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Limitations of Oil Production to the IPCC Scenarios: The New Realities of US and Global Oil Production

James W. Murray[1]

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Abstract Many of the Intergovernmental Panel on Climate Change's Special Report for Emission Scenarios and Representative Concentration Pathways (RCP) projections (especially RCP 8.5 and 6) project CO_2 emissions due to oil consumption from now to 2100 to be in the range of 32–57 Gb/yr (87–156 mb/d) or (195–349 EJ/yr). World oil production (crude plus condensate) was almost constant from 2002 to 2011 at about 74 ± 1 million barrels per day (mb/d) (US Energy Institute Agency, US EIA). There was an increase in world oil production after January 2011 that was mostly due to a surge of about 6 mb/d in light tight oil (LTO) production in the USA. This increased global oil production to just above 80 mb/d. Meanwhile, production in the rest of the world remained constant. The surge in the USA resulted in a sustained situation where supply was greater than demand globally, and this initiated a crash in the price of oil. The price of oil decreased from about $100 per barrel in mid-2014 to less than $30 per barrel in early 2016. Once the oil price declined, it was further enhanced and sustained by a decrease in demand due to a slowdown in the global economy. Because LTO is expensive to produce and was unprofitable after the price crash for the exploration and production companies, the surge in US production ended in about April 2015. Now, production of LTO in the USA is declining and global oil production is as well. New oil discoveries have reached a 70-year low, which does not bode well for future production. If the present patterns persist, it is unlikely that world oil production will exceed present US EIA oil production values of about 27–29 Gb/yr (equivalent to 75–80 mb/d) or (171–182 EJ/yr). It is unlikely that the demand for oil production required for CO_2 emissions in RCP8.5 and RCP6 will be met.

Keywords Oil production · Light tight oil · IPCC · RCP · SRES

✉ James W. Murray
jmurray@u.washington.edu

[1] School of Oceanography, University of Washington, Box 355351, Seattle, WA 98195-5351, USA

Introduction

While it is clear that global climate is changing, driven by increases in atmospheric CO_2 and other greenhouse gases (GHG), the speed and magnitude of the changes yet to come are still uncertain. One way that models of future climate change are imprecise is that they use scenarios whose inputs are based on forecasts of the demand of energy production and resulting future CO_2 emissions from integrated assessment models (IAMs). In this paper, I will explore one part of those forecasts—future oil consumption—and evaluate whether the forecasts by the Intergovernmental Panel on Climate Change (IPCC) are consistent with what we know about present-day oil production, taking into account recent increases in light tight oil (LTO) production in the USA.

Fossil fuel resource availability is a key driver of IPCC emission pathways. However, the uncertainty in this parameter has not been sufficiently analyzed in these emission scenarios. The IPCC developed a clear vocabulary about uncertainty related to different aspects of climate change (e.g., ranging from virtually certain = 99–100% probability to exceptionally unlikely = 0–1% probability) but did not apply these characterizations to the amount of fossil fuels required to produce the CO_2 scenarios. The IPCC Special Report for Emission Scenarios (SRES) for increasing atmospheric CO_2 (Nakicenovic et al. 2000) were driven by emission scenarios of GHG produced by burning fossil fuels (oil, natural gas, and coal). These reflected expert judgments by teams of energy economists regarding plausible future emissions based on trends in energy demand represented in IAMs. For the IPCC's Fifth Assessment Report (AR5) (IPCC 2013), the SRES scenarios were replaced by Representative Concentration Pathways (RCPs), which utilized radiative forcing (W m^{-2}) to emphasize that their primary purpose was to provide time-dependent projections (trajectories) of the climate forcing by atmospheric GHG concentrations to the climate modeling community for the Coupled Model Intercomparison Project phase 5 (CMIP5) (van Vuuren et al. 2011a, b). The models applied for the SRES and RCP forecast demand for fossil fuels and assumed that discoveries and technological improvements will make available the energy resources demanded by the economy at an affordable cost.

Fossil fuel production and the evolution of fossil fuel prices are important factors that influence the direction of the global energy system. However, uncertainties concerning fossil fuel resource availability have traditionally been deemphasized in climate change research. Fossil fuel resource abundance, understood as the vast geological availability of oil, coal, and natural gas accessible at an affordable price, is a default assumption in most IAMs used for climate policy analysis. These estimates are subject to critical uncertainties. IAMs have been utilized to study the large uncertainties in the development of fossil fuel resources. A robust finding of one IAM inter-comparison exercise, conducted as the Energy Modeling Forum 27 (EMF27), was that the cumulative fossil fuel consumption foreseen by the models is well within the range of estimated recoverable reserves and resources found in the literature (McCollum et al. 2014). These authors concluded that fossil fuel resource constraints are unlikely to limit future GHG emissions, and thus global climate change, during this century. However, in a different study, Capellan-Perez et al. (2016) applied an IAM to study the likelihood of climate change pathways. They found that the highest RCP pathways (RCP6 and RCP8.5) have very low probabilities of being achieved due to fossil fuel limitations. This conclusion was similar to that of Höök and Tang (2013) and Wang et al. (2016) who argued that fossil fuel resource scarcity will ultimately be a limiting factor in the twenty-first century for GHG emissions growth.

In this paper, we focus on the oil component of fossil fuel production because oil consumption currently produces about 36% of the anthropogenic CO_2 from fossil fuels. Oil is also the main form of energy required for 95% of transportation and is an essential input into current agricultural and mining processes. This discussion will include the role played by the recent surge in LTO production in the USA for global oil production. The price of oil has recently undergone a price crash that has impacted LTO production. There have been similar discussions about uncertainties in future coal production (Höök et al. 2010; Rutledge 2011; Höök and Tang 2013; Kennedy 2015). The lack of updated, transparent, and robust estimates for coal reserves at the global level is especially problematic. The common perception of coal abundance (e.g., Kharecha and Hansen 2008) is not supported by the data. Several studies have indicated that cumulative CO_2 emissions from coal production will be less than any of the IPCC emission scenarios (Energywatch Group 2007; Mohr and Evans 2009; Höök et al. 2010; Patzek and Croft 2010). Coal reserve estimates for the USA are especially out of date (NAS 2007; Pierce and Denman 2009). There has been less examination of future production of natural gas, including the recent increases in production of shale gas (but see Höök and Tang 2013).

