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Emissions Scenarios in the Face of Fossil-Fuel Peaking

Robert J. Brecha
University of Dayton, rbrecha1@udayton.edu

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Physics Department and Electro-optics Program, University of Dayton, Dayton, OH 45469-2314

Abstract

Emissions scenarios used by the Intergovernmental Panel on Climate Change (IPCC) are based on detailed energy system models in which demographics, technology and economics are used to generate projections of future world energy consumption, and therefore, of greenhouse gas emissions. We propose in this paper that it is useful to look at a qualitative model of the energy system, backed by data from short- and medium-term trends, to gain a sense of carbon emissions bounds. Here we look at what may be considered a lower bound for 21st century emissions given two assumptions: first, that extractable fossil-fuel resources follow the trends assumed by "peak oil" adherents, and second, that no climate mitigation policies are put in place to limit emissions. If resources, and more importantly, extraction rates, of fossil fuels are more limited than posited in full energy-system models, a supply-driven emissions scenario results; however, we show that even in this "peak fossil fuel" limit, carbon emissions are high enough to surpass 550ppm or 2°C climate protection guardrails. Some indicators are presented that the scenario presented here should not be disregarded, and comparisons are made to the outputs of emissions scenarios used for the IPCC reports.

Key words: IPCC, emission scenario, peak oil

1 Introduction

Since 1990 the Intergovernmental Panel on Climate Change (IPCC) has been carrying out reviews of scientific literature with the aim of periodically updating and gathering in one report the current state of knowledge of the global climate system. Six scenario groups, as described in the Special Report on

Email address: brecha@udayton.edu (Robert J. Brecha).

Emissions Scenarios (SRES) [1], are used to generate inputs to climate models, which in turn deliver projections for global average temperature or sea-level change for a wide range of potential future greenhouse gas (GHG) emissions. A key point is that the scenarios assume a large fossil-fuel resource base, and no fundamental limits to establishing a rate of production that is sufficient to support the economic development, population growth, and technological change assumed as inputs to each scenario. Energy costs are an integral part of the feedback loop between "social system" scenarios and greenhouse gas emissions in that increasing demand of a finite resource may lead to prices high enough to limit consumption, and therefore emissions.

The goal of this paper is to present a simplified limiting case supply-driven scenario, using current qualitative indicators of increasing fossil-fuel scarcity. Here we take an increasing difficulty of extraction of fossil fuels to be plausible, and use that input to determine the resulting GHG emissions. Economic effects in this schematic model will be essentially neglected, although we provide some evidence for the view that this may not be a bad first approximation. In effect we will argue that the size of the total resource base and the relationship between quantity and cost, as discussed by Rogner [2], may be optimistic with regard to future fossil-fuel availability. One way to view the present work is as a complementary scenario to that investigated by Bala *et al.* [3], in which all of the resources cited by Rogner are consumed, reaching a peak of emissions at 30 GtC/year early in the 22nd century. In that case, atmospheric CO_2 concentrations will exceed 1400 ppmv and global average temperatures increase by 8°C by the 23rd century.

Another contribution of the current work is to look at the arguments for "peak oil", or "peak fossil fuels" in general, but to consider some of the economic arguments that might be used to reject or support the relevance of claims that limits to the geologic world supply of cheap fossil fuels could be the actual limiting factor in greenhouse gas emissions scenarios.

2 Scarcity or Abundance?

Given that consumption of petroleum represents 35% of world primary energy use, with natural gas and coal making up 24% and 28%, respectively, it is an understatement to say that the world economy depends critically on these non-renewable resources. The default position for some governmental agencies, such as the U.S. Energy Information Administration, appears to be that the fossil-fuel resource base is large enough that economic considerations are of primary importance. That is, one can make projections of demographic and population trends, along with assumptions about how technology and energy efficiency will develop, and the resources will be present to meet the resulting demand. Thus, according to this view, there will be no fundamental, or geological, supply-side restriction for the foreseeable future, but at most potential demand-driven bottlenecks. One indication of this approach is that the EIA's annual International Energy Outlook has been consistently very optimistic about future petroleum production levels, even under low-price scenarios, whereas prices in the past few years far higher than even their high-price scenario have not resulted in increasing production in areas such as the North Sea, the U.S. or Mexico.

Beyond the uncertain estimates of the total available fossil-fuel resource base, due to either geological or political obstacles, the question of plausible rates of extraction is crucial when constructing scenarios for CO_2 emissions. There are two different ways in which the time variable is important, which might be characterized as geological and economic factors. The latter becomes important when considering the speed with which capital investments in the relevant fossil-fuel industries can be made, and will necessarily involve a component that relates to expected profits that can be made in the industry under projected demand scenarios. The geological time factor is related to another important concept, that of energy return on energy invested (EROEI); essentially, as petroleum (and/or natural gas and/or coal) becomes more difficult to extract, the rate of extraction may very well slow. In any case, for deep water oil, or even more noticeably, for non-conventional oil extracted from tar sands or shale, a significant fraction of the energy gained from the drilling or mining process must be "re-invested" in extracting the next unit of energy.

Although there is an inherent uncertainty present in all current estimates of oil, natural gas and coal reserves, over a time span of approximately three decades into the future there can be a fair sense of the general outlines of the energy system, simply because the fossil-fuel industries are making plans for that time frame. In addition, there are historical trends that can be evaluated for relevance in making projections about future oil, gas and coal production. We begin with a review of arguments for "peak oil" production in the near future, and consider the potential for alternatives to conventional oil.

3 Peak Oil

Since oil, natural gas and coal are finite natural resources, it is clear that at some point in time, production will reach a maximum and begin to decline. Again, there are essentially two different arguments as to why this might happen. The "geological" argument postulates simply that the finite amount of fossil fuel in the ground means that once we start extraction, rates will increase initially, level out once the easiest reserves have been extracted, and decrease as extraction becomes more and more difficult, until the total extractable resource is consumed. An "economic" argument for a peak in oil production is that of efficient substitution. As extraction costs increase once the easily obtained reserves are gone, market forces will create favorable conditions for a transition, and an alternative source of energy will be found. Of course, there is some amount of interaction between these two approaches to considering "peak oil."

In the case of oil production in the United States, in 1956 a petroleum geologist at Shell Oil Co., M. King Hubbert, projected that production of oil in the U.S. would reach a peak around 1970 and begin an inexorable decline thereafter. Hubbert based his prediction on a version of the "geological" argument given above, along with a simple mathematical model, and his own knowledge that discoveries of oil in the lower 48 states had been diminishing since the 1930s. As shown in Fig. 1a, oil production did reach a maximum in 1970. Furthermore, Hubbert's prediction was made before the discovery and beginning of production of oil in Alaska or in the Gulf of Mexico. In spite of these additional discoveries and the high oil prices in the late-1970s and early 1980s, production did not significantly change its downward path after the peak-production year. In Fig. 1a a smooth symmetric curve (to be described below) has been fit to the actual production data as representative of a mathematical description of resource production.

There are many different sources of oil (*e.g.* conventional on-shore drilling, off-shore deep-water drilling, tar sands, etc.) and different authors use more or less strict definitions of which oil types "count". In general, from "oil" we want to obtain liquid transportation fuel; once the initial raw material has been transformed into something that appears at a filling station, the provenance is not important. From that point of view (essentially an economic one) all oils are equivalent. Another very basic point to recall is that all of the fossil fuels are finite, and therefore will demonstrate "peaking" behavior; the relevant question is simply when that maximum will occur and how high the maximum rate of production will be.

Hubbert wrote many articles over the years, including a later review paper [4] in which he explained some of the numerical methodology he used in arriving at his predictions for peak oil production in the US, and for the possibility of peak oil production in the world at some point in the future. One of the mathematical models he used was to consider oil production as an example of the Verhulst or logistic curve. The logistic equation is given by

$$\frac{dQ}{dt} = bQ\left(1 - \frac{Q}{Q_\infty}\right) \tag{1}$$

where Q_∞ is the ultimately recoverable amount of oil (URR), Q is the cumulative production of oil, and $\frac{dQ}{dt}$ is the rate of extraction. The initial (exponential) rate of growth of reserve production is described by the constant b. Physically,

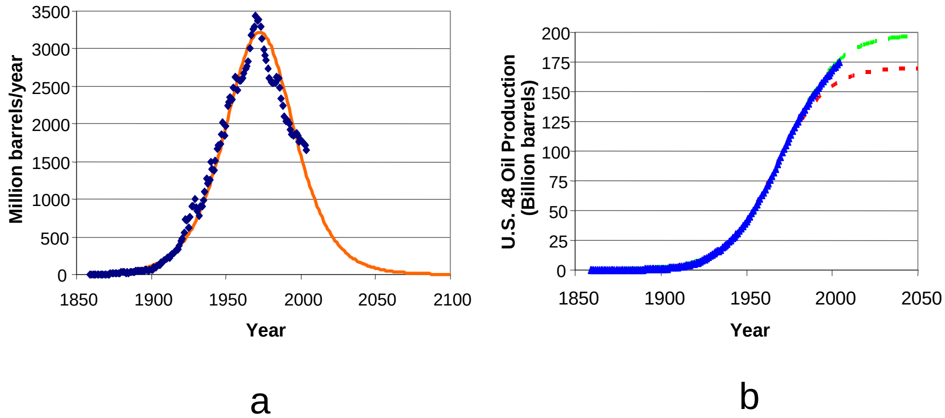


Fig. 1. Oil production and logistic function fit, a) in millions of barrels per year, and b) cumulative production, both as a function of time. Data are from the U.S. EIA [5]; the logistic curve has parameters corresponding to the initial production rate increase of 7% per year. The data shown here represent oil from the continental U.S., but includes no natural gas liquids or nonconventional oil from other processes.

the logistic equation is given the interpretation that the rate of production of a resource will initially increase exponentially, the ultimate limit to the resource being at first unimportant. As the cumulative production becomes a significant fraction of the ultimate reserve, extraction becomes more difficult, and the rate of extraction decreases. Since there is an ultimate limit to the amount of oil in the ground, at some point in time the rate of production will go to zero. The solution to the Verhulst equation is given by

$$Q(t) = \frac{Q_\infty}{1 + \left(\frac{Q_\infty - Q(0)}{Q(0)}\right) e^{-bt}} = \frac{Q_\infty}{1 + ae^{-bt}} \qquad (2)$$

