout the past 800,000 years, methane also fluctuated between upper and lower boundary conditions, as measured from ice cores, and since the Industrial Revolution has increased dramatically to the present value of 1800 ppbv.

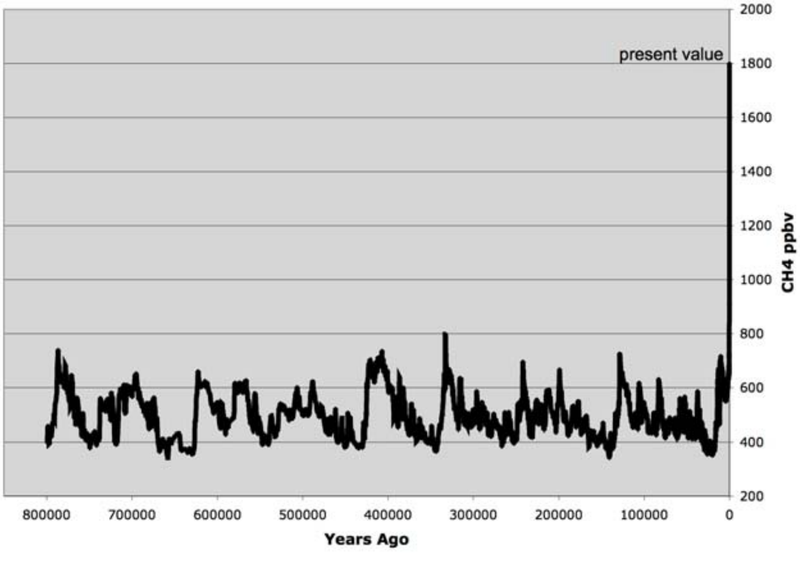

Fig. 2. Record of atmospheric CH_4 in ppbv over the past 800,000 years to the present. Ice Core data from online Supplementary materials in Loulergue et al, 2008, including Delmotte et al, 2004; Spahni et al, 2005; Lisiecki and Raymo, 2005; recent data from Dlugokencky, E., et al, 2009.

The increase of atmospheric methane since the Industrial Revolution is attributed to increased anthropogenic activities including land use changes, increased rice cultivation, and growth in the number of ruminant livestock. Fugitive emissions of methane from coal, oil, and natural gas extraction and transportation are also a factor in the increase in atmospheric methane. Presently, agriculture and fossil fuel exploitation account for two-thirds of annual anthropogenically derived CH_4 emissions (Montzka et al, 2011). The main contributor is agriculture (dominated by ruminant emissions and rice cultivation). Extraction and transportation of natural gas and oil, followed by coal, are the dominant energy related emission sources of CH_4 (Montzka et al, 2011), and contribute 18% of anthropogenic CH_4 emissions globally (U.S. Environmental Protection Agency [EPA], 2011). It should be noted however, that the United Nations Framework on Climate Change (UNFCC) data on gas production and emissions are only reported for Annex-I parties (IEA, 2011a) and thus actual emissions may be higher.

The distribution of anthropogenically produced greenhouse gas emissions, expressed in CO_2 equivalents, is shown in Table 2 below. This does not include greenhouse gas emissions from natural sources (e.g. volcanoes, wetlands). The unit of measure, CO_2 eq, is defined as "the amount of CO_2 emission that would cause the same time-integrated radiative forcing, over a given time horizon, as an emitted amount of a long-lived GHG or a mixture of GHGs" (IPCC, 2007, p. 14). This value is obtained by multiplying the amount of a GHG by its Global Warming Potential (GWP) over a given time horizon (IPCC, 2007). The GWP is a means of comparing the relative climatic impacts of the different gases (Montzka et al, 2011).

Greenhouse Gas	Source	Percentage of Annual Anthropogenic Global Emissions in CO_2 eq
CO_2	Fossil fuel use	56.6
CO_2	Deforestation, decay of biomass	17.3
CO_2	Cement production and natural gas flaring	2.8
CH_4	Agriculture and fossil fuel production	14.3
N_2O	Combustion, agriculture	7.9
F	Hydrofluorocarbons (HFC's), perfluorocarbons (PFC's) and sulphur hexafluoride (SF_6)	1.1

Table 2. Distribution of anthropogenically generated GHG by sector in CO_2eq. From IPCC (2007)

Fugitive emissions are all GHG emissions from the oil and gas industry except for emissions from fossil fuel combustion (IPCC, 2006). The sources of fugitive emissions include leaks, evaporation, venting, flaring, pipeline breaks or dig-ins, and well blowouts. Some are well characterized, e.g. tank evaporation, process vents, and flare systems (IPCC, 2006), but others are accidental and unpredictable.

3. Oil

The industrial use of fossil fuels began in the 18th C with coal, and oil followed in the late 19th C. Oil is now the dominant fuel in the global primary energy mix, accounting for 33% of energy used in 2008 (IEA, 2010). In 2010 there was a 3.1% increase in global oil consumption from 2009 (British Petroleum [BP], 2011). This was in part driven by the emerging economies of China and India, which will increasingly shape global energy demand (IEA, 2010). "China is currently the most important country in shaping future energy markets" (IEA, 2011a, p. 15), and it has surpassed the U.S. as the world's largest energy consumer (BP, 2011). Transportation is expected to continue to be the main driver for the increased demand for oil (IEA, 2010).