The uncertainties associated with future oil supply and how it impacts the global energy system should be given serious consideration. We will first need to describe some important geological and economical characteristics of oil production that will limit a future increase in production.

Definitions of Oil and the Price of Oil

We cannot discuss the production of oil without first defining different categories of oil and clarifying some major points about how data are reported. Who reports data for oil production and what data do they include? This is important to clarify as different agencies report oil production differently. The definition of oil for which a price is quoted is different as well. The IPCC SRES and RCP reports were built using the International Energy Agency (IEA) definitions and databases for oil production.

Oil reserves are the faction of oil resources (the amount of proven or geologically possible available on the earth) that can be produced economically using present technologies and at the current price. Estimates of resources and reserves are inherently uncertain due to the methods used to assess their availability, such as sampling, simulation, and extrapolation. The lack of methodological standardization and transparency in the reporting of data adds uncertainty (Capellan-Perez et al. 2016). Conventional oil can be extracted from a reservoir using the natural pressure of the wells and pumping operations. Unconventional oil is petroleum produced using specialized procedures or techniques. Unconventional oils include extra-heavy oil (as from the Orinoco in Venezuela), tar or kerogen sands (from Canada and the western USA), ethanol from biofuels, gas-to-liquids (GTL), coal-to-liquids

(CTL), and deepwater oil. LTO produced from shale formations using horizontal drilling and fracking is an example of unconventional oil. They are more expensive to produce and have low energy returns on energy invested (EROI) (Hall and Klitgaard 2012). The production rate from unconventional reserves is usually less than that from conventional reserves. Hence, it can be misleading to make conclusions about future production rates of unconventional oil based on estimates of resources/reserves alone.

When a price is reported for oil (e.g., Brent, West Texas Intermediate or WTI), it is the price for crude oil having a density of API < 45 (NYMEX Rulebook, Chapter 200, Light Sweet Crude Oil Futures. http://www.cmegroup.com/rulebook/NYMEX/2/200.pdf), The API density scale is defined in Levorsen (1967). The Brent price (CPI adjusted) from January 2003 to July 2016 is shown in Fig. 1. When agencies report production of oil, they include several liquids that are not oil by this definition. The US EIA (US DOE) reports crude oil plus condensates (http://www.USEIA.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_m.htm). The IEA in Paris reports total liquids as crude + condensates + natural gas liquids + biofuels + processing gains (https://www.iea.org/oilmarketreport/omrpublic/).

No agencies track actual crude oil production, for which the price is applied (Cobb 2014). Condensates are very light, volatile, hydrocarbons (C5–C9) that are gaseous under in situ conditions, then condense at the surface. They have an API density between 45 and 70. Condensates are difficult to quantify separately (which is why they are combined with crude oil by the US EIA and IEA). The best estimate for the average condensate contribution for total US production appears to be about 14%, but they make a much larger contribution (possibly 70–100%) for some LTO production (Fielden 2013; Cook et al. 2014). Natural gas liquids (NGL) consist of butane, ethane, pentane, propane, and other non-methane components of natural gas. Biofuels are essentially ethanol and biodiesel. These additional liquid hydrocarbons have many uses, but they have a lower energy content (Table 1) and are not perfect substitutes for crude oil. Refinery gains are the most puzzling addition to crude oil supply calculations by the IEA. They are merely the increase in volume of refinery outputs such as gasoline, diesel, and jet fuel relative to the volume of crude oil inputs. They are due to the expansion of the liquids produced, and represent no actual gain in energy. On average, refinery gains are 13% of the total volume of refined products. In fact, they represent a