There are three undetermined constants that can be found by comparison with actual data; in addition to b and Q_∞, the initial condition parameter a essentially adjusts the shape of the logistic curve. In reality, the actual oil production curve would not necessarily be expected to follow exactly a simple mathematical function, especially because economic and political factors in the 1970s and 1980s led to a noticeable readjustment to trends in world oil production. In Fig. 1b are shown the data for cumulative oil production in the U.S. along with two logistic curves. The lower curve corresponds to parameters found by Hubbert [4] ($Q_\infty = 170$ Gb, $b = 0.069$, $a = 1500$), while the upper curve is a fit using additional data for the past twenty years since Hubbert's paper ($Q_\infty = 200$, $b = 0.065$, $a = 1450$). Hubbert predicted an ultimately recoverable reserve of about 170 Gb for the U.S. lower 48; it now appears that the trend will lead to an amount closer to 200 Gb. In fact, in his original 1956 prediction of U.S. peak oil production, Hubbert simply estimated that the URR would be between 150 and 200 Gb. It should be noted that for at least a decade after Hubbert's prediction, the United States Geological Survey (USGS) was positing a recoverable reserve in the U.S. of approximately 600 Gb [6]. Hubbert did not include the Alaskan North Slope or consider off-shore deep-water oil in his estimates. On the one hand, an argument against the concept of peak oil is that we will *always* find another source of oil or replacement energy when the economic and technological conditions are ripe; on the other hand, those new sources of oil did not change the fact of a peak in U.S. production in 1970.

A second point to notice here is that in the early, exponential growth stages of resource production, it is very difficult to determine the final trajectory of the production curve based on the logistic (or any other) model. It is only when the limiting factors become important that the two curves shown in Fig. 1b separate.

The concept of using the logistic curve can be extended to the more uncertain projection of total world oil production. By doing a non-linear least-squares fit to cumulative production data, the extent to which oil production is following the resource-limited exponential growth path represented by the logistic equation can perhaps be determined. In fact, the best fit (as measured by the χ^2 value) to the production data is found to be given by the parameters $Q_\infty = 1440$ Gbbl, $b = 0.07$ and $a = 12,800$. This result for the URR is significantly lower than typical estimates. For example, using the proven reserves as reported in the BP Annual Review of World Energy [7], one arrives at a URR of approximately 2000 Gb; taking the results of the USGS estimate from 1998 of current proven reserves and possible reserves plus new discoveries [8], [9], the URR would be about 3000 Gb.

If we constrain the URR to either 2000 Gbbl or 3000 Gbbl in our least-squares routine, the overall fit to the data is still satisfactory, as shown in Fig. 2. The exercise shows again the difficulty in making concrete predictions using the results of curve-fitting techniques to under-parameterized data. Near or before the inflection point (equivalent to the peak in yearly production) it is possible

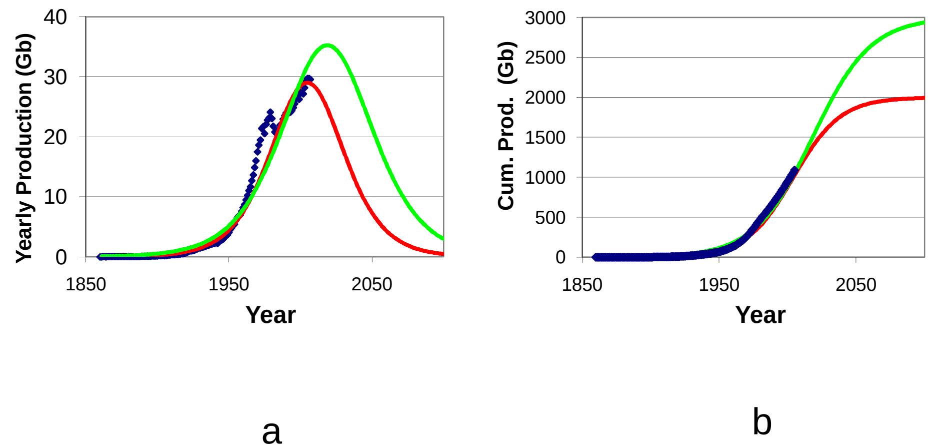


Fig. 2. World cumulative and yearly oil production and the logistic model. Data are from the U.S. EIA [5]. Parameters for the logistic curves are (as defined in the text) the same for the curves in a) and b). In each case a non-linear least-squares fit was made to world oil production data, with the ultimately recoverable reserve (URR) held fixed at $Q_\infty = 2000$ Gbbl (lower curve) and $Q_\infty = 3000$ Gbbl(upper curve). The other parameters from the fit to actual production data are $b = 0.058$ and $a = 4300$, and $b = 0.047$, $a = 1700$, for $Q_\infty = 2000$ and 3000 Gbbl, respectively. The actual production data shown for years until 2007 represent oil, as well as natural gas liquids and oil from non-conventional sources.

to find different parameters that seem to fit the data well. Thus, the different estimates for URR do not give definitive information about potential scarcity. However, both of these scenarios lead to a peak in world oil production within ten to twenty years.

Up to this point the focus of this work has been on determining the size of the petroleum, or more broadly, the liquid fuels, resource. A key point to bear in mind is that having the commodity in the ground may not be equivalent to being able to extract it at the desired rate. In fact, it is this possible limitation that is of crucial importance to the current discussion, and will be of particular significance over the next twenty to thirty years at a minimum.

To address the issue of extraction rates vs. resource potential, we consider industry and other published estimates of the near- to mid-term capacities for production of non-conventional oil from tar sands, shale oil, coal-to-liquids production and biofuels. Given the long lead-times necessary for starting and increasing a new energy industry, it is fairly safe to say that the liquid fuels that will make the most impact as possible substitutes for conventional petroleum are those that currently make at least some contribution.

Reynolds [10] has very nicely treated a point relevant to non-conventional resources that will be further considered in Section 5 below. A sectoral switch from high-quality to low-quality fuels (as measured by net energy density, for example), because of rising price of the former, carries with it an entropy penalty. Put simply, the lower quality fuel necessarily needs a significant quantity of higher-quality input feedstock, and thus the economic viability of the lower-quality resource is called into question in the long term. As the price of oil and natural gas rises, so to will the production and exploration costs for the non-conventional resources. This is not to say that none of the larger non-conventional resource is economically recoverable, but the substitution involves complicated dynamical interactions.

3.1 Tar Sands

Alberta's tar sands have received a great deal of attention as a large new resource for petroleum extraction and liquid fuel production. As of 2003 175 Gb of reserves were added to Canada's officially reported totals, all from tar sands [7]. Estimated resources in place are roughly ten times this amount, which potentially makes Canada the biggest future source of petroleum products in the world. Even the officially declared reserves of 175 Gb are second only to those of Saudi Arabia. In a recent paper, Söderbergh, *et al.* [11] analyze projections for production from tar sands over the next forty-five years. While acknowledging the presence of large reserves and an even larger resource base, the authors of Ref. [11] conclude that, "A short-term crash program from the Canadian oil sands industry achieves about 3.6 MMbd by 2018. A long-term Crash program results in a production of approximately 5 MMbd by 2030." The Canadian Association of Petroleum Producers has issued a recent report [12] with a slightly updated estimate for production in 2020 of 4.0 MMbd, a broadly similar conclusion to that of Söderbergh, *et al.*

Current tar sand oil production is approximately 1 MMbd, as compared to a world total liquid fuel production of slightly less than 85 MMbd. According to the EIA International Energy Outlook, world liquid fuel consumption is projected to be 104 MMbd in 2020 and 118 MMbd in 2030 [14]. Thus, as a percentage of world production, tar sands will certainly contribute a growing share, rising from 1% currently to 4% in 25 years. However, as pointed out by Söderbergh, *et al.*, a comparison between these estimates and projections for the future continuing decline in production of North Sea oil shows that the two taken together essentially balance one another, leaving no net gain in liquid fuel for world consumption [11]. In fact, given the relatively poor net energy gain for synthetic crude oil derived from tar sands, there will certainly be *less* net energy with respect to today's production.

3.2 Shale Oil

Another large potential resource for liquid fuel production exists in the western United States in the form of shale oil. As is the case with tar sands, although the size of the potential resource in place is believed to be extremely large, the economic viability of producing large amounts of oil from shale is not as clear. Shale oil is produced from solid bitumen trapped in sedimentary rock, which is then heated so that the resulting liquid can be captured. Heating the rock essentially completes the unfinished geologic processes begun millions of years ago. According to a report issued by the RAND Corporation under contract with the National Energy Technology Laboratory of the U.S. Department of Energy, the size of the potentially recoverable resource is between 500 billion barrels and 1.1 trillion barrels, thereby dwarfing all estimates of conventional oil prospects [15].

In spite of the fact that this resource has been known for decades, and was even seriously pursued during the 1970s, the actual feasibility of industrial-scale extraction is not yet clear. According to the RAND report, in an optimistic case "at least 12 and possibly more years will elapse before oil shale development will reach the production growth phase. Under high growth assumptions, an oil shale production level of 1 million barrels per day is probably more than 20 years in the future, and 3 million barrels per day is probably more than 30 years into the future." [15] Thus, although the resource base for shale oil production is even larger than that for tar sands, rates of extraction are more uncertain, and therefore the ability of this resource to make up for conventional oil production declines when they occur, is questionable.

3.3 Coal-to-Liquids (CTL)

Of current interest, both in the United States and in China, is the potential for converting a part of those countries' domestic coal reserves into liquid fuels. Given relatively large coal reserves (more on this below), and the fact that the Fischer-Tropsch process for obtaining fuel from coal is well-understood [16], it would seem that CTL would be a natural choice as a backstop liquid fuel technology when oil products become more expensive and scarce. At present, the only significant production of liquid fuel from coal is in South Africa, at 170,000 bpd [17]. Chinese companies, supported by government subsidies, are making large investments in CTL plants with the aim of increasing production capacity to approximately 770,000 bpd by 2020 [18]. In the U.S., a first commercial CTL plant is to begin operation by 2010, producing slightly more than 1000 bpd; proposals for federal subsidies to encourage industry investment in capital-intensive CTL projects have thus far not succeeded.