Oil resources are classified as conventional and unconventional. Conventional oil consists of crude, natural gas liquids (NGL), and condensates (IEA, 2010; Sorrel et al, 2010). Crude oil is a mixture of hydrocarbons that exists as a liquid under surface conditions (IEA, 2010). It initially flows easily from a well and is one of the least expensive and easiest to process of the petroleum products. The bulk of the oil that has been used to date on the planet was the easily accessible crude oil. NGL's are light hydrocarbons that are produced within a natural gas stream in a hydrocarbon reservoir (IEA, 2010). Condensates are light liquid hydrocarbons recovered from gas reservoirs, and are classed as NGL's (IEA, 2010).

Unconventional oil is derived from sources that include extra-heavy oil, bitumen[1] (tar/oil sands), oil shale, coal (coal-to-liquid CTL), and natural gas (gas-to-liquid GTL); (IEA, 2010; Sorrel et al, 2010). Primary fields of unconventional oil are the bitumen deposits in Alberta, Canada and the heavy oil in the Orinoco Belt of Venezuela. Unconventional oil requires the addition of resources – natural gas, energy and water – to extract and transform the material into oil that can then be processed at conventional refineries. Biofuels and coal-to-liquid (CTL) are not included in this paper.

The variation between conventional and unconventional oil is illustrated by API values (Table 3). API gravity is a measure of the density of a petroleum liquid relative to water. An API >10 means lighter than water, <10 is heavier than water (Stratton et al, 2010).

Oil	API°
Light crude	>35
Medium	26-35
Heavy	<20
Extra-heavy and Bitumen	<10

Table 3. API gravity values for the different oils (IEA, 2010; Martinez-Palou et al, 2011).

3.1 The peak of conventional and the rise of unconventional oil

The annual global production and consumption of oil, from all sources (crude, bitumen, shale oil, and NGL's), is shown in Figure 3[2]. Production has risen from 31.8 mb/d in 1965 to 82.1 mb/d (million barrels a day) in 2010 (BP, 2011). There have been dips, due to the oil

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[1] In this paper, the term bitumen is used. It is an objective descriptor of the extra-heavy petroleum found in Northern Alberta, Canada, and avoids "taking sides" in the oil vs. tar sands debate.

[2] "Differences between these world consumption figures and world production statistics are accounted for by stock changes, consumption of non-petroleum additives and substitute fuels, and unavoidable disparities in the definition, measurement or conversion of oil supply and demand data." BP, 2011, p. 9.

embargo in the early 1970's, the Iranian Revolution of 1979 and ensuing global economic downturn (Patterson and Perl, 2007), and most recently the 2008-09 recession, but overall the trend has grown inexorably upwards.

Oil is a finite resource. M. King Hubbert forecast the peak in production in U.S. oil, based on his observations in Texas oil fields (Hubbert, 1949). Production from an individual well and aggregates of wells that make up a field, rises steadily at first and then, when approximately half the reserve has been extracted, the yield peaks and declines in the form of a normal distribution. Based on these observations, Hubbert (1971) went on to predict an estimate for the peak in production of global oil. This concept was revisited in the now-classic Campbell and Laherrère paper "The End of Cheap Oil" (1998).

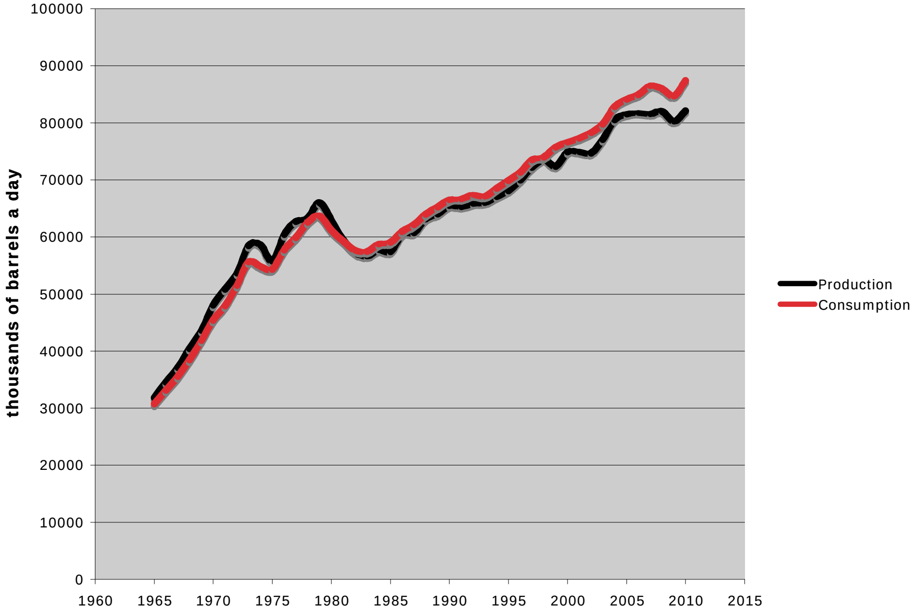

Fig. 3. Global oil production and consumption 1965-2010. Data from BP (2011).

Currently, production of conventional crude is at 68-69 mb/d, with unconventional oil, NGL's, and condensates making up the balance. In 2009, world production of oil was 81.0 mb/d (IEA, 2010). Of this, 67.9 mb/d of crude were produced; natural gas liquids (10.8 mb/d) and unconventional oil (2.3 mb/d) made up the balance (IEA, 2010). It appears that the peak of production of conventional crude oil was at 70 mb/d in 2006 (IEA, 2010). The International Energy Agency believes that if governments put in place the energy and climate policies that they have currently committed to, then the peak of conventional crude oil has indeed probably passed (IEA, 2010).