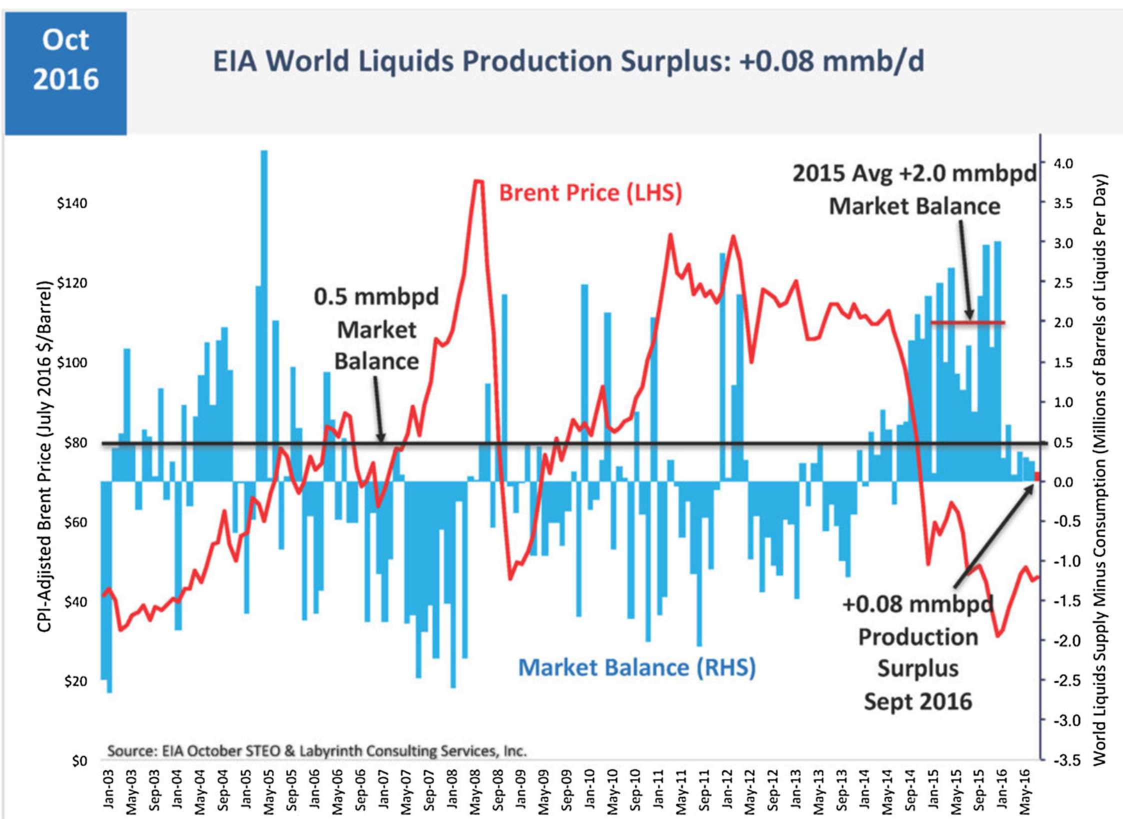

Fig. 1 Brent oil price and EIA world liquids production surplus from January 2013 to September 2016. The price is adjusted for the CPI. *Source*: The Petroleum Truth Report by Art Berman on October 13, 2016. EIA October Short Term Energy Outlook (STEO) and Labyrinth Consulting Services, Inc., http://www.artberman.com/world-oil-production-in-balance-u-s-natural-gas-production-way-down/. Shown with permission of Art Berman

Table 1 Energy content of hydrocarbon liquids included in the US EIA/IEA totals

Type	Fraction of energy content relative to crude oil	10^9 J per barrel
Crude oil	–	6.11
Natural gas liquids	0.70	4.28
Biofuels	0.66	4.04
Syncrude (from tar sands)	0.70	4.28
Condensates	0.70–1.00	<6.11

Values given for conversion from barrels to joules. The numbers in parentheses give the fraction of energy content relative to crude oil

loss of energy as energy is expended in the refinery process during their production. Thus, there is a disconnect between the way the price of oil is defined and how oil production is defined (Cobb 2014). When comparing oil production with price, it is best to use US EIA data, because it is closest to the definition of real crude oil. But all forms of "oil" (except refinery gains) produce CO_2 when consumed, so the IEA definition is best for comparison with oil consumption in the IPCC SRES and RCP scenarios. The conclusions of this paper are the same regardless of which definition of oil is used.

Light tight oil (LTO) discussed in this paper is called light because its API density is typically less dense than API = 45 and tight because it is produced from shale rocks (which have very low permeability) (Levorsen 1967) by a combination of lateral drilling and hydraulic fracking.

Global Oil Production

World oil production (US EIA) increased to about 74 million barrels per day (mb/d) by January 2005 (85 mb/d for the IEA) and was then fairly constant until 2011 (Murray and King 2012) when it increased to 80.5 mb/d in July 2015 (97 mb/d IEA) [Fig. 1a (US EIA) and Fig. 1b (IEA)]. This spectacular increase of about 6.5 mb/d (US EIA) and 12 mb/d (IEA) was almost entirely due to a sharp increase in unconventional production of LTO in the USA and Canada. US LTO production reached about 5.7 mb/d by July 2015 and has declined since. Meanwhile, world oil production minus this increase in North American LTO production has been essentially constant since 2005 at about 74 mb/d. (US EIA) or 85 mb/d (IEA). For the period from 2011 to 2015 (when the price of oil was high), 80% of the increase in oil production was due to unconventional LTO in the USA and tar sand production in Canada. An increase in oil production in Iraq since the 2003 war contributed ~18% (IEA data analyzed by Mearns 2016a). Increases in production in Russia, Iran, Iraq, and Saudi Arabia did not offset declines in the rest of the world (IEA data analyzed by Mearns 2016a). During the 8 years when the price of oil was greater than $100 per barrel, global conventional oil production was essentially constant. North American and world oil production are in decline (Patterson 2015). Because a principal cause of the increase in global oil production was due to the increase in the USA, we need to look at the recent increase in North American LTO oil production in more detail.

The Light Tight Oil Revolution in the USA and Its Limitations

The modern tight oil industry has some important characteristics that make it strikingly different from past production of conventional oil. These are important for understanding future production. It is important to review these aspects in order to evaluate whether the oil production required for the IPCC scenarios can be met.

Why the Sudden and Sharp Increase in US LTO Production Starting in 2011?

LTO production started increasing in 2011 when the price of oil increased to greater than $90/barrel (Fig. 1). Tight oil is expensive to produce. According to Bloomberg BusinessWeek (October 13, 2014), the horizontal drilling process for a single well can cost about $6–$9 million. The production of LTO increased because the price of oil increased, not because of new technologies. The techniques of horizontal drilling (since 1930s) (e.g., Curtis 2011; Blackmon 2013) and fracking (since 1940s) (e.g., Manfreda 2015) with sand and chemicals at high pressure to increase production have long been known, although improvements have continuously been made. Fracking was first used on a large scale to extract natural gas beginning in about 2005. It expanded to the oil fields around 2010. Shale is normally a source rock for hydrocarbons and has very low permeability. The shale revolution began because:

1. more attractive, less expensive conventional opportunities were exhausted, and
2. the market price of oil climbed to support the cost of extraction of unconventional LTO.

Policy exemptions and technological change contributed, but they do not explain the timing. There are many exemptions for hydraulic fracturing under US federal law: The oil and gas industries are exempt or excluded from certain sections of a number of the major federal environmental laws. The most important was The Energy Policy Act of 2005 (https://www.epa.gov/laws-regulations/summary-energy-policy-act), which included the exemption (known as the Halliburton Loophole) of hydraulic fracturing from key provisions of the Safe Drinking Water Act (http://www.nytimes.com/2009/11/03/opinion/03tue3.html; Whitney and Behrens 2010; Hauter 2015). There were technological improvements such as improvements in 3D seismic imaging and (especially) techniques of horizontal drilling. But the main factor that enabled the oil and gas industry to extract oil from shale rock over the past 7 years was higher price. If it were not for higher oil prices, the capital investment needed in the oil and gas sector would not have occurred, and US oil production would have continued to decline.