Overall, and in spite of relatively large coal reserves and the fact that production of liquid fuels from coal likely has a significantly better energy return ratio than either tar sands or shale oil, plans for near-future expansion of this energy sector look very weak, and therefore unlikely to supply a noticeable fraction of world oil demand. In the most recent edition of the International Energy Outlook, the EIA projects, in a baseline scenario, production of approximately 2.5 MMbpd of coal-to-liquids fuel by 2030[14].

3.4 Biofuels

Biofuels (chiefly biodiesel, for example from rapeseed, and ethanol from sugar cane and corn) are already playing an increasingly important role in world liquid fuel supplies. The United States currently produces about 6.5 billion gallons of ethanol [19] from corn per year (equivalent in volume to 400,000 barrels/day (bpd)), with low net energy gain [20]. Congress has mandated a production increase to 520,000 bpd by 2012. Brazil currently produces 270,000 bpd of ethanol from sugarcane, and predictions are for an increase to 442,000 bpd by 2010 [21]. (Note that one barrel of ethanol has only two-thirds the energy content of a barrel of oil.) Germany produced 36,000 bpd of biofuels, mostly biodiesel, in 2004 [7] and plans to steadily increase production to roughly three times that level by 2010. These three countries make up the bulk of biofuel production in the world, giving roughly a 10^6 bpd production in five years' time. While this represents a significant amount of liquid fuel production, there are serious questions as to the sustainability in growth for these fuels. For example, it is estimated that ethanol plants in operation or being built will require inputs equal to at least one-third of the projected 2008 corn harvest [22], and that to satisfy only 6% of U.S. liquid fuel demand.

Cellulosic ethanol has the *potential* to be a fuel that can be produced economically and with greater energy-efficiency than corn ethanol. There are many hurdles to overcome before it becomes viable economically, however [23]. For the purposes of this work, cellulosic ethanol will be ignored, partly because of the large uncertainties as to the fuel itself, at least in the near term, partly because production of cellulosic ethanol would represent a much smaller source of greenhouse gas emissions than conventional liquid fossil fuels, and partly because the switch to biofuels is in some sense a sign of the very premise of this paper, *i.e.* that cheap fossil fuels are becoming scarce.

There may be benefits to be gained in terms of greenhouse gas emissions reductions by carefully switching to increased biofuels production, but climate change considerations are certainly not the current driving force in the United States. In Europe, the demand for biodiesel has had the unintended consequence of displacing greenhouse gas emissions from European automobile tailpipes to decreased carbon uptake capacity from lands in Malaysia being cleared to produce biofuels, with little to no net benefit.

3.5 Gas-to-Liquids (GTL)

Another potential source of liquid fuels to substitute for declining petroleum in a peak oil scenario is to use the Fischer-Tropsch process to convert natural gas to liquid fuel. Currently, the U.S. EIA projects very modest growth in GTL production by 2030 due to the high capital costs of these projects (similar in magnitude to CTL) and because of the sensitivity of costs per barrel of oil equivalent to the price of natural gas [14]. Under the EIA scenario of high oil prices, and therefore high incentive to find a substitute for petroleum, U.S. production is projected at 200,000 bpd by 2030, and total world production under the same conditions may reach 1.5 MMbd, mostly from Qatar.

Two points that will have an impact on the viability of future GTL projects are the supply of natural gas and the high capital costs of all energy projects, both of which will be discussed below. While a country such as Qatar may have large natural gas supplies well into the future, there will be strong competition for different uses of natural gas going forward, given that North America is in production decline, and will likely soon be joined by Europe in that regard. High energy costs and energy demand will also likely continue to drive up the cost of starting large new projects such as GTL plants, and therefore present something of a moving target for profitability. Therefore, even the numbers presented here for future GTL production might be optimistic.

Current total production of these alternative fuels is about 1.7 MMbd or 0.6 Gb/year, with most of that being from Canadian tar sand production. By 2030 production taken as the sum of all the above non-conventional sources is projected to be slightly less than 6 Gb/year, growing to 7.7 Gb/year in 2050. The EIA makes its projections only to 2030; the scenario mapped out here corresponds to about 25% more alternative fuels supply than that of the EIA "high oil price" scenario, *i.e.* the totals presented here might be considered optimistic even compared to the EIA. For both supply and economic reasons to be discussed below, all of these alternatives might become less attractive than they currently appear.

The net result from the increase in production of alternative liquid fuels in the case of the smaller URR of 2000 Gb for conventional oil is to offset a decline in production of conventional oil currently and for about a decade subsequently, but after 2020 total liquids production declines from present levels. Two points should be noted here. First, in this case there is no further growth in total liquids supply into the future, and second, over the past three years we have seen this scenario developing, with conventional oil production decreasing slightly and non-conventional oil barely enough to keep total production constant. In the larger URR case of 3000 Gb, total liquids production increases for another decade before reaching a plateau for another decade at about 39 Gb/year (110 MMbd), followed by a decline. Due to the fitting of the logistic curve to historical production, and with the constraint of 3000 Gb URR, as discussed in Sec. 3, this latter scenario indicates a level of production that is currently 10% higher than what is currently observed.

As mentioned above, relevant to all of the above alternatives is the net energy penalty that is paid when making a switch from high-quality, easily extracted fuels, to lower quality fuels. It is clear that a qualitative difference exists between conventional petroleum and fuels derived from tar sands and shale. As the price of oil and natural gas rises, so too will the production costs for the non-conventional resources, a dynamic already being seen. Furthermore, the relatively poor net energy gain for non-conventional liquid fuels implies that there will be a competition for fossil fuel energy among various sectors. For example, as coal and natural gas are in higher demand to be either turned directly into liquid fuels, or indirectly used to generate electricity for industrial processing of non-conventional oil, those quantities of fossil fuels will not be available for the rest of the economy.

There are other natural resource constraints that should be considered when looking at the recovery of unconventional petroleum and production of crops for biofuels. For example: "An operation producing 100,000 barrels per day requires approximately 1.2 GW of dedicated electric generating capacity." [15] The potential greenhouse gas emission consequences of needing ten additional large electrical power plants for each million barrels per day of production are enormous, given that the most readily-available fuel for electricity generation might be coal. It is also estimated [15] that for each barrel of shale oil produced, approximately three barrels of water are required, an important issue that is beyond the scope of the present work. Likewise, in the case of tar sands, approximately four barrels of water are needed for each barrel of synthetic crude oil produced [11], while CTL production in China is estimated to require nine barrels of water per barrel of oil produced [24]. Corn is one of the most intensively irrigated crops in the U.S.; thus all of the potential substitutes for conventional petroleum threaten to place an increased burden on already fragile water supplies.

Finally, we close out this section by noting a current trend that bears on the discussion of peak oil and that will be watched with great interest in the coming years. The importance of the link between petroleum consumption and economic activity can be seen by examining time series data for world GDP growth (`http://www.ers.usda.gov/Data/Macroeconomics/#Historical MacroTables`) and for petroleum consumption (http://www.eia.doe.gov/ipm/). Since at least 1970, decreases petroleum consumption or in the growth rate of consumption have always correlated with decreases in the growth rate of world GDP. For the first time ever, over the past two to three years petroleum production has been flat (zero growth) whereas economic growth has remained at a fairly robust rate of 3.5%.

4 Natural Gas and Coal Reserves

Natural gas and coal are often seen as the obvious partial substitutes for petroleum, the former a cleaner-burning alternative and potentially available for liquid-fuel production, while the latter represents the largest conventional fossil-fuel resource, and as we have discussed, can also be turned into liquid fuel as well. As finite resources, however, it is clear that both natural gas and coal will show a similar behavior to oil in terms of an eventual peaking in production. The crucial projection is then the date of peak production. We discuss in this Section some of the data leading to a plausible scenario in which both natural gas and coal reach production peaks before the middle of this century.

Natural gas production in the U.S. has been flat or slightly declining for two decades. In spite of this, the Energy Information Administration yearly predicts future increases in discoveries, reserve additions and production for twenty-five years into the future [25]. EIA data also show that, due to steadily higher prices over the last few years, drilling activity has increased to record levels. In addition, technological progress has borne fruit in that the percentage of successful wells drilled has also increased, to nearly 90%. These issues will be revisited briefly below when economic issues are addressed explicitly.

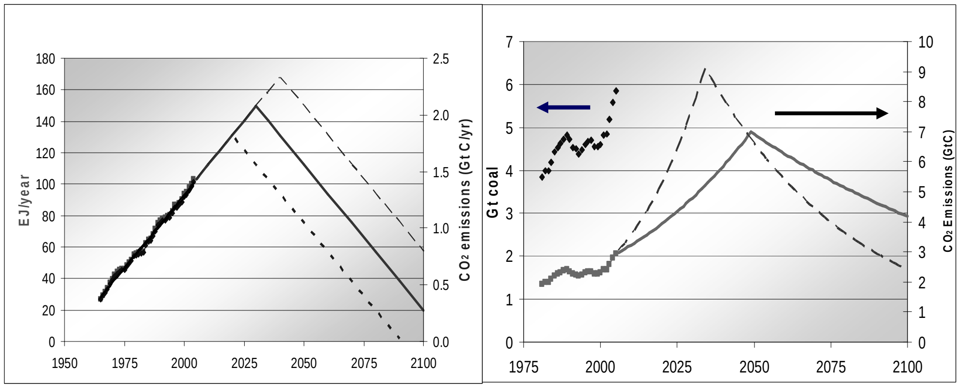
The U.S. is not alone in struggling to maintain production of natural gas. Canada has had virtually no growth in production for the past six years, and as was mentioned above, will be requiring significantly more natural gas in the future as an input to the tar sands production process. The tight connection between unconventional oil production and the availability of other fossil fuels demonstrates all too well one of the main contentions of this paper, namely, that a simple switching from conventional resources to nonconventional resources may not be accomplished as easily as many would like to believe.

To complete the tour of North America, Mexico produces only 1-2% of world natural gas supplies, and given that natural gas is not easily transported except through pipelines, and to a smaller extent, as liquified natural gas (LNG), large reserves in distant countries will likely not change the situation in North America greatly.