There is tremendous debate about the size of remaining conventional reserves (Sorrel et al, 2010). For example, with the decline of Arctic sea ice in the summer months, new fields are available for exploration. Offshore discoveries, including deepwater, have contributed significantly to conventional reserves since the 1990's. Since 2000, more than half the oil discovered is in deep water (IEA, 2010). However, the average size of new fields has continued to fall (IEA, 2010), and it is thought unlikely that new giant fields of conventional oil will be found (Sorrel et al, 2010). Rather than a peak of production of conventional oil, Sorrel et al (2010) suggest that the production values from conventional fields may form a "bumpy plateau".

Patterson and Perl (2007) discussed the possibility of two paths for world energy consumption, with the peak of production of conventional crude oil. Replacements for conventional crude are all more costly, hence it was postulated that the increased price in oil could have the effect of reducing oil consumption that CO_2 climate mitigation policies (e.g. Kyoto Protocol) had failed to achieve. The other path was increased utilization of unconventional resources and rising global oil combustion, with concomitant emissions, regardless of price.

The record of global average oil prices is shown in Figure 4. Although there have been significant fluctuations, the average annual price has remained above US$60 for six years now (BP, 2011). Given the apparent unresponsiveness of consumption to high prices, there seems to be no monetary throttle on the continued rise in oil production and consumption.

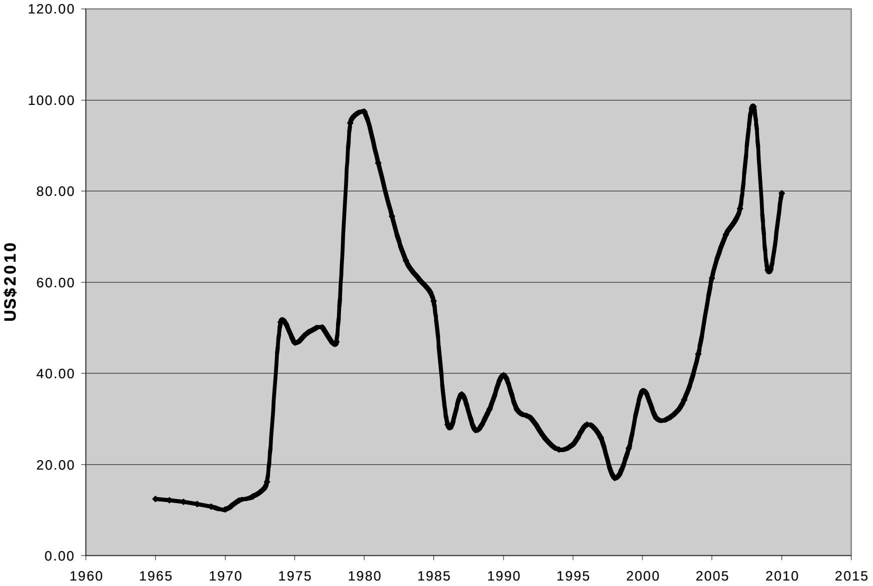

Fig. 4. Oil Prices 1965-2010 adjusted to US$2010. Data from BP (2011).

The decline in production from producing conventional fields means that new production must come from other sources if demand is to be met. In 2010, this means an extra 3 mb/d must be added each year either from enhanced recovery of existing conventional fields, discovery of new conventional fields, or through the exploitation of unconventional resources (Sorrel et al, 2010).

Oil from unconventional sources is predicted to play an increasing role in the world oil supply (IEA, 2010). Over 50% of the world's petroleum reserves (Head et al, 2003) consist of degraded oil, preserved either as heavy oil or bitumen. Heavy oil and extra heavy oil production is currently rising around the world (Martinez-Palou et al, 2010), and Venezuela is expected to increase output from the Orinoco belt (Watkins, 2010). Some estimates, reported in Baynard (2011), suggest that oil exploration and production activities in the Venezuelan heavy oil belt may increase by 600% in the next two decades.

The Canadian bitumen deposits of Alberta will also play a significant role. Estimates for future production from the Canadian bitumen sand are varied and conflicting. Rates of production of 3.7 mb/d are forecast for 2025, (Canadian Association of Petroleum Producers [CAPP], 2011), while predictions for production in 2030 range from 5 mb/d (Soderburgh et al, 2007) to 6 mb/d (Cambrian Energy Research Associates [CERA], 2009).

Evidence for the predicted growth in production from Alberta bitumen deposits can also be seen in plans for pipeline development. As of this writing the contentious Keystone XL pipeline, from northern Alberta to Texas, has passed Canadian and U.S. Environmental Protection Agency (EPA) approval and is contingent upon approval by the White House. In Canada, the Northern Gateway Pipeline has been proposed to run from northern Alberta to the deep-water port of Kitimat B.C. for export overseas, presumably to the Chinese market. These plans are meeting fierce opposition (see http://www.huffingtonpost.ca/2011/09/02/keystone-xl-protest-naomi-klein_n_947117.html; http://www.tankersnothankers.ca). Also, Enbridge Pipelines Inc. has requested permission from the National Energy Board of Canada to proceed with the Trailbreaker project. This would initially change flow in a portion of the pipeline in Ontario. Ultimately, a reversal in pipeline flow between Portland, Maine, (U.S.A.) and Montreal, Canada would allow Alberta bitumen products to travel to the east coast of the U.S., for export overseas and to southern U.S. ports and refineries (Vanderklippe, 2011a). Finally, both Canadian railways, Canadian National, and Canadian Pacific, are exploring increased oil movement by rail as business options (Vanderklippe, 2011b).