LTO Production in the Rest of the World

So far, most LTO production has occurred in the USA, and US LTO production is in decline. The US EIA assessed global shale oil resources (US EIA 2013) and concluded that 41 countries have technically recoverable resources. These resource assessments were updated in 2015 (US EIA 2015a). International LTO production requires favorable geology, which includes marine oil source rocks, total organic carbon (TOC), hydrogen index, thermal maturity, and depth of burial (pressure). When you eliminate non-marine shales and shales with insufficient TOC, are overmature and are either too deep to be commercially horizontally drilled and hydraulically fracked or too shallow to have sufficient pressure to produce, there are not that many prospective basins in the world (Art Berman, personal communication, November 2016). Economic recoverability also depends on above-the-ground factors, such as financial resources, ownership of subsurface mineral rights (which are absent in most countries), extensive infrastructure (rigs, pipelines, rail, roads, service companies), the right physical setting (onshore, easy terrain, unpopulated), and availability of water resources. There is certainly potential for tight oil elsewhere in the world, but the possibility of replicating the success of the US LTO boom in other parts of the world will be difficult (Maugeri 2013). The USA and Canada are unique in terms of the amount of drilling (drilling intensity) that has taken place, which has defined the geological distributions. They also have the most favorable surface/mineral rights regulations and the onsite knowhow with equipment (especially drill rigs), people, and infrastructure. High-quality tight oil plays are not ubiquitous—half of the tight oil production in the USA comes from just two plays (Bakken and Eagle Ford)—and take a lot of capital. Besides the USA, Western Canada (Duvernay Shale), West Siberia (Bazhenov Shale), China (Dagang Formation), and Argentina (Vaca Muerta Shale) are currently the only countries in the world that are producing low but commercial quantities of LTO (US EIA 2015b). Poland is a representative example of where there were initial estimates of large reserves of shale gas (not LTO) that were reduced significantly after initial exploration revealed that there was low permeability and complex faulting. (Economist, 2014, http://www.economist.com/blogs/easternapproaches/2014/11/polish-fracking).

High First Year Decline Rates Require a Drilling Treadmill

In a seminal report, David Hughes (Hughes 2014) analyzed all of the individual LTO producing wells in the USA and determined that the average declines in production rates over the first year were typically 40–70%. The average decline rate for conventional oil wells is about 5–7% per year, meaning that 3.5–4 mb/d of new production are required each year just to stay constant. Because of the high decline rates, an increasing number of new wells are required to just to maintain present production. This drilling treadmill has been called the “Red Queen Effect” (from Lewis Carroll’s “Through the Looking Glass”) (Likvern 2013). To illustrate this, we see that to maintain production of 1 mb/d requires 60 new wells per year in Iraq and 2500 new wells in the Bakken in North Dakota.

“Hot Spots” are Drilled First

The production from shale formations is spatially highly variable. In the case of the Bakken Formation, four counties account for 85% of the production. As of March 2013, there were 5047 wells, producing 0.70 mb/d for an average of 140 barrels per day per well. That average production per well has decreased with time as the “hot spots” have become depleted, and subsequent new wells were less productive (Hughes 2014). For comparison, production of wells in conventional oil fields can be 1000s of barrels per day per well.

Tight Oil is Not Profitable!

Estimates of the break-even price for light tight oil vary but range from about $75 per barrel (presentation by Paal Kibsgaard (CEO Schulumberger) at the Scolia Howard Weil 2015 Energy Conference, http://www.slb.com/news/presentations/2015/2015_0323_pkibsgaard_howard_weil.aspx) to greater than $90 per barrel. There are many reports in the press of lower break-even prices, but these do not take into account full costs, which vary between different oil plays (Berman 2015a). The true story can be seen in the individual companies' full-year 10-K earnings reports filed with the Securities and Exchange Commission. Full-year free cash flow has been negative for most tight oil Exploration and Production (E&P) companies since 2009. The composite free cash flow for the 19 largest LTO E&P companies was −$2.9B in 2013. For the same group, it decreased by −$7.5B to −$10.5B in 2014 (Berman 2015b). This total negative cash flow of $10.5B in 2014 was for a year when the average Brent price was $93/barrel. These losses continue. All of the E&P companies in the tight oil business had negative cash flow in the first quarter of 2016 except EP Energy and Occidental Petroleum. Nine companies increased their capital expenditures (capex)-to-cash flow ratios compared with full-year 2015 results and six increased that ratio by more than 2.5 times (Berman 2016). Even ExxonMobil has had progressively decreasing free cash flow from $24B in 2011 to $1.0B in 2016 YTD. The industry consistently spends more cash than it generates, even while trying hard to cut costs.

Cheap Money Helped Inflate LTO Production

The E&P companies have been financed by high risk, high-yielding "junk bonds" issued by the industry (Wall Street Journal, Zero Hedge, 1 June Zero Hedge 2016). The Federal Reserve lowered the Fed funds rate essentially to zero at the end of 2008, but the economy continued to worsen. So the Fed tried to see what it could accomplish by buying huge quantities of longer-term securities (called quantitative easing) in order to stimulate the US economy. Junk debt earned the name for a reason: It means risky business for investors, but also a higher yield if the bet goes well. The yields on energy junk bonds varied between 5 and 9% from 2010 to 2015 but increased to as high as 10.8% in February 2016 (Abramowicz 2016). This provided the cash needed for E&P companies to do necessary exploration and production. That tells us that LTO producers are heavily dependent on debt. Were it not for the Federal Reserve's policy, the ever-accelerating drilling treadmill (see "High First Year Decline Rates Require a Drilling Treadmill" section) would likely slow down, making shale oil and gas production a less lucrative endeavor for oil and gas companies and the financiers bankrolling it.

In addition to the availability of high interest rates, analysts and investment bankers encouraged the investment that helped promote the LTO surge (Rogers 2013). The story for LTO was pretty much the same as for shale gas. Both gas and oil reserves were initially vastly overestimated (Rogers 2013). Wells are characterized by steep decline rates that resulted in underperformance relative to original projections. Market gluts of gas and oil resulted from overproduction in order to meet financial market's production targets and to provide cash flow. Prices were driven to new lows, and this opened the doors to transactional deals and consolidations that secured large fees for the investment banks, who profit regardless of the profitability of the E&P companies.