For the broader perspective, according to the data in the BP Statistical Review of World Energy [7] world natural gas reserves are slightly, but steadily, increasing over time, in spite of increasing production. Unfortunately reserve growth is not necessarily an indicator of long-term production growth. Officially reported reserves can grow up to the point of peak production (see, for example of oil and natural gas production in the United Kingdom, Ref. [7]). In addition, in recent years the growth rate of reserves has been decreasing, and is now significantly less than the growth rate of consumption, 0.6% over five years as opposed to 3% over the same period, respectively. There can be many reasons given for a disparity between additions to reserves (through new discoveries or through reclassification) and production, including those of politics and economics. However, for the purposes of the projected scenario made in this paper, an assumption will be made that reserve additions will continue, but that consumption will catch up and surpass the ability of reserve replacements to be made.

Fig. 3a shows alternative scenarios for remaining recoverable reserves of natural gas, using data from Ref. [7] as a baseline, assuming the current stated world reserves of 180 tcm (6200 tcf) represents the remaining recoverable natural gas, an unlikely lower-bound case. Two further scenarios project remaining natural gas reserves of 50% and 100% greater than this baseline number, 270 tcm and 360 tcm. The emissions scenarios discussed below are based on these conjectured resource amounts. (An approximate conversion is 1 cf $\equiv$ 1000 Btu $\equiv$ 1 MJ.)

Coal represents an interesting case, as world reserves have been decreasing over time; according to various editions of the BP Statistical Review of World Energy and of the EIA Annual Energy Review, the rate of decrease in coal reserves for the past decade has been even faster than the rate of production, from stated reserves of 1038 billion metric tonnes (Gt) to 908 Gt. In the same time period, total production of coal has been 58.5 Gt. Both prices and demand for coal have also increased over the same period, with production shown in Fig. 3b. The reasons for restatements of coal reserves vary from one country to another; in many cases the driver appears to be simply an overly-optimistic original estimate of the resource base [27]. According to the Energy Watch group report, there are only two cases of a country upgrading its coal reserve



a b

Fig. 3. World natural gas and coal production and CO_2 emissions. a) Energy production from natural gas is shown in EJ/year for three different projections of total ultimate recoverable reserve (URR). The lower curve uses the Ref. [7] data, assuming no further additions. The two upper curves assume an URR of 50% more and of 100% than the most recent reserves data. b) Coal production, with the resultant CO_2 emissions are shown for two different future "peak" scenarios. The assumption is that the world coal reserves are 1000 Gt, with different production growth rates of 4%/year and 6%/year assumed. After the peak, the decline rate slows to one-half the growth rate in each case.

numbers, and many cases in which reserves have been dramatically revised downwards, and this in spite of generally rising prices for coal in the recent past [27].

Reserves for coal (and other fossil fuels) are often misleadingly stated in terms of the reserves-to-production ratio (R/P), a practice that is particularly prevalent in discussions of coal reserves. Currently, world R/P = 147 years [7], while that for the U.S. is 234 years. Although at first glance reassuring, the point is, that consumption is *not* continuing at the current rate as assumed in calculating the R/P ratio. In fact, using BP data again, in 1993 the R/P ratio was 250 years, while from other data sources we find coal "lifetimes" for the

U.S. of 3800 years in 1939, and 1900 years in 1953 [26]. For the current world reserves, and assuming a modest growth rate in coal consumption of 3%/year (it is currently 5%/year worldwide), the lifetime of the coal reserves shrinks to only 60 years. Furthermore, that result assumes that coal will be mined at increasing rates until the reserves are depleted, at which point no further coal will be mined. Certainly there will be a "peak coal" phenomenon, as there have been peak oil and peak natural gas developments in various countries already. It is interesting to note that anthracite production in the U.S. has followed this pattern remarkably well [4], although it is a high-energy density, low sulfur (*i.e.* desirable) fuel [27].

Three recent reports have cast some doubts on the complacency with which the world is intending to rely upon the "immense" reserves of coal for future energy needs. First, the German Energy Watch Group [27] published a report in which they address several points related to the reporting of world coal reserves, among others that estimates of overall reserves around the world have generally been downgraded in recent years, and that in many countries the stated reserves numbers have not been updated at all for as much as two decades. Furthermore, in the country with the largest reported coal reserves, the United States, although coal mining tonnage has increased slightly in recent years, total energy supplied from coal mining has decreased slightly due to a switch to lower-energy-density (but also lower sulfur) sub-bituminous coal. Finally, also in the U.S., mining productivity (tons/miner/day) has been decreasing for several years, after decades of increase.

The second report that is of relevance is from the National Academy of Sciences [28]. It is easiest to quote an excerpt directly from that work, "... there is no question that sufficient minable coal is available to meet the nation's coal needs through 2030. Looking further into the future, there is probably sufficient coal to meet the nation's needs for more than 100 years at current production levels. However, it is not possible to confirm that there is a sufficient supply of coal for the next 250 years, as is often asserted." To be sure, the NAS does not conclude that the reserves are *not* present, but they do raise the question as to the reliability of the data upon which reserve estimates are based.

Finally, and viewing the coal question from another angle, the most recent reports by the IPCC, released in early 2007 [29], present clear evidence of climate change effects and make abundantly clear the severity of future changes without concerted action to reduce emissions of greenhouse gases. Thus, if short-term solutions to energy shortages from potential oil or natural gas peaking were to be compensated by increases in coal consumption for electricity and liquid fuels, the climate change problem would only be exacerbated.

For our demonstration supply-limited scenarios, we take the current reserves estimates of approximately 1000 Gt of coal as being substantially correct as an indicator of future supply. Different production growth rates (taken here to be 4%/year and 6%/year) lead to a projection for CO_2 emissions, as shown in Fig. 3b. After the peak the decline rate is assumed to be equal to one-half the growth rate in each case. The timing of peak coal production in this simplified scenario is determined by the combination of the growth and decline rates and the total assumed resource base. In either case, the peak in world coal production occurs before the middle of the century. This once again points to the misleading nature of thinking about fossil fuel resources in terms of the number of years remaining at current production rates.

Up to this point we have concentrated on "geological" issues concerning the production of fossil fuels, mentioning a few economic considerations only in passing. It is clear that economics plays an important role in any estimate of the world energy system. We now turn to a brief consideration of the energy economics literature, which provides some indication that it really is geology that fundamentally matters in the end.

5 Economic Issues

Oil is an easily traded and transported commodity, so one could make the argument that falling production in a given region such as the United States is simply a matter of economic decision-making on the part of the markets. If it is cheaper to produce oil elsewhere and import it to the U.S., then it makes no economic sense to go to greater efforts to raise production here. On the other hand, natural gas is not easily traded if an ocean lies between the supply and the demand. North America thus makes a fair test case for investigating the change in supply availability in the face of increases in demand and price.

Data from the EIA show that over the past five years, beginning in 2002, natural gas drilling activity, as measured by the number of exploratory and development wells drilled, has tripled [30]. From the same source, prices for natural gas have tripled from the roughly stable 1980s nominal price of approximately \$2.00/MMBtu. Looking at the EIA time-series data it is also clear that prices drive exploration and drilling activity; after a spike in price in 2000 - 2001, activity increased for a year, followed by a decline when prices retreated. More recently, higher prices and demand have been accompanied by increased drilling activity as well. The key point, however, is that U.S. production actually *decreased* slightly during the same time periods, and total reserves increased only very slightly. A very similar pattern exists for Canada, where demand for natural gas is increasing (primarily due to tar sands production needs?) and production is at best constant, although prices have been rising steadily for several years.

Natural gas production trends illustrate another facet of the arguments used to reassure consumers about the availability of fossil-fuel resources for the future, namely, that technology advances will inevitably lead to increased availability with time. Ref. [30] shows that over the past three decades successful drilling of exploratory wells for oil and natural gas have increased from roughly 25% to over 50%, reflecting technological improvements. The average number of feet drilled per well has increased with time as well, again associated with improved technology, but at the same time implying more expenditures for drilling. Finally, and counter to the previous examples of technology improvement, the productivity of natural gas well production (per well) has decreased by 25% over the past five years after having been roughly constant for the previous decade.

In another report, the EIA published a study of changing costs in U.S. domestic oil and gas operations over the past thirty years [31]. Data from this report, updated annually, show that changes in the costs of fossil fuels are strongly correlated with increases or decreases in the operating costs and the capital equipment costs in the industry. A simple regression model using the logarithm of capital costs as the dependent variable and the logarithm of oil price as the independent variable indicates that changes in the latter represents 80% of the variation in the former, and results in an estimated elasticity of 0.3. It is not surprising that capital costs in a highly mechanized industry should depend on fuel and (fuel-intensive) raw material costs. Somewhat more surprising is the degree to which operating costs are also dependent on fuel costs. However, it can be anticipated that moving toward non-conventional fossil fuel resources, with correspondingly higher energy inputs, will increase rather than decrease these couplings.

Looking more deeply at the interaction between materials and oil prices, current rapid economic growth in China and India, along with continued consumption from developed countries, helps drive up the costs of many raw materials. There has been a consistent in-phase relationship between oil and raw materials prices ovser the past three decades [32] . Since the interaction between oil price, oil demand, economic growth and raw materials prices is a feedback loop, it is difficult to attribute cause and effect directly. However, one way to look at this correlation is in terms of the famous wager made by Julian Simon and Paul Ehrlich [33]. Their bet was made at a (then) historical high-point for both oil and metal prices, and as both fell in tandem in the years following the 1980 bet, Ehrlich lost by a large margin. However, had the bet been made in 1970, or in any year after 1990, Ehrlich would have won, since oil price rises in those time periods were accompanied by increased metal prices.

All of the above data taken together seem to indicate that a) prices alone are not able to significantly drive changes in oil and natural gas discovery or production, and b) as the price of conventional fossil fuels increases, the cost of building additional infrastructure will tend to increase as well. With respect to the first point, technological advances do allow some additional recovery of the resource in place, but appear mainly to make up for the decline in production of the easily available reserves. As to the second point, it will not matter if price increases are due to an actual geologically-determined peak in production, or because of increasing demand running up against supply capacity; either way, creating a new energy sector in non-conventional fuels may only further the cost spiral. For some non-conventional fuel sources the price increases could conceivably conspire to keep large amounts of a given resource just out of reach of profitability. It remains to be seen if such an out-of-control feedback takes place, or if some significant change to previous patterns occurs in the future.