3.2 Production of unconventional oil; energy and resources required

The production of conventional oil involves exploration, drilling, establishment of the wellhead, and construction of pipelines to move the oil to refineries. In later stages, as the well becomes depleted, secondary recovery with pumping, or water or CO_2 injection, is used to extract the oil. The enhanced recovery techniques add to the energy costs of the production of conventional crude oil. Greenhouse gas emissions associated with the production of conventional crude oil are combustion related CO_2 from construction, operation, and transportation. Methane emissions from field operations include venting, oil storage tanks, and well venting and flaring (IPCC, 2006; EPA, 2011). Natural gas in remote locations is often disposed of by flaring (Martinez-Palou et al, 2011).

In the case of conventional crude oil, the product that flows out of the well needs little modification before entering the pipeline. However, this is not the case with the unconventional oil. Any existing technology for the conversion of unconventional fossil fuel to liquid hydrocarbon suitable for refining as conventional petroleum carries significant environmental burdens. The unconventional resource must be extracted, separated from the host rock and, depending upon the composition, upgraded before being sent to a refinery. All of this requires energy, water, and feedstock for upgrading. In the section below the processes used to produce oil from bitumen are used as an outline to illustrate the energy and resources required.

Bitumen is a complex hydrocarbon that requires enhanced extraction techniques and upgrading before the liquid product can be sent to a conventional liquid petroleum refinery. Bitumen has a high viscosity and will not flow unaltered. There are two methods by which the bitumen is produced; surface mining followed by extraction of the bitumen from the sand, and in-situ separation of the bitumen and removal from the ground. In both cases, upgrading of the bitumen to a lighter hydrocarbon fluid resembling conventional petroleum is required before refining of the product can take place. Currently most of the bitumen that is removed by surface mining is upgraded as part of the overall on-site process, and these are known as integrated operations (CAPP, 2009). Only some of the in situ operations upgrade the product before transportation to refineries; the bitumen from other in situ plants is blended with a diluent to enable the non-upgraded material to flow in pipelines to southern upgrading and refining facilities (CAPP, 2009).

In the open-pit mining sites, truck and shovel operations are the main method of extracting and transporting the oil sand from the ground (Isaacs, 2007). Ore is transported to crushers by heavy truck (Alberta Chamber of Resources, 2004) with energy supplied by diesel fuel. At the crushers, the ore is broken down (Alberta Chamber of Resources, 2004) and then the crushed ore undergoes slurrying and hydrotransport in pipelines (Isaacs, 2007) to the separation facility (Alberta Chamber of Resources, 2004). In this process, called conditioning, the crushed oil sand is mixed with steam and water. In the dynamic movement, the separation of oil from sand begins (Isaacs, 2007; Chow et al, 2008). Most separation of mined bitumen is done by using the Clark method (Hyndman and Luhning, 1991), involving hot water, NaOH, and steam (Holowenko et al, 2000); first developed by Dr. Karl Clark in 1929 (Chow et al, 2008). The separation of the bitumen from the sand is an iterative process in which as much bitumen as possible is extracted from the sand slurry before being sent to the tailings pond (Alberta Chamber of Resources, 2004; Chow et al, 2008).

Following extraction of the bitumen it is sent for upgrading, the process whereby the extracted bitumen is transformed into a synthetic crude oil that can be sent by conventional pipeline to refineries where it can be used as a feedstock, similar to conventional petroleum (Hyndman and Luhning, 1991). The upgrading step is a complex petrochemical engineering process that reduces the viscosity of the hydrocarbon product and decreases the sulphur, nitrogen, and metals content (Hyndman and Luhning, 1991; Isaacs, 2007; Humphries, 2008). Natural gas is the principle feedstock for hydrogen in the upgrading process (Soderburgh et al, 2007; Humphries, 2008).

Extraction of bitumen from the host sandstone at depths too great for economically viable surface mining is accomplished by the use of techniques that reduce the viscosity of the bitumen and allow it to be pumped to the surface (Chow et al, 2008). In the development of an in situ operation, seismic lines are cleared, drilling sites are constructed, roads are built, and pipelines are constructed (Johnson and Miyanishi, 2008; Schneider et al, 2003).

Steam assisted gravity drainage (SAGD) is a forefront technology for in situ extraction, and is the most economically attractive method for the deep deposits of the Athabasca field (Chow et al, 2008). Advances in horizontal drilling have aided the development of this technology. Two horizontal wells are drilled, one above the other; steam at 250°C is injected into the top well, and the loosened bitumen is collected in the bottom production well (Isaacs, 2007). A new technology involves the use of expanding solvents. In this technique, expanding solvent steam assisted gravity drainage (ES-SAGD) combines steam and solvent in the injection process (Chow et al, 2008).

The Cyclic Steam Stimulation (CSS) process involves the injection of high temperature steam at high pressure into the bitumen deposit underground (Chow et al, 2008). The high-pressure steam fractures the sediment, allowing the steam to spread and heat the bitumen, reducing its viscosity and allowing it to flow (Chow et al, 2008).

Once the bitumen is extracted from underground, the majority of the product is treated with diluent so that it will flow and goes by pipeline to refineries, while the remainder is upgraded in northern Alberta (Alberta Chamber of Commerce, 2004). The main source of the diluent is natural gas. Blending with traditional condensate diluent requires a 70:30 ratio of bitumen to condensate (CAPP, 2009). Upgraded light crude can also be used and is blended in a 50:50 ratio with the bitumen for pipeline transport to refineries (CAPP, 2009). The production of heavy and extra-heavy oils face similar production challenges.

The transportation of bitumen, heavy or extra-heavy oils that have not yet been upgraded from the fields to the energy markets, pose technological challenges because of high density, viscosity, low API gravity, and salt and heavy metal content (Martinez-Palou et al, 2011). While sending oil by pipeline is the most efficient and convenient method of transportation, the low mobility of these oils, and wax and ashphaltene deposits on pipeline walls, create technical problems (Martinez-Palou et al, 2011).