Why did companies continue producing LTO when they were losing so much money? The answer is complicated. The executives have their incentives, often based on stock performance. Their goal is to keep shareholders happy and ensure that cash flow at least covers interest costs. They continued drilling new wells to keep their reserves and production growing and to maintain the illusion of profitability. The shareholders are looking for production growth. They see E&P companies as growth companies (the International Oil Companies (IOCs) with dividends are an exception). As long as there is reserve and production growth, they will stay with the stock and discount the lack of present profitability. The easy money policies created an environment where yield-hungry investors pushed into riskier assets. High yield justifies high risk. If cash flow covers debt, they are satisfied. Depletion gets ignored because it is not a cash item. Capital expenditures are ignored because they presumably are funding future growth.

The recently accumulated debt is massive. The total industry debt increased to $3 trillion with at least $1 trillion being spent on unprofitable projects (Financial Times, March 21, 2016). The companies on the Bloomberg North American Independent E&P Index spent $4.15 in operating expenses for every dollar earned selling oil and gas in the first quarter 2015 (Bloomberg Business, June 18, 2015). Standard and Poor's assigns junk rating to 45 out of the 62 companies on this index. Access to cheap cash via capital markets has allowed money-losing producers to keep drilling even at low prices. Even so, 69 oil and gas producers have filed for bankruptcy in North America as of May 2016 (Forbes May 9, 2016).

The Oil Price Crash

A systematic decline in the price of oil began after June 2014 (Fig. 1). This roughly 70% decrease in price over 2 years had a strong impact on production of expensive LTO production in the USA. The fundamental cause of the price crash was initially due to an imbalance in supply relative to demand, driven primarily by the rapid increase in US LTO production (Berman 2015d). From October 2014 to January 2016, oil production exceeded demand by about 1.5–3 mb/d (Fig. 1) and the imbalance was still 0.5–1.0 mb/d in early 2016 (Berman 2016). Production in the rest of the world was constant and is now in decline, in spite of a recent (2015–2016) increase of ~0.13 mb/d in Russian production and an increase of ~0.65 mb/d by the OPEC 12 countries (which includes a dramatic increase of about 0.7 mb/d in Iran due to lifting of sanctions) (Mearns 2016a, b). The low prices were then sustained by the weakened global economy and stronger dollar. There has been much speculation on what other factors may have caused and maintained the price crash. For example, some argued that this was a planned response by the Kingdom of Saudi Arabia (KSA) to keep their share of global oil production; yet, Saudi oil production was constant through this time period. Their decision to not cut oil production was a response to the price crash, not a cause. The KSA argued that if excess production in the USA caused the price crash, why should they be the ones to cut production and suffer financially (Saab and Manning 2015). They did not want to reduce their market share. We can only speculate about their motives, but they may have wanted to keep the price low to force a reduction in expensive LTO production in the USA.

Overall, global demand for oil remains weak. It is counterintuitive to envision that lower oil prices can cause a global recession, but that was recently argued by Hamilton (2016). The economies of many countries, especially Russia, Saudi Arabia, Venezuela (and petrostates like North Dakota, Texas, Alaska and Louisiana in the USA) depend on oil revenues. Baumeister and Kilian (2016) explored the effect on US real GDP growth due to the sharp drop in the price of oil. The increase in discretionary income resulting from lower oil prices was mostly balanced by the decrease in investment due to low oil prices. The net stimulus on the US economy since June 2014 has been effectively zero. With the oil prices as low as they are at present, a major source of income for these countries/states is much reduced. The expectation (e.g., Berman 2015c; Berman 2016) is that the price of oil will remain low for at least the rest of 2016 and into 2017, continuing to put pressure on the financial bottom lines of the E&P companies and LTO production.

The negative economic impacts due to higher oil prices have also been studied (Murray and King 2012; Murray and Hansen 2013). High energy prices erode budgets and act as a head wind against economic recovery (e.g., Tverberg 2012). Ten of the eleven recessions in the USA since World War II were preceded by a spike in oil prices, including the most recent one that started in December 2007 (Hamilton 2009).

The price crash reflects the inability of the world market to support the cost of new expensive unconventional oil. A high price of oil reduces demand that reflects the connection between oil price, debt, and personal income (Stern 2004; Cobb 2006; Kumhof and Muir 2014). Conventional economic theory says that an increase in the price of oil will stimulate increased production, but it also induces conservation and decreases demand, until the price trends toward a new equilibrium.

The Price Crash Initiated a Decline in US Oil Production

As a consequence of the geological and economic limitations listed above, after 4 years of rapidly increasing production starting in 2011, LTO production in the USA started to decline in early 2015. According the US EIA's Monthly Productivity Reports, US LTO production peaked in March 2015. Production from the Bakken and Eagle Ford regions peaked in January 2015 and March 2015, respectively (Patterson 2015). As a result of the price crash, the number of oil drill rigs decreased from over 1600 in July 2014 to a low of 476 in March 2016. Some major producers (e.g., Chesapeake Energy, Continental Resources, Whiting Petroleum) totally suspended drilling operations until prices increase. Nevertheless, USA shale oil production continued to increase for some time after the initial price crash. Shale oil producers were remarkably resourceful in keeping production up by fracking wells already drilled and only drilling new wells in the sweetest of sweet spots. The capital costs were already expended so this kept operating costs low. In spite of the risks involved, Wall Street has continued to provide investment capital (Berman 2016).

In Fig. 2, we show that the increase in global oil production was due to increased production of LTO in the USA. Even though the price was high from 2011 to 2014, most global producers did not (or could not?) increase production to take advantage of the high prices. With North American tight oil production apparently in decline, the world could be close to an all-time peak in oil production. Regardless of whether this is the ultimate peak or not, the data for the past 10+ years show that except for the surge in LTO in the USA, world oil production has been on a plateau of about 75 mb/d (US EIA) or 85 mb/d (IEA).

How Does This Relate to Uncertainty in Climate Change?