One way to explicitly treat economic incentives to increase the production of liquid fuels is to return to the logistic equation. A simple first approximation is that higher prices, and more generally, technological advances, will lead to the discovery and development of additional sources of energy. We can think of this as a continually growing "URR," even if the reserve in question consists of a mix of conventional and non-conventional reserves.

We can write the modified logistic equation as

$$\frac{dQ}{dt} = bQ\left(1 - \frac{Q}{Q_\infty\,(1+rt)}\right) \tag{3}$$

The rate of growth of the URR is given by r; data from BP [7] indicates that the URR, as determined from reserve and cumulative production data, is growing by about 2%/year. This equation can be solved numerically to find the time dependence of cumulative production; the derivative is then the yearly production.

In Fig. 4a we show the results for the modified logistic equation output as a plot of the cumulative production for fixed URR. The two curves are very nearly identical during the exponential growth phase of production, but separate later. For fixed reserves the cumulative production asymptotically reaches the URR (here 2000 Gb), whereas the continual growth logistic result has no finite asymptote. Fig. 4b shows the corresponding yearly production curves; even though the reserves are continually increasing, the production reaches a peak, then falls back to a constant level. Both plots are shown as a function of the number of years since the beginning of production. Parameters have been chosen such that the cumulative production curve for the first 140 years matches actual world oil production. It should be noted that even in this case for which the amount of oil to be produced is essentially infinite, there is a peak in production.

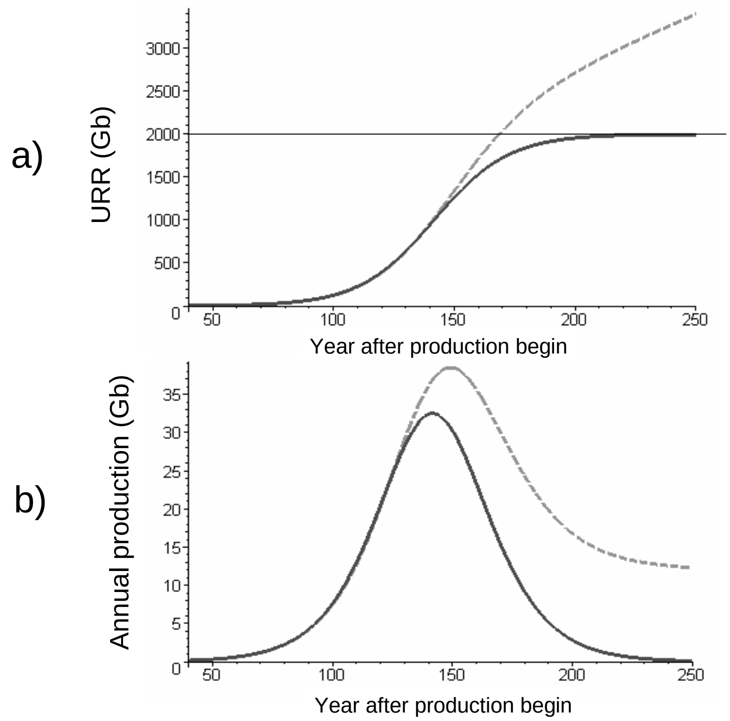


Fig. 4. Modification of the logistic equation to include the potential for continual growth of reserves. In a) are shown two curves, one (solid) for which the URR is fixed at 2000 Gb, the other (dashed) for which the URR grows by 2%/year, and therefore has an infinite limit. The corresponding yearly production rates are shown in b).

After the foregoing mostly qualitative survey, it will be useful to look more closely at results from the energy economics literature. There we find additional quantitative indications that tend toward the conclusion that oil supply is not strongly driven by prices, and furthermore, that demand is a very inelastic function of price. For example, Gowdy and Juliá [34] examine two mega-oilfields, one in the U.S. and one in the North Sea, and come to the conclusion that "technology temporarily increases the rates of production at the expense of more pronounced rates of depletion in later years." Reynolds [35] uses a non-time-series approach to look at supply elasticity and concludes, "that cumulative discovery explains approximately 70 per cent of the quadratic Hubbert curve for discovery over time for the US lower 48 states, whereas the price of oil is an inelastic factor ..." These two investigations certainly do not represent a conclusive argument concerning the economics of fossil fuel supplies. They do, however, support the point of this paper, which is to concentrate on one under-appreciated scenario, namely the possibility of fossil-fuel supply scarcity becoming a driving force in carbon dioxide emissions.

In an analysis of a more general point, Reynolds [36] analyzes a mineral-based economy in which the ultimate reserve of the commodity in question is not known *a priori*. The result of his modelling demonstrates that decreasing extraction and exploration costs, together with decreasing real prices, are not necessarily indicative of decreasing scarcity. At some point there can be a sharp up-turn in both costs and market prices as an inflection point is reached. Interestingly, the conclusion by Reynolds is very similar to what one finds based on the simple logistic equation model without any economic input, in that signals of an impending qualitative change in sectoral dynamics are very poorly predictable.

Another indicator of increasing scarcity of fossil-fuel resources in the near-term rather than the long-term is to compare assumptions for marginal extraction costs of carbon made by using the work of Rogner [2] or Nordhaus and Boyer [37] with actual data. As a general trend, the parameters used in the above-cited references for marginal extraction costs as a function of cumulated extraction, would indicate that those costs should begin increasing significantly for cumulative carbon extraction five to ten times current amounts. Yet, as was discussed above, current projections are for increasing demand for resources such as tar sands, shale oil and coal liquefaction within the next decade or two, at extraction costs several times higher than baseline costs for conventional oil. Inverting the logic of the marginal extraction argument leads to the implication that rapidly increasing costs are an indicator that production is at least beginning to approach a finite cumulative limit.

In Fig. 5 we show the marginal extraction costs as a function of cumulative extraction. The solid curve is based on assumptions from the above-cited works; the three boxes represent current estimates of the price of oil necessary for a source to be profitable, which is clearly related to marginal extraction costs. The boxes do not represent total amounts available of each resource. Rather, if one considers that over the past few years, tar sands projects (and North Sea oil projects) were working with costs of roughly \$25/barrel, and current world cumulative extraction of oil is roughly 140 Gtoe, then the curve should reflect that cost as being the current cost of the marginal barrel of oil; the height of the box expresses this point. The second box, reflects the marginal costs of coal-to-liquids production at current estimated costs of \$50/barrel, and projected to be viable within the next 5-10 years (20-50 Gtoe additional cumulative extraction) on a large scale. Finally, the third box is for shale oil with similar considerations, but at (currently estimated) \$75/barrel costs and large-scale production 20 years or more in the future, as discussed above. The key point of this graph is that the apparent marginal extraction cost curve, as represented by the boxes, is rising much more rapidly than projected just a decade ago.

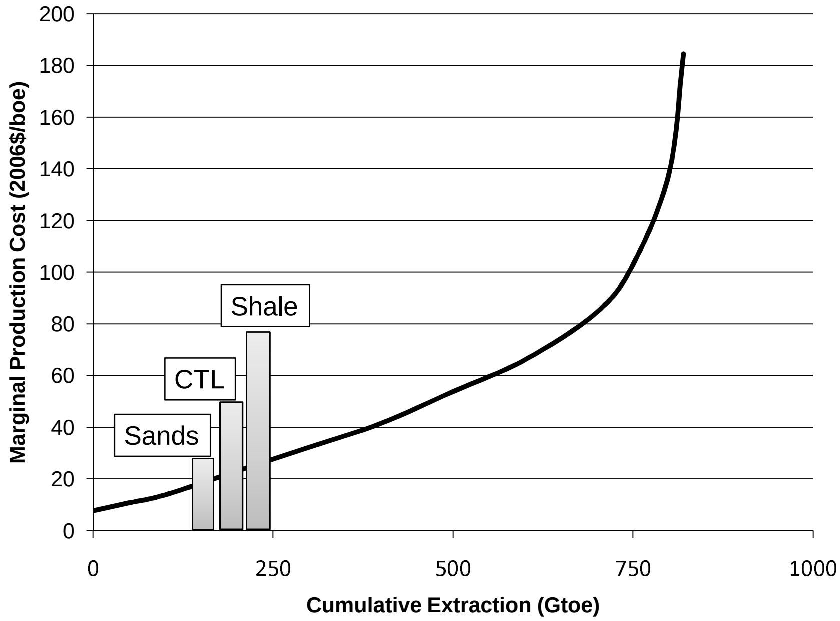


Fig. 5. A schematic marginal extraction costs curve. The solid line is based on estimates from Rogner. The boxes represent the fact that tar sands are currently the marginal production barrels, coal-to-liquids are estimated to soon be profitable, and planning is underway for shale oil production, each at costs much higher than those that have been typically estimated for the relevant stage of cumulative extraction.

6 Supply-Driven Emissions and SRES Scenarios

The foregoing discussion of fossil-fuel production can be summarized by choosing representative paths for each of the main fossil fuels and then calculating the resulting CO_2 emissions. The estimates are made as follows: For oil production, including the non-conventional petroleum such as tar sands and shale oil, two simple time-symmetric functions of production are chosen such that the URR is 2000Gb and 3000 Gb, roughly consonant with the BP current reserves and the USGS mean projection, respectively. The latter implies a remaining recoverable resource of about 2000 Gb, approximately twice that assumed by many of those currently concerned about "peak oil".