To overcome these problems, pipeline transportation of heavy oil can be effected by reducing the viscosity of the oil, minimizing wall drag in the pipe, and in-situ upgrading of the oil prior to transport (Martinez-Palou et al, 2011). Viscosity can be reduced by dilution with natural gas condensates, partial upgrading, formation of oil/water emulsions, reconfiguration of internal shear, and heating the oil and pipelines. Adding heat to the oil and pipeline and re-heating through directed fire heaters at pumping stations is the second most common method for reducing the viscosity of the heavy oil. (Martinez-Palou et al, 2011). In offshore settings, subsea pipelines must be heated when transporting heavy or extra heavy oil. All these techniques have added energy costs, and consequently greenhouse gas implications, particularly the direct heating of the heavy oil along the length of the pipeline.

3.3 Quantification of Life cycle Greenhouse gas emissions associated with conventional and unconventional petroleum

The greenhouse gas emissions associated with both conventional and non-conventional liquid petroleum fuels have been investigated as these industries have grown, and concern over greenhouse gas emissions from these sectors has increased (e.g., (S&T)^2 Consultants Inc., 2008; Skone and Gerdes, 2008; Charpentier et al, 2009; Stratton et al, 2010). These are the emissions associated with fuel production, from extraction out of the ground to transportation to the refinery, including flaring of associated natural gas. These emissions include fugitive greenhouse gases from the wells and venting. In the case of the Canadian bitumen this includes all emissions associated with extraction and upgrading, including fugitive methane emissions from open-pit mining operations.

Generally speaking, the ratio of energy used to the energy in the final product (energy produced) is about 6% for conventional crude oil, approximately 20-25% for extra-heavy oil and nearly 30% for bitumen in sandstone (IEA, Energy Technology Systems Analysis Programme [ETSAP], 2010). Comparison of the emissions produced through the production of conventional and unconventional oil, produced from bitumen, are shown in Table 4, below. The values for conventional crude include recovery and transportation emissions, and exclude oil from Angola and Nigeria. The values for the unconventional oil are for Alberta bitumen, extracted either by open pit mining or by in situ processes (SAGD), and then upgraded to synthetic crude oil. The values are taken from the review by Charpentier et al (2009) and Stratton et al (2010).

Fuel Product	gCO_2eq/MJ
Conventional crude	4.5 – 9.6 (Charpentier et al, 2009)
	5 – 10 (Stratton et al, 2010)
Synthetic crude oil	
Mining	9.2 - 26.5 (Charpentier et al, 2009)
SAGD	16.2 - 28.7 (Charpentier et al, 2009)

Table 4. Upstream CO_2eq energy by feedstock.

Life cycle analysis can be undertaken for bitumen that ultimately is used in transport vehicles. These GHG life cycle emissions are divided based upon the extraction method; open-pit mining, SAGD, or CCS. For example, the emissions associated with the life cycle of fuel that is ultimately burned in a light duty vehicle (conventional automobile) are referred to as “well-to-wheels”; that is, from the drilled well or mining pit to the fuel tank of the vehicle and subsequent combustion. Similarly, aviation kerosene emissions are referred to as “well-to-wake” (Stratton et al, 2010).

Examples of conventional versus unconventional liquid petroleum life cycle greenhouse gas emissions are presented in Table 5, below. The greenhouse gases considered are combustion and non-combustion related products, CO_2, CH_4, and N_2O, and are reported in total as CO_2 equivalents (CO_2eq), based on the GWP of each gas (IPCC, 2007). The “well-to-wheels” values are presented as gCO_2eq/km for the production and combustion of the final refined product (gasoline) in vehicles ((S&T)^2 Consultants Inc., 2008). Values are presented gCO_2eq /MJ of energy in the “well-to-wake” aviation fuel (Stratton et al, 2010).

	Conventional crude gCO_2e/km	Unconventional (bitumen) gCO_2e/km	Ratio Unconventional/ conventional
Light Duty vehicle "well-to-wheels"[3]	316.3	354 (surface mining)	1.12
		390 (SAGD)	1.23
		384 (CSS)	1.21
	Conventional crude gCO_2e/MJ	Unconventional (bitumen) gCO_2e/MJ	Ratio Unconventional/ conventional
Aviation Kerosene[4] Jet A "Well-to-Wake"	87.5	99.8 (surface mining)	1.14
		108.2 (SAGD)	1.24

Table 5. Comparative life cycle GHG emissions for gasoline for light duty vehicles and aviation kerosene for conventional and unconventional oil feedstocks.

4. Natural gas

Natural gas is the third most abundant fuel in the global energy mix (Table 1), and is projected to overtake coal in projections of energy use to 2035 (IEA, 2011). Power generation is the main sector for gas demand, where gas has been replacing coal (IEA, 2011). In 2007, 33% of the global natural gas production was consumed for electrical generation (EIA, 2010). Figure 5 shows production and consumption of natural gas since 1970[5]. Natural gas production has tripled in the past 35 years and is tightly followed by consumption. The influence of China is seen also in the development of the natural gas market. For example, China is installing liquefied natural gas (LNG) re-gasification terminals and buying shale gas resources in North America (IEA, 2011a).