Uncertainty in climate change is usually reported as due to results from climate models driven by increases in CO_2 from the present to 2100. Uncertainty results from changes in extensive variables in models like cloud cover, ocean warming, albedo, snow, and ice cover driven by the warming generated by increases in fossil fuel CO_2. The

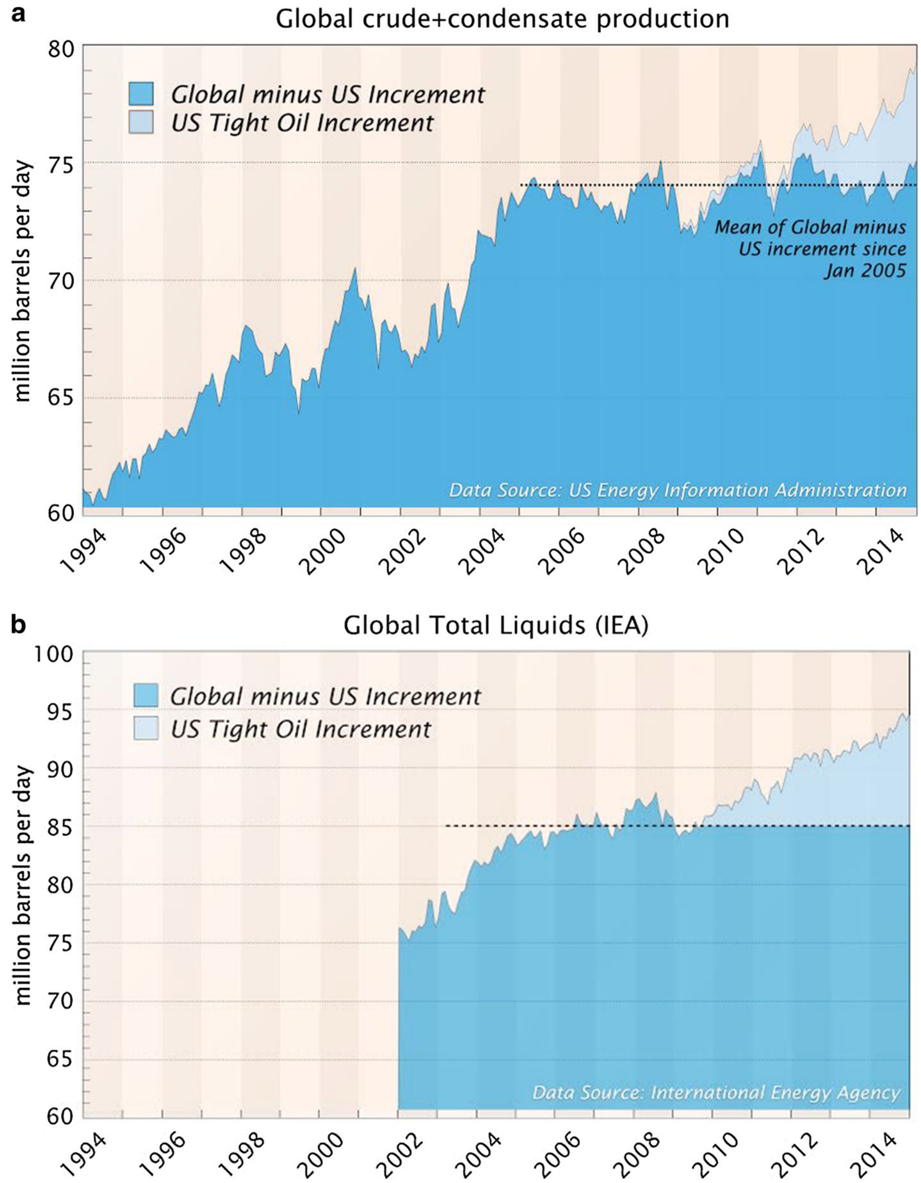

Fig. 2 Global oil production in million barrels per day from the US EIA from 1994 to present (June 2015) and from the IEA (2002–2015). The *lighter colored* increment since January 2008 is that due to the increase in US LTO production. For the US EIA data, global oil production minus the recent increase in US LTO production has averaged 74 ± 1 mb/d since 2005. For the IEA data, that constant value has equaled 85 ± 1 mb/d. **a** Data from the US EIA. **b** Data from the IEA

increases in atmospheric CO_2 that drive these models are prescribed by various scenarios. The IPCC initially presented its report on possible scenarios for emission of CO_2 in The Special Report on Emission Scenarios (SRES) (Nakicenovic and Swart 2000). I include the SRES in this study as they are still used for comparison in many studies. Four scenario families were developed, and 40 SRES scenarios were prepared by six modeling teams. Resource availability (total reserves plus resources) was obtained from energy economists at the International Institute for Applied Systems Analysis (IIASA) (Rogner 1997; Gregory and Rogner 1998) based on data available in the late 1980s. A fundamental assumption was that vast unconventional hydrocarbon occurrences exist, and historically observed rates of technology change would allow hundreds of years of availability of fossil energy with low long-term costs, i.e., not significantly higher than the market price of the 1990s (~$20/barrel). In essence, reserves are "replenished" by shifting resources into reserves (see also Adelman and Lynch 1997). Technological advances were given as a reason for improved recovery and development of previously uneconomic reservoirs. No consideration was given to how economic limitations of energy return on investment (EROI) (Hall and Klitgaard 2012) might impact this assumption, how demand destruction that occurs at high prices (Hamilton 2009) or how economic recessions caused by low prices (Hamilton 2016) might impact oil production. There was no consideration of the fact that oil cannot be produced at the same rate from unconventional and conventional reservoirs (geological limitation). Resources and reserves (quantities) cannot be equated to production (a rate).