The remaining recoverable natural gas resource is assumed in the first scenario to be equal to the BP reserves estimate and in the second scenario to be 50% greater than that current estimate [7], with the latter implying continued discoveries and additions to current reserves. For coal, the remaining reserve is held fixed at 1000 Gt, but the two scenarios assume that consumption growth

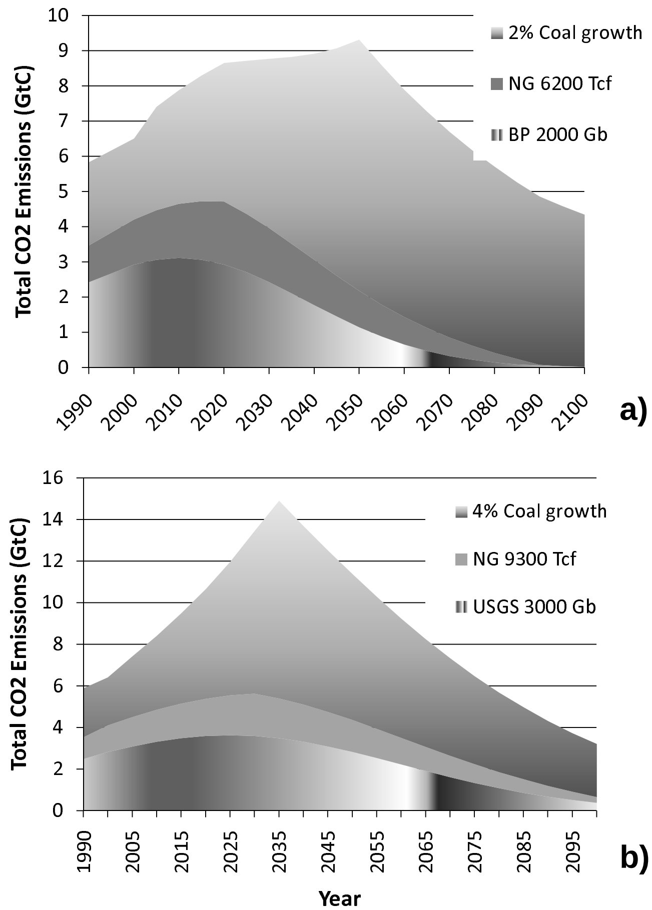


Fig. 6. Total CO_2 emissions plotted for the next century. a) Total oil URR of 2000 Gbbl (peak production 2010), total natural gas original resource 82×10^{15} tcf (peak production 2020), total coal resource originally in place, 1300 Gt (peak production 2050, after 2%/year growth). b) Total oil URR of 3000 Gbbl (peak production 2025), total natural gas original resource 108×10^{15} tcf and a peak production year of 2030, and a peak coal production in 2035 following growth of 4%/year to that point, using the same 1300 Gt original resource.

will be at 2%/year, with a decline after a peak of 1%/year, and at 4%/year, with 2% decline.

Fig. 6 shows the result for total CO_2 emissions in the two scenarios. An interesting point is that all three fossil-fuel sources reach a production peak within a span of two decades from about 2030 to 2050, with first oil, then natural gas, and finally coal experiencing maximum production.

Finally, how do the above scenarios compare to those reported in the IPCC SRES report [1]. In Figs. 7 and 8 a comparison is shown between representative scenarios in the A1, A2, B1 and B2 “storylines” [1], with the first two representing a stronger emphasis on economic growth and the last two weighted more toward environmental sustainability. Chosen for comparison here are the models AIM, MESSAGE and MiniCAM; the other three (ASF, MARIA and

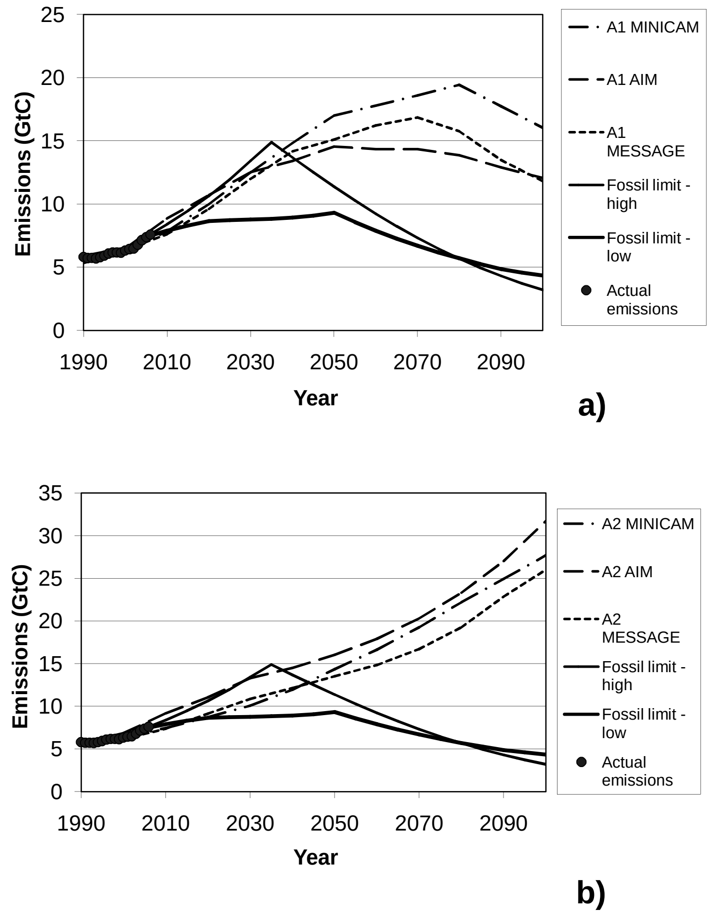


Fig. 7. Carbon emissions projected for the future using IPCC scenarios and models from three of six contributors to the Special Report on Emissions Scenarios (see text), along with the fossil-fuel-limited scenarios presented in this work (represented by a solid line). a) A1 storyline b) A2 storyline

IMAGE) models are not shown simply to preserve some clarity in the plots. It is not surprising that our resource-limited scenarios initially follow most closely the A1 scenarios from the IPCC, since these represent a world of rapid economic growth and little worry about environmental issues. The scenarios for fossil fuel peaking follow essentially the path discussed in Ref. [36], where markets have not been capable of delivering signals of impending scarcity, and thus little attempt is made to change the energy system.

Likewise, it is not surprising that the B1 scenario for the second half of the twenty-first century is similar to the fossil-fuel-limited case, although the driving factors are different. In the B1 scenario global cooperation and environmentally sustainable solutions to the world energy supply are postulated, thereby leading to a sharp decrease in consumption of fossil fuels. A post-peak limit on availability would lead to roughly the same, but now enforced, decrease in fossil fuel consumption.

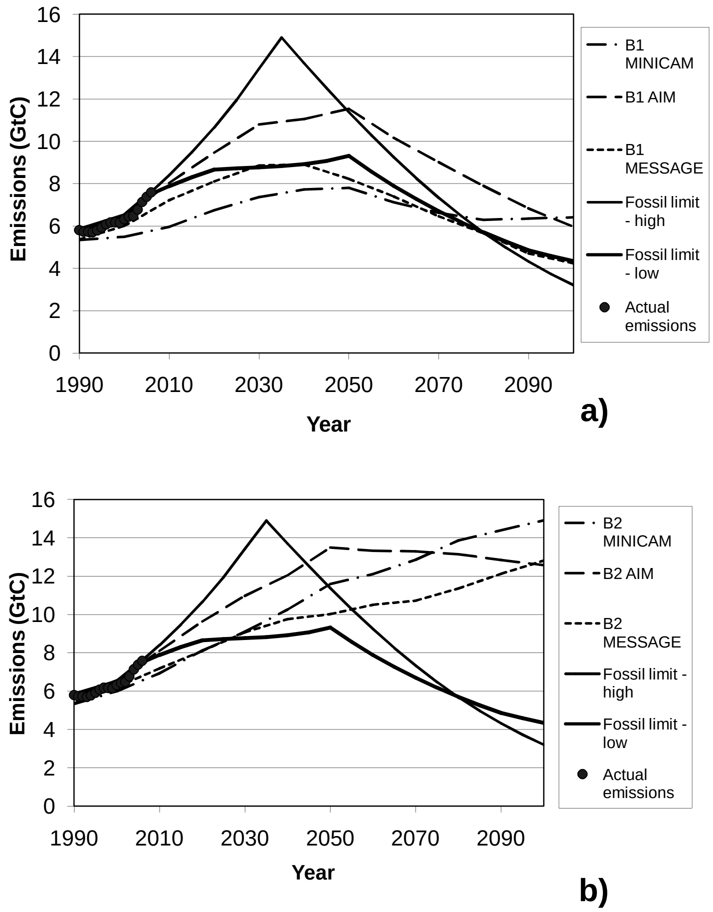


Fig. 8. Carbon emissions projected for the future using IPCC scenarios and models from three of six contributors to the Special Report on Emissions Scenarios (see text), along with the fossil-fuel-limited scenarios presented in this work (represented by a solid line). a) B1 storyline b) B2 storyline.

The emissions projection for a fossil-fuel limited world can be used as the input to a climate model, in this case MAGICC (Model for the Assessment of Greenhouse-gas Induced Climate Change) as distributed by the National Center for Atmospheric Research (NCAR) [38]. For each of the scenarios described above, the model output for CO_2 concentrations, temperature change from 1990, and for sea-level rise are shown in Figs. 9 and 10. During the first half of this century, carbon dioxide concentrations under both scenarios rise at roughly the same rate as in a business-as-usual (BAU) scenario selected for comparison purposes, as shown in Fig. 9a. Due to the peak in emissions around 2050, with a relatively slow rise before the peak, in the "low emissions" scenario, atmospheric CO_2 concentration reaches a maximum (at slightly above 500 ppmv), but not until the latter third of the century, and will begin to fall after that. The "low emissions " scenario thus falls into the class of those that limit changes in greenhouse gases to less than a doubling with respect to pre-industrial levels. The "high emissions" scenario, arrive at a maximum CO_2 concentration of 560 ppmv somewhat earlier, around 2075, and also begins to fall slowly towards the end of the 21st century. Thus, either in the case of a quick peak in oil and natural gas production, or a somewhat delayed peak, the resulting emissions will still result in going to the limit of the commonly-accepted bounds of "harmful interference" as marked by holding CO_2 concentrations at twice the pre-industrial level of 280 ppmv.

The corresponding temperature changes (with an assumed sensitivity of 3°C for a doubling of atmospheric CO_2) are shown in Fig. 9b. Little difference is seen between the fossil-fuel-limited scenarios and the BAU scenario until past mid-century, when the decrease in emissions in the "high emissions" scenario leads to a temperature increase of 2.5°C with respect to 1990, before very slowly levelling out. The uncertainty in temperature projections is approximately ±1°C by the end of the 21st century; shown on the plot is the uncertainty range from both scenarios. The "low emissions" scenario shows a temperature increase of 2.3°C by the end of this century, but is still increasing slowly at that time. The somewhat counter intuitive result that the tempearture is still rising at the end of the century in the low emissions scenario is due to the long "tail" of emissions in that scenario.