Conventional natural gas reservoirs may be found with or without oil. Gas that accumulates with oil is referred to as associated gas, while non-associated gas does not accumulate with oil (Energy Information Agency [EIA], 2010). Conventional gas reservoirs are sandstone or carbonate formations that have both porosity and permeability (interconnected pores so that the gas can flow) (Holditch, 2006). With conventional gas reservoirs, once the well is drilled the gas is easily extracted. Gas production involves drilling to the reservoir and setting up the wellhead and pipelines for gas to flow from the reservoir to market. Processing involves stripping out impurities (e.g. H_2S). Pipeline quality natural gas is 95-98% methane (EPA, 2011). The gas is transmitted along high-pressure pipelines with pumping stations distributed along the length of the pipeline, with final distribution to end-users.

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[3] Data from (S&T)[2] Consultants Inc., 2008.

[4] Data from Stratton et al, 2010. The values presented are the baseline scenario; the value for conventional crude is the weighted average of all crude oil fed into U.S. refineries except for Canadian oil sands.

[5] "The difference between these world consumption figures and the world production statistics is due to variations in stocks at storage facilities and liquefaction plants, together with unavoidable disparities in the definition, measurement or conversion of gas supply and demand data." BP, 2011, p. 23.

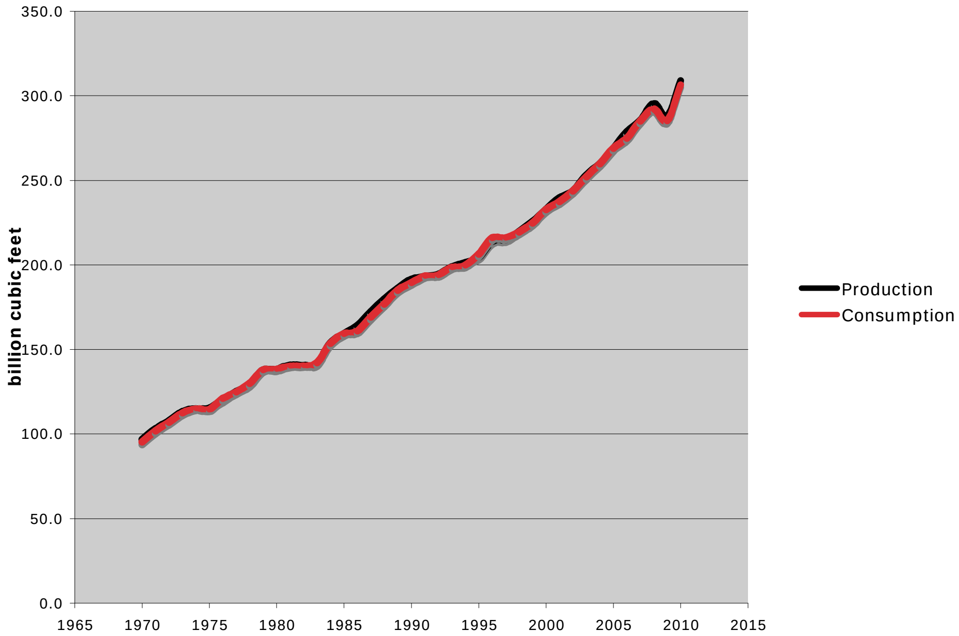

Fig. 5. Global Natural Gas Production and Consumption 1970-2010. Data from BP (2011).

4.1 Unconventional gas

The principal sources of unconventional gas are tight gas, coal-bed methane, and shale gas (Bourdaire, 2011; Holditch and AdDeenMadani, 2011; IEA, 2011a). Tight gas and coalbed methane (CBM) have been produced economically for four decades now, with shale gas production being relatively recent (Bourdaire, 2011; IEA, 2011a). In the U.S., the production of unconventional gas up to 2008 was distributed approximately as 70% from tight gas, 20% CBM, and 10% from shale gas (Bourdaire, 2011).

Globally, approximately 13% of marketed gas is from unconventional sources (IEA, 2010). Presently, unconventional gas is principally being produced in Canada and the U.S. In 2009, the production of unconventional gas exceeded conventional in the U.S., and it now makes up ~60% of marketed production in that country (IEA, 2011a). The peak of production of conventional gas was shown to have been reached in 2008 (IEA, 2011a, Figure 1.13, p. 36), and consequently, unconventional gas is increasingly meeting global demand. The production of unconventional gas doubled in the last eight years to 350 bcm in 2010 (IEA, 2010).

Deposits of unconventional gas are predicted to increasingly meet the growing demand for natural gas, and there are large quantities of this resource. In China, India, and Australia, unconventional gas development is focused on coal-bed methane, while tight gas is of interest in North Africa and shale gas in Poland (IEA, 2011b). Globally, the share of unconventional gas is predicted to rise from 13% of total natural gas production to 25% in 2035. Total global annual production is predicted to rise from 3.3 trillion cubic metres (tcm) in 2010, to 5.1 tcm in that time period (IEA, 2011a).

Unconventional gas reservoirs have low permeability and cannot produce at economic flow rates or economic volumes unless the reservoir is pumped or stimulated by hydraulic fracture treatment, horizontal wellbores, and/or multiple wellbores (Holditch, 2006). Recovery factors for unconventional gas tend to be much lower than for conventional gas, only about 15-30% of gas initially in place (GIIP) versus 80% recovery of GIIP for conventional deposits (Massachusetts Institute of Technology [MIT], 2010).

4.1.1 Tight gas

Tight gas development started in the 1970's (American Association of Petroleum Geologists [AAPG], 2011). Global tight gas production has risen from 6 billion cubic metres (bcm) in 1993 to 93 bcm in 2009 (Shell, 2011). It is estimated that at least 6000 trillion cubic feet (tcf) are in place in the US alone (NETL, 2011). Tight gas is trapped in impermeable, low-permeability, or non-porous sedimentary rock (Holditch, 2006; NETL, 2011). The extraction of tight gas requires fracturing and chemical alteration, which makes it costly. To get economic flow rates and/or to recover economic volumes the formation must be stimulated using hydraulic fracturing and/or horizontal well bores (AAPG, 2011).