For the Fifth Assessment Report (AR5) (IPCC 2013), SRES scenarios were replaced by Representative Concentration Pathways (RCPs) which were differentiated by the global radiative forcing (W m^{-2}) they achieved in 2100 (van Vuuren et al. 2011a, b). A set of four new Representative Concentration Pathways (RCPs) reported as RCP2.6, RCP4.5, RCP6.0, and RCP8.5 were developed. These future scenarios included CO_2 concentration and emissions, and were generated by four IAMs. Each of the modeling teams developed its own scenario and each uniquely linked input assumptions regarding population growth and energy efficiency with their model to create an RCP (Hanaoka et al. 2006; Clarke et al. 2009; Edenhofer et al. 2010). These are documented in a special issue of *Climatic Change* focused on development of the RCPs (van Vuuren et al. 2011a, b). These RCPs were designed to inform climate models about emissions and land use. In parallel, new socioeconomic scenarios (SSPs) were developed (Moss et al. 2010). The concentrations of CO_2 required, and the sources of that CO_2 were reported in Chapter 6 of AR5 (IPCC 2013). The RCPs reported CO_2 (and other GHG) emissions (see the RCP database tntcat.iiasa.ac.at/RcpDb/) but breakdown of which fossil fuels these emissions come from has not been published. The RCPs implicitly assume at least the same resource availability as the SRES scenarios (Wang et al. 2016). The underlying values of production of the various fossil fuels that produce the CO_2 of the RCPs were not published in detail in AR5 or in Moss et al. (2010). The evolution from 2000 to 2100 of the relative global energy supply, including the various fossil fuel sources of CO_2 for RCP8.5, is shown graphically in Riahi et al. (2011). That figure also compares what the partitioning of CO_2 from the different fossil fuels sources will be for all four RCP scenarios in 2100. A bar graph summary of primary energy sources for the different RCPs in 2100 was published by van Vuuren et al. (2011a, b).

Each of the four families of SRES (CO_2 emissions) and RCPs (radiative forcing) is demand-driven, fundamentally linked to assumptions about future consumption of oil, coal, and gas. The various scenarios generate predictions of demand for oil (and other fossil fuels) and assume that production will meet that demand. This underlying assumption is not often considered as a factor contributing to uncertainty in climate change.

In Fig. 3, the present-day maximum US EIA oil production (minus the increment in LTO) of 75 mb/d (28 Gb/yr) and IEA oil production (minus the increment in LTO) of 85 mb/d (31.0 Gb) are compared with oil consumption required for the four RCPs and the four families of SRES Scenarios (van Vuuren et al. 2011a). The RCPs report oil consumption in EJ/yr, and these are also shown as Gb/yr to enable comparison with the units conventionally used for oil production. The conversion is 1 barrel of crude oil = 6.117×10^9 J, but the energy content of much of the "oil" reported by IEA and US EIA (e.g., condensates, natural gas liquids, biofuels, and syncrude) is less (Table 1). Because the decline rate for LTO oil wells is so large, we assume that the surge in global production due to US LTO will be largely removed in a few years. That assumption can be debated, but for the conclusions of this paper, it would not matter if the surge in LTO is included or not. Most of the demand-driven projections in Fig. 3 require oil supply from 32 Gb/yr to 57 Gb/yr (equivalent to 87–156 mb/d) (200 to 350 EJ/yr) by about 2075. The higher values (e.g., RCP 8.5) would require a doubling of world oil production. The comparison shows that if world oil production (C + C) does not exceed 75 mb/d (28 Gb/yr equal to 175 EJ/yr) (or using IEA data: 85 mb/d, 31.0 Gb, 189 EJ/yr), then it is highly unlikely that the components of the higher CO_2 scenarios from oil production will be reached. They would require a much higher rate of production than we have seen in the data of the last 10 years. This uncertainty of climate change will be the same regardless of whether referring to SRES or RCP scenarios.

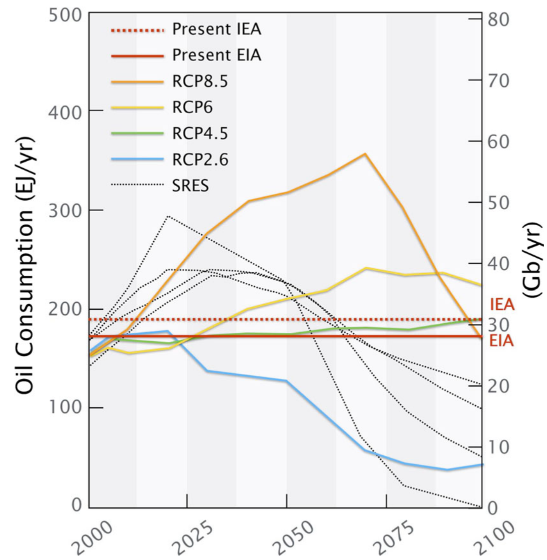

Fig. 3 Oil consumption for the four RCPs compared with 2015 data from the US EIA and the IEA. The *dotted lines* indicate the averages for the four SRES scenarios families. Using US EIA data, present-day oil production minus the increment in LTO (*solid red line*) equals 28 Gb/yr, equivalent to 75 mb/d, equivalent to 175 EJ/yr using a conversion of 1 barrel of oil = 6.117×10^9 J. Using IEA data, present-day oil production minus the increment in LTO (*dotted line*) equals 85 mb/d or 31.0 Gb/yr or 189 EJ/yr. The maximum oil production for RCP8.5 is equivalent to 57 Gb/yr (about twice present-day production) (Modified from van Vuuren et al. 2011a, b)

About 65% of global GHG emissions are generated by fossil fuel emissions. Oil is the source of 36% of those. To reduce emissions, we either have to capture and store atmospheric CO_2 or we have to reduce fossil fuel combustion. The prospects for carbon capture (e.g., clean coal) are widely discussed. Unfortunately, what is not usually discussed is that capture and condensation of CO_2 requires about 25% of the gross starting energy. In addition, the scale of the problem is usually not appreciated. Chu (2009) reported that the world burns 6 billion tons of coal C each year. The volume triples after conversion to CO_2 so the storage volume required would be 39,000 km^3 per year, which is equal to 600 Niagara Falls. This does not consider removal of existing atmospheric CO_2 or CO_2 produced by burning other fossil fuels. In 2014, annual growth rate of CO_2 emissions did slow from +2.4% per year (average for the decade before) to +0.6%, and then in 2015, they decreased to −0.6% (Jackson et al. 2016), but it is unclear whether this decrease in the rate of CO_2 production was the result of policy actions or a slowing of the global economy. A longer record is required. Even though the rate of emissions slowed, the concentration of atmospheric CO_2 continued to increase and our concerns about future climate change are not diminished.