Finally, in Fig. 10 we show the projected sea-level rise for the business-as-usual and the two fossil-fuel-limited scenarios. It is sea-level rise that provides one of the best indicators of the tremendously long timescales over which current energy system policies will have their consequences. In all three scenarios there is a continuous increase in sea level that is not nearly in equilibrium by the end of the 22nd century. Furthermore, recent work by Rahmstorf [39] and by Hansen, *et al.* [40] provides evidence that projections from models such as MAGICC, but also from those used by the IPCC in its Fourth Assessment Report, may underestimate sea-level rise by a factor of two or more even by the end of this century.

As a general matter, one can imagine that a "peak oil," "peak natural gas" and/or "peak coal" scenario might be welcome from the point of view of climate change mitigation. There are several caveats, however. First and foremost is the fact that a surprise shortage of energy carries with it serious economic consequences, as seen in the late 1970s and early 1980s, which in turn complicate the dynamics of energy use scenarios. A rapid price increase of oil, for example, can lead on the one hand to inflation, economic downturn, and demand destruction, all of which then lead to decreased demand for oil, and perhaps, price relief. At the same time, higher prices, at least when they occur rapidly, lead to increased energy efficiency and the development of alternative energy sources, again potentially lifting pressure from supplies of fossil fuels and therefore on prices. The past few years have seen significant price increases in fossil fuels, but little change in consumption; there are, however, increasing efforts at developing alternatives to fossil fuels, partly driven by prices and partly by climate change concerns.

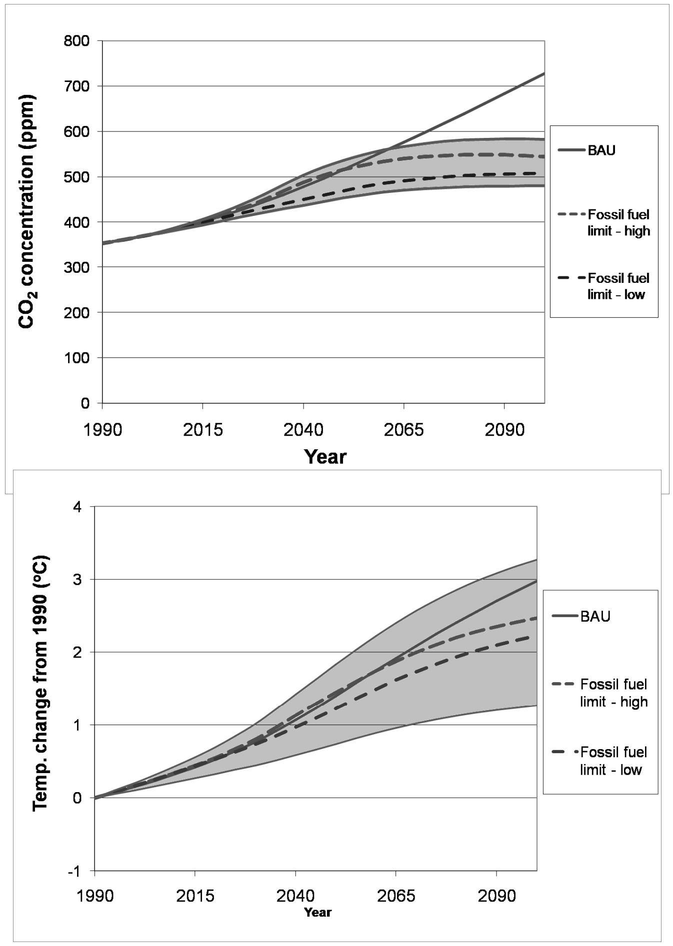


Fig. 9. Output from MAGICC (see text) for the fossil-fuel scenario based on limited resources. a) Carbon dioxide concentration for both scenarios, compared to a business-as-usual scenario of steady greenhouse-gas emission increase. b) Global average temperature rise for the same two scenarios. For each plot the shaded area represents the estimated combined uncertainty for the two scenarios.

Viewed from a different perspective, various integrated assessment economic models have shown that it is possible to make deliberate, targeted policies, implemented with the goal of avoiding dangerous anthropogenic interference in the climate system, without thereby causing undue economic hardship [41]. Some of the potential climate-change mitigation paths, for example those with the goal of keeping CO_2 levels below 450 ppm, are stringent enough as to require a switch from fossil fuels over the course of the 21st century that would keep emissions below the levels in the peaking scenarios presented here. It should be noted that the same 450 ppm scenarios investigated in Ref. [41] correspond to the maximum permissible levels discussed by Hansen *et al.* [40] for prevention of likely dangerous consequences for the climate system. The IPCC AR4 WGIII report [29] details some of the results of economic studies of mitigation strategies. It appears that economic damages can be minimized; however, if change is not undertaken carefully, with plenty of time for techno-

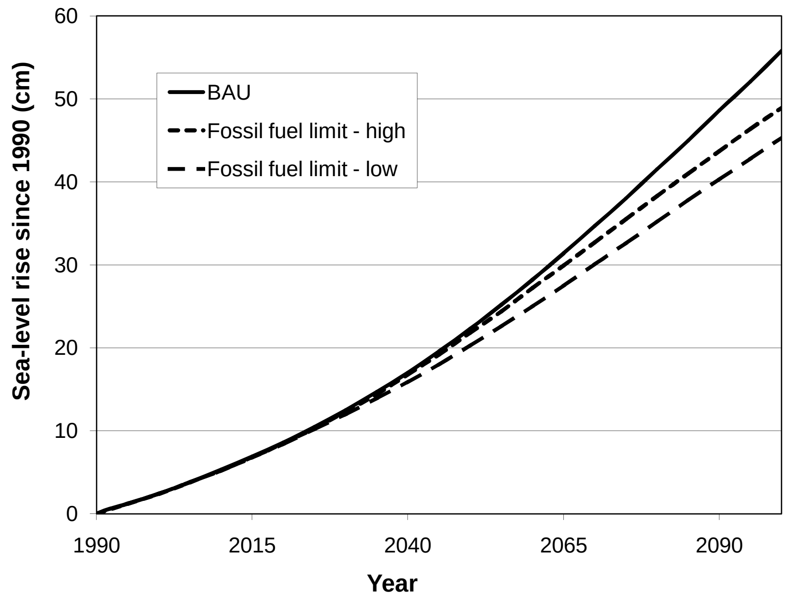


Fig. 10. Output from MAGICC (see text) for the fossil-fuel scenario based on limited resources. Sea-level rise for a business-as-usual scenario and the two fossil-fuel-limited scenarios described in the text.

logical and learning-by-doing effects to occur, the economy and energy system would be most likely to take unpredictable, and perhaps unfortunate, paths. Some of these issues have been recently addressed by Farrell and Brandt [42].

7 Conclusion

The fossil fuel emissions scenarios presented here are admittedly over-simplified, not being based on a full energy system model. As discussed above, however, there are geological and economic grounds for believing that far less of that resource will be extracted than is commonly believed. If production of one or more of the conventional fossil fuels does go into decline in the near future, there will undoubtedly be a race to effect substitution to the degree possible; such a strategy, or reaction, would only speed the depletion of the other fuels. As touched upon in the discussion above on economic aspects of resource recovery, as conventional fossil fuels, primarily petroleum, become more expensive due to either scarcity or strong demand, all further infrastructure also becomes much more expensive, thereby making non-conventional resource recovery potentially far less profitable than would initially appear to be the case.

The scenarios presented here (in terms of size of remaining reserves, given restrictions on recoverability of less-accessible resources) still lead to a significant near-term growth in carbon emissions by the middle of this century, followed by an enforced decrease in emissions with concomitant slowed rate of increase and peak in atmospheric concentrations of CO_2. One can easily imagine a complicated dynamical interaction created by scarcity of fossil fuels, in which high prices of oil lead to decreased economic activity, which in turn leads to less demand and then a decreased price for petroleum, similar to the historical example of the late 1970s. If peak oil scenarios are accurate, however, there will be no single shock that leads to the "scarcity", but rather a continual apparent sense of short supply every time the world recovers from a period of demand destruction.

Although it is often claimed that the world economy is becoming less carbon intensive, that is true only to a very minor extent at best, and not at all in recent years. Current economic growth in China and India, coupled with an apparent reluctance on the part of those countries as well as the United States to accept limits on carbon emissions might give one a somewhat pessimistic view of the possibility that humanity will voluntarily make the steps needed to avoid serious anthropogenic interference in the climate system. One way to look at the scenario presented in this paper is that it serves as a kind of best-case result (for global climate) in the case that political and societal institutions do not demonstrate the foresight needed for a smooth decarbonization of the energy system. The limited-fossil-fuel future described here, which is seen as unrealistically pessimistic by some, might be barely sufficient to limit CO_2 concentrations to the doubling of pre-industrial levels that optimists hope might limit temperature and sea-level rises within an acceptable range, but goes somewhat above the limits set for holding to a 2°C global average temperature change, which roughly corresponds to a CO_2 concentration of 450 ppm.

One of the great challenges in addressing the threat of dangerous anthropogenic interference in the climate system is that of convincing large segments of the developed world to accept policies that have, at least initially, benefits that are both temporally and spatially remote. On the other hand, without those actions by the developed world, it is very difficult to convince those in the developing world to change policies that the wealthy countries often claim (whether correctly or not) would be too onerous economically. To some extent, a geologically enforced (with economic assistance) limit to our capability for adding carbon dioxide to the atmosphere and oceans might be the best option available for breaking the positive feedback loop of fossil-fuel burning and climate change.

References

[1] N. Nakićenović, *et al.*, 2000. Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

[2] H.-H. Rogner, 1997. An Assessment of World Hydrocarbon Resources. Annu. Rev. Energy Environ. **22**,21762.

[3] G. Bala, K. Caldeira, A. Mirin, M. Wickett and C. Delire, 2005. Multicentury Changes to the Global Climate and Carbon Cycle: Results from a Coupled Climate and Carbon Cycle Model. J. of Climate **18**, 4531-4546.

[4] M.K. Hubbert, 1981. The World's Evolving Energy System. Am. J. Phys. **49**, 1007-1023.

[5] Energy Information Administration, 2006. U.S. oil production record from 1859. `http://tonto.eia.doe.gov/dnav/pet/pet_crd_crpdn_adc_mbbl_a.htm`, last accessed June 2006.