4.1.2 Coalbed methane

Methane has historically always been a problem in coalmines, due to the risk of explosion during mining operations (EPA, 2004). In the formation of coal from organic material, methane gas is produced and is adsorbed onto the sides of small pores of the coal (EPA, 2004). Coal is structurally weak and consequently fractures easily so coal beds are typically characterized by networks of connected fractures (EPA, 2004). Water in coal beds contributes to the hydrostatic pressure that keeps methane gas adsorbed to the surface of the coal (United States Geological Survey, 2000; NETL, 2011).

As a natural gas, coalbed methane is difficult to produce, although it is relatively pure and does not contain H_2S (Government of Alberta, 2011). Coalbed methane is produced by reducing pressure in the coalbed (National Energy Board [NEB], 2007). When pressure is reduced the methane desorbs, diffuses through the coal, and then flows through the fractures (NETL, 2011). This reduction in pressure may be achieved by drilling and pumping out the groundwater in the coal bed, which brings water to the surface (Berquist et al, 2007; USGS, 2010; NEB, 2007; NETL, 2011). The initial pumping-out of groundwater may need additional flow enhancement and generally is followed by more drilling and hydraulic fracturing to enlarge pre-existing natural fractures in the coal seams (EPA, 2004; NEB, 2007; NETL, 2011). Fracturing fluids containing proppants (usually fine sand) are injected into the coal bed and then pumped back out, leaving the proppants to keep the fractures open, and thus increasing the permeability and allowing the methane to flow (EPA, 2004).

4.1.3 Shale gas

Shales are dense, fine-grained rocks, with very limited porosity (Kargbo et al, 2010). Shales hosting natural gas are rich in organic material (Kargbo et al, 2010; Kerr, 2010; Osborn et al, 2011), with natural gas in the pores of these rocks (Kargbo et al, 2010). Shales are so impermeable that they often act as cap seals on reservoirs of conventional oil and gas.

Therefore, extraction of the gas is very difficult. It is the last unconventional gas to be developed (Bourdaire, 2011).

Shale gas is extracted utilizing directional drilling and hydraulic fracturing techniques, the same as those used for tight-gas and coalbed methane recovery (Osborn et al, 2011). Multiple wellheads are required (Osborn et al, 2011). Multi-stage fracturing techniques are used with horizontally drilled wells (Kargbo et al, 2010). The drilling "fracking" fluid contains gels, acid, biocides, surfactants, and scale inhibitors to prevent precipitation of sulphate and carbonate (Kargbo et al, 2010). With development of the Marcellus Shale in Pennsylvania and New York, the wells are fractured laterally for just under a kilometer (954m) from the wellbore (Kargbo et al, 2010).

With each well, the hydraulic fluid mix is pumped in with millions of gallons of water mixed with chemicals and sand. Sand grains are proppants, keeping the fractures open and artificially creating permeability so the gas can flow (Kerr, 2010). The multistage fracturing techniques use large amounts of water, which must be managed (Kargbo et al, 2010). In the Marcellus Shale, the fracturing of each horizontal well requires 2-10 million gallons of water (7.7-38 ML) (Kargbo et al, 2010), with other estimates of 3-4 million gallons per well (Kerr, 2010). As much as 80% of the fluid may not be recovered (Kargbo et al, 2010). After drilling the wastewater must be treated onsite or trucked to a wastewater treatment facility. Flow from a new well can decline 60-80% in the first year of production (Kerr, 2010) and may have to be repeatedly fractured in order to continue producing.

4.2 Greenhouse gases from conventional and unconventional gas production and transportation

Greenhouse gases from both conventional and unconventional natural gas include direct and indirect combustion related CO_2 emissions and fugitive methane emissions. Direct CO_2 emissions are related to end-use combustion (Howarth et al, 2011; Wood et al, 2011). Indirect emissions of CO_2 are those produced by extraction, development, and transportation of the natural gas to market (Howarth et al, 2011). This includes combustion of fossil fuels, usually diesel, to drive pumps, drills, compressors, and to transport equipment and resources to and from the well site (Wood et al, 2011).

The energy used as a percentage of the energy produced for conventional gas is about 6% (IEA ETSAP, 2010). When comparing conventional natural gas to unconventional shale gas, the additional direct and indirect "well-to-burner" CO_2 emissions are only marginally higher for shale gas (Howarth et al, 2011; IEA, 2011a; Wood et al, 2011). The ratio between energy used to energy produced between conventional natural gas and that from unconventional tight gas, CBM, and shale gas is relatively small (IEA ETSAP, 2010). Indirect emissions from shale gas in the U.S. are estimated to be 1.2 – 1.7 gC/MJ (Marcellus shale; Santoro et al, 2011), compared to 15 gC/MJ for direct end-use combustion (Hayhoe et al, 2002). Wood et al (2011) estimate that additional direct emissions of CO_2 from shale gas are only 0.14 to 1.63 tonnes of CO_2e/TJ greater than those from combustion of conventional natural gas (57 tonnes of CO_2e/TJ). Therefore, for conventional and shale gas, the GHG emissions are dominated by CO_2 from direct end-use burner combustion and also by fugitive methane emissions, discussed below (Howarth et al, 2011; Wood et al, 2011).