Covert et al. (2016) argued that because the ratio of proven fossil fuels reserves to production (equal to the number of years of current consumption) has been constant at 50 years for the past 30 years, that a supply side argument that the world would run out of inexpensive fossil fuels is countered by new discoveries and advances in technology. They argue that this will ensure that there is a nearly limitless amount of fossil fuels available. This argument faces a number of problems, however. First, there has been a dramatic decrease in discovered volumes of conventional oil over the past 4 years. There have been four consecutive years of declining oil discoveries, which has never happened before, and this portends a supply gap in the future. Discoveries of new oil reserves dropped last year to their lowest level in the last two decades. Despite high prices, the oil industry discovered only 12 billion barrels of new reserves in 2015, about one-third of annual global production and only about one-tenth as much oil as annually discovered since 1960 (Holter 2016). After the price crash, investment in exploration has decreased even more. Second, such traditional arguments about reserves by energy economists are uncertain because so-called proven reserves are not proven by anyone and there is much evidence that they are wildly inflated (Murray and King 2012; Aleklett 2012). Covert et al. (2016) praise the recent technological advances that have made oil from tar sands and shale formations available. But, in fact the timing of events suggests that it was the sharp increase in the price of oil and not new technologies that made this oil available. Because of the price crash, production from Canadian Tar Sands has reduced from 3.9 mb/d in 2015 to about 1 mb/d (Cunningham 2016) and production of LTO from shale formations has begun to decline.

Conclusions

The production of unconventional LTO is unlikely to make total world oil production grow in the future. Many projections of conventional oil production are also downward over the twenty-first century (e.g., Aleklett 2012; Capellan-Perez et al. 2016). Present data suggest that, due to both geological and economic factors, it is unlikely that world oil production (minus the recent surge in LTO production in the USA) will increase much higher than it is at present [75 mb/d (US EIA) or 85 mb/d (IEA)]. The increment in LTO production will not be long-lasting due to its rapid decline rate (geology) and high costs (economic). Thus, some of the highest oil consumption components of the IPCC scenarios (especially in RCP 8.5 and 6) (which reach 87–156 mb/d by 2075) are unlikely to occur.

In this analysis, we focused on the uncertainty in the contribution of oil consumption. We see that global oil production (US EIA) increased after 2011 by about 6 mb/d, but essentially all of that increase was due to US LTO production. The timing of the increase in US LTO began when the price of oil increased above $90 per barrel not due to innovative new technologies, which already existed. However, LTO is expensive produce and limited to a small number of "hot spots" in the USA. Even at that price, most E&P companies were losing money. In spite of the negative cash flow, investors were attracted to these low-grade but high-yielding investments, providing the resources for LTO production to continue to grow. Because of the extremely high first year decline rates, production required a drilling treadmill (new wells to replace the declining production) just to keep production constant. A price crash soon followed in early 2014, initially caused by the surge in US overproduction relative to demand, but then sustained by the slowdown in global economy that resulted.

Uncertainties about fossil fuel resource availability have not traditionally received much emphasis in climate change research. Global scenarios have been built on the assumption of abundant fossil fuel resources for the twenty-first century. However, current estimates are very uncertain (Capellan-Perez et al. 2016). The production of CO_2 from oil consumption in most of the IPCC CO_2 scenarios has probably been overestimated. There will have to be a significant change in the pattern of production that we have observed over the past 10+ years for world oil production to grow much higher than the present value of 75/85 mb/d (US EIA/IEA data). The higher versions of oil demand-driven consumption in the IPCC SRES and RCP scenarios will be difficult to reach. All RCPs are supposed to be equally plausible (Moss et al. 2010); yet, RCP8.5 gets used frequently as a BAU scenario. Maybe it is valid to emphasize the most extreme case, but this is unfortunate because, due to fossil fuel imitations, it may be the least plausible scenario (Capellan-Perez et al. 2016; Wang et al. 2016).

We need improved collaboration between IAM developers and researchers focusing on energy resource limitations. In this paper, we focused on oil, but similar conclusions apply to coal and natural gas as well. Climate models should be run with scenarios that consider resource limitation for fossil fuels (oil + coal + gas). Wang et al. (2016) illustrated how this would work by using a summary of CO_2 produced by world production of conventional fossil fuels in peer-reviewed literature as input into the MAGICC 6.3 climate change model to calculate expected atmospheric CO_2 levels. In their analysis, the median atmospheric CO_2 concentration and global-mean surface temperature increase were about 610 ppm and 2.6 °C, respectively, by 2100.

Another example was the study by Capellan-Perez et al. (2016), who incorporated the latest references with revised estimates of fossil fuel resources (ultimate recoverable resources, URR) as input to an IAM (The Global Change Assessment Model; GCAM 3.2) which includes the climate model MAGICC 5.3. Their results showed that the energy resource base for oil used by the IPCC was in the top of the range obtained with URR methodology. The two highest IPCC RCP emission pathways (RCP6 and RCP8.5) have low probabilities of being achieved of 42 and 12%, respectively. This is likely due to depletion of fossil fuels during the second half of the twenty-first century. However, the probability of temperature exceeding 2 °C by 2100 remains very high (88%). Climate change is still a serious threat, but it is possible that the IPCC has overestimated the upper-bound of possible climate change.

World political leaders agreed in Copenhagen (COP15, 2009) to keep the temperature increase below 2 °C (or even 1.5 °C)—this was re-affirmed in Paris (COP21, 2015). McGlade and Ekins (2015) estimated how much reserves will have to be left "in the ground" to meet these goals. When the goal of 2 °C is pursued, the majority of fossil fuel reserves (perhaps as much as 80% according to the IEA) have to stay underground. That may occur, but it remains to be seen how much compliance here will be for the COP agreements. There is also the uncertainty of what "proven reserves" actually are, as they are not proven by anyone, but based on unverified reports by the participating countries. If the price crash in 2014 resulted from demand destruction due to the high price of oil, then a case can be made that oil will be left in the ground, not because of political agreements, but because it is too expensive to produce.

There are other implications for society if less oil is available, than commonly thought, for climate change. We like to think that global economic growth was driven by ingenuity, knowhow, and technology, but there is the real possibility that it happened because we had the good fortune to discover an energy dense, versatile, inexpensive, and easily transportable resource (oil). If increases in oil production do not materialize, plans need to be developed for how to deal with the transition to a lower fossil fuel energy future. The timing required for this transition remains an essential uncertainty.

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