[6] V. E. McKelvey, United States Geological Survey,1961. Domestic and world resources of fossil fuels, radioactive minerals and geothermal energy. Nov. 28, 1961, cited in Ref. [4].

[7] BP Statistical Review of World Energy 2007, `http://www.bp.com/statisticalreview`, last accessed June 2007.

[8] U.S. Geological Survey World Petroleum Assessment Team, 2000. U.S. Geological Survey World Petroleum Assessment 2000 - Description and results: U.S. Geological Survey Digital Data Series DDS-60, 4 CD-ROMs.

[9] T.R. Klett, D.L. Gauthier and T.S. Ahlbrandt, 2005. An Evaluation of the U.S. Geological Survey World Petroleum Assessment 2000. AAPG Bulletin **89**, 1033-1042.

[10] D.B. Reynolds, 1998. Entropy Subsidies. Energy Policy **26** 113-118.

[11] B. Söderbergh, F. Robelius and K. Aleklett, 2007. A Crash Program Scenario for the Canadian Oil Sands Industry. Energy Policy **35**, 1931-1947.

[12] Canadian Association of Petroleum Producers, 2006. Canadian Crude Oil Production and Supply Forecast 2006 - 2020. `http://www.capp.ca/raw.asp?x=1&dt=NTV&e=PDF&dn=103586`, last accessed December 2006

[13] Energy Information Administration 2007. `http://www.eia.doe.gov/emeu/international/oilproduction.html`

[14] Energy Information Administration, 2007. International Energy Outlook, `http://www.eia.doe.gov/oiaf/ieo/index.html`

[15] J. T. Bartis, T. LaTourrette, L. Dixon, D.J. Peterson, G. Cecchine, 2005. Oil Shale Development in the United States: Prospects and Policy Issues, RAND Corporation report, prepared for the National Energy Technology Laboratory of the U.S. Department of Energy, available at http://www.rand.org, last accessed July 2007.

[16] Wikipedia, Coal http://en.wikipedia.org/wiki/Coal#Liquefaction

[17] SASOL Annual Report 2006, http://sasol.investoreports.com/sasol_ar_2006/review/html/sasol_ar_2006_50.php

[18] http://www.greencarcongress.com/2007/04/china_ctl_outpu.html

[19] http://www.ethanolrfa.org/, last accessed March 2008.

[20] A.E. Farrell, R.J. Plevin, B.T. Turner, A.D. Jones, M. OHare, Daniel M. Kammen, 2006. Ethanol Can Contribute to Energy and Environmental Goals, Science **311**, 506-508.

[21] E. Marris, 2006. Drink the best and drive the rest. Nature **444**, 670-672.

[22] American Council for Ethanol, 2007. Website with updated list of ethanol facilities currently in operation and under construction: http://www.ethanol.org/index.php?id=37&parentid=8, last accessed July 2007.

[23] Department of Energy, 2006. Breaking the Biological Barriers to Cellulosic Ethanol. DOE/SC-0095. Available at http://www.doegenomestolife.org/biofuels.

[24] http://www.mineweb.net/mineweb/view/mineweb/en/page38?oid=22032&sn=Detail

[25] Energy Information Administration, 1998-2006. Annual Energy Outlook http://www.eia.doe.gov/oiaf/archive.html#aeo

[26] S. Schurr and B. Netschert, 1960. Energy in the American Economy 1850-1975. Johns Hopkins Press, Baltimore.

[27] Energy Watch Group, 2007. Coal: Resources and Future Production. http://www.energywatchgroup.org/files/Coalreport.pdf, last accessed April 2007.

[28] National Academy of Sciences, 2007. Coal: Research and Development to Support National Energy Policy. National Academies Press, Washington.

[29] Intergovernmental Panel on Climate Change, 2007. Climate Change 2007 - The Physical Science Basis Contribution of Working Group I to the Fourth Assessment Report of the IPCC. Cambridge Univ. Press, Cambridge, UK; Climate Change 2007 - Impacts, Adaptation and Vulnerability - Contribution of Working Group II to the Fourth Assessment Report of the IPCC. Cambridge Univ. Press, Cambridge, UK; Climate Change 2007

- Mitigation of Climate Change Contribution of Working Group III to the Fourth Assessment Report of the IPCC. Cambridge Univ. Press, Cambridge, UK.

[30] Energy Information Administration, 2007. Monthly Energy Review. http://www.eia.doe.gov/emeu/mer/

[31] Energy Information Administration, 2006. Costs and Indices for Domestic Oil and Gas Field Production and Operations, 1987-2005.

[32] J. Baffes, 2007. Oil Spills on Other Commodities. World Bank Policy Research Working Paper, Number 4333, available at http://econpapers.repec.org/paper/wbkwbrwps/4333.htm, last accessed, December 2007. http://www.eia.doe.gov/pub/oil_gas/natural_gas/data_publications/cost_indices_equipment_production/current/coststudy.html

[33] Wikipedia, 2007. http://en.wikipedia.org/wiki/Ehrlich-Simon_bet.

[34] J. Gowdy and R. Juliá, 2005. Technology and Petroleum Exhaustion: Evidence from Two Mega-Oilfields. Rensselaer Working Papers in Economics, Number 0512, http://www.economics.rpi.edu/workingpapers/rpi0512.pdf.

[35] D.B. Reynolds, 2002. Using non-time-series to determine supply elasticity: how far do prices change the Hubbert curve?, OPEC Review June 2002, 147-167.

[36] D.B. Reynolds, 1999. The Mineral Economy: How Prices and Costs Can Falsely Signal Decreasing Scarcity. Ecol. Econ. **31**, 155-166.

[37] W. Nordhaus and Boyer, 2000. Warming the World: Economic Models of Global Warming. MIT Press, Cambridge, MA.

[38] UCAR. MAGICC software is available for free download at http://www.cgd.ucar.edu/cas/wigley/magicc/index.html.

[39] S. Rahmstorf, 2007. A Semi-Empirical Approach to Projecting Future Sea-Level Rise. Science **315**, 368-370.

[40] J. Hansen, M. Sato, P. Kharecha, G. Russell, D. W. Lea and M. Siddall, 2007. Climate change and trace gases. Phil. Trans. R. Soc. A **365**, 19251954.

[41] Energy Journal, 2006. Endogenous Technological Change and the Economics of Atmospheric Stabilisation, Special issue.

[42] A.E. Farrell and A.R. Brandt, 2006 Risks of the oil transition. Environ. Res. Lett. **1**, 014004.

Figure captions

Fig. 1 - Oil production and logistic function fit, a) in millions of barrels per year, and b) cumulative production, both as a function of time. Data are from the U.S. EIA [5]; the logistic curve has parameters corresponding to the initial production rate increase of 7% per year. The data shown here represent oil from the continental U.S., but includes no natural gas liquids or nonconventional oil from other processes.

Fig. 2 - World cumulative and yearly oil production and the logistic model. Data are from the U.S. EIA [5]. Parameters for the logistic curves are (as defined in the text) the same for the curves in a) and b). In each case a non-linear least-squares fit was made to world oil production data, with the ultimately recoverable reserve (URR) held fixed at $Q_\infty = 2000$ Gbbl (lower curve) and $Q_\infty = 3000$ Gbbl(upper curve). The other parameters from the fit to actual production data are $b = 0.058$ and $a = 4300$, and $b = 0.047$, $a = 1700$, for $Q_\infty = 2000$ and 3000 Gbbl, respectively. The actual production data shown for years until 2007 represent oil, as well as natural gas liquids and oil from non-conventional sources.

Fig. 3 - World natural gas and coal production and CO_2 emissions. a) Energy production from natural gas is shown in EJ/year for three different projections of total ultimate recoverable reserve (URR). The lower curve uses the Ref. [7] data, assuming no further additions. The two upper curves assume an URR of 50% more and of 100% than the most recent reserves data. b) Coal production, with the resultant CO_2 emissions are shown for two different future "peak" scenarios. The assumption is that the world coal reserves are 1000 Gt, with different production growth rates of 4%/year and 6%/year assumed. After the peak, the decline rate slows to one-half the growth rate in each case.

Fig. 4 - Modification of the logistic equation to include the potential for continual growth of reserves. In a) are shown two curves, one (solid) for which the URR is fixed at 2000 Gb, the other (dashed) for which the URR grows by 2%/year, and therefore has an infinite limit. The corresponding yearly production rates are shown in b).

Fig. 5 - A schematic marginal extraction costs curve. The solid line is based on estimates from Rogner. The boxes represent the fact that tar sands are currently the marginal production barrels, coal-to-liquids are estimated to soon be profitable, and planning is underway for shale oil production, each at costs much higher than those that have been typically estimated for the relevant stage of cumulative extraction.

Fig. 6 - Total CO_2 emissions plotted for the next century. a) Total oil URR of 2000 Gbbl (peak production 2010), total natural gas original resource 82×10^{15}

tcf (peak production 2020), total coal resource originally in place, 1300 Gt (peak production 2050, after 2%/year growth). b) Total oil URR of 3000 Gbbl (peak production 2025), total natural gas original resource 108×10^{15} tcf and a peak production year of 2030, and a peak coal production in 2035 following growth of 4%/year to that point, using the same 1300 Gt original resource.

Fig. 7 - Carbon emissions projected for the future using IPCC scenarios and models from three of six contributors to the Special Report on Emissions Scenarios (see text), along with the fossil-fuel-limited scenarios presented in this work (represented by a solid line). a) A1 storyline b) A2 storyline.

Fig. 8 - Carbon emissions projected for the future using IPCC scenarios and models from three of six contributors to the Special Report on Emissions Scenarios (see text), along with the fossil-fuel-limited scenarios presented in this work (represented by a solid line). a) B1 storyline b) B2 storyline.

Fig. 9 - Output from MAGICC (see text) for the fossil-fuel scenario based on limited resources. a) Carbon dioxide concentration for both scenarios, compared to a business-as-usual scenario of steady greenhouse-gas emission increase. b) Global average temperature rise for the same two scenarios. For each plot the shaded area represents the estimated combined uncertainty for the two scenarios.

Fig. 10 - Output from MAGICC (see text) for the fossil-fuel scenario based on limited resources. Sea-level rise for a business-as-usual scenario and the two fossil-fuel-limited scenarios described in the text.