A significant amount of gas is also flared at the wellhead, releasing CO_2. In 2010 an estimated 134 bcm of natural gas was flared (IEA, 2011a). The World Bank has initiated the Global Gas Flaring Reduction programme to attempt to reduce this waste from flaring. Given total annual global production of 3193 bcm of natural gas (BP, 2011), losses of 95bcm due to venting and leakages, and flaring of 134 bcm, approximately 7% of annually produced natural gas is lost to the atmosphere as greenhouse gases.

For both conventional and unconventional gas production, methane emissions result from drilling, wellhead establishment, normal operations, routine maintenance, and fugitive emissions. A significant amount of raw methane is released to the atmosphere by pressure venting, leakages, or due to accidents (IEA, 2011a). Fugitive methane emissions occur during transportation, storage, distribution, from connections between pipes and vessels, valves, leaks from wellheads, and along transmission lines (Howarth et al, 2011; Wood et al, 2011). Fugitive emissions also include gas that migrates to the surface around the outside of the wellhead casing (IPCC, 2006). The U.S. EPA in 2006 estimated annual releases of 95 bcm of gas due to leaking and venting, with a greater loss due to leakage rather than venting. The gas industry is now using enhanced sensing equipment to locate and seal leaking wells and pipelines (Kargbo et al, 2010).

The amount of fugitive methane produced is much higher for unconventional natural gas than for conventional. Hydraulic fracturing (fracking) fluids used in tight gas and shale gas beds come back up the well as “flow back” fluids, with large quantities of methane in the fluid (Howarth et al, 2011). It is estimated that in conventional well completion, fugitive emissions account for only 0.01% of methane emissions over the lifetime of the well, versus an estimated 0.6-1.3% in tight sandstones, and 1.9% for shale gas (Howarth et al, 2011).

Fugitive methane emissions can continue after well completion from shale gas deposits. Cement casing of wells becomes more challenging with depth and may cause aquifer contamination (Kargbo et al, 2010; Wood et al, 2011). There is documentation of systemic contamination by methane of aquifers overlying the Marcellus and Utica shales where they have been exploited in northeast Pennsylvania and upper New York State (Osborn et al, 2011). Measured methane concentrations increased in drinking water wells when a gas well was within 1 km (Osborn et al, 2011). Isotopic $\delta 13C - CH_4$ data was consistent with the methane being of deep, thermogenic origin, and not biogenic (Osborn et al, 2011). Methane in wells, close to the surface of the earth, can easily migrate and escape to the atmosphere. Wood et al (2011) contains a review of numerous examples of wellbore failure and migration of methane from the fractured rock to the surface, with explosions in some cases. In Quebec, of 31 shale gas exploration sites, 19 leaked methane. All have now been shut and a moratorium placed on any shale gas activity (Marsden, 2011).

5. Conclusions

Since the Industrial Revolution in the mid-18th Century, fossil fuel use has become the dominant energy source for humans on the planet. Fossil fuels now supply 81% of the global energy mix (IEA, 2011a). The primary use of oil is in transportation, and the greatest demand for natural gas is in electrical power generation. Global production of oil has doubled since 1970, and production of natural gas has tripled in the same interval (BP, 2011).

Oil and natural gas are both present in conventional and non-conventional forms. Conventional oil and natural gas deposits located on continents and nearshore marine shelves - at shallow depths - made them easily, and therefore cheaply, accessible. The late portions of the first decade of the 21st Century saw the peak of production of conventional crude oil (IEA, 2010) and also conventional natural gas (IEA, 2011a). Easily accessed deposits of conventional oil and gas have been largely depleted, and enhanced recovery techniques need to be used on these diminished reserves. Extraction is now focused on deepwater offshore oil and unconventional deposits of oil and gas.

With increased extraction and use of fossil fuels have come amplifications in the atmospheric abundance of carbon dioxide and methane, the two most abundant greenhouse gases. Concentrations of both gases are now at higher levels than at any time in the past 800,000 years (Luthi et al, 2008; Loulergue et al, 2008). Enhanced levels of greenhouse gases in the atmosphere are believed by the majority of scientists to be responsible for warming of the planet, and concomitant climate change. Policy efforts (e.g. the Kyoto Protocol) and price increases in oil have failed to rein-in usage of fossil fuels and the production of combustion related greenhouse gases. The peak of production of conventional oil has not resulted in diminished use of oil; rather it has resulted in increased production of oil from unconventional sources. Similarly, natural gas from unconventional sources is assuming an increasing role in the global gas market (IEA, 2011b). Demand continues to grow, even though prices remain near historical highs for oil.

To meet the demand for these fuels, rates of exploitation of both unconventional oil and natural gas are growing each year. Both unconventional oil and natural gas share common denominators in that they require extra energy and resources, and are more expensive to produce. They both have higher carbon intensity, producing more greenhouse gases per unit of energy delivered as a final product than conventional oil and natural gas products. There is an increased use of unconventional fuels in order to fill the shortfall left by the peak of production of conventional oil and natural gas. Given that each unit of unconventional oil and natural gas has up to 20% more associated greenhouse gas emissions than a conventional equivalent, there is an enhancement of greenhouse gas in the atmosphere as consumption of unconventional fossil fuels increases.

It is difficult to envisage what will stop the juggernaut of fossil fuel consumption and related GHG increases, barring a global economic collapse. Infrastructure exists, and continues to be built, for both established and developing societies dependent upon oil and natural gas. The large potential reserves of unconventional oil and natural gas can fuel industrialized economies well into the future. It is increasingly difficult to be optimistic of any mitigation of atmospheric GHG growth and climate change in light of the ongoing exploitation of unconventional oil and natural gas.

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