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World energy analysis: H_2 now or later?

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Abstract

This is a study of world energy resource sustainability within the context of resource peak production dates, advanced energy use technologies in the transportation and electricity generation energy use sectors, and alternative fuel production including hydrogen. The finding causing the most concern is the projection of a peak in global conventional oil production between now and 2023. In addition, the findings indicate that the peak production date for natural gas, coal, and uranium could occur by 2050. The central question is whether oil production from non-conventional oil resources can be increased at a fast enough rate to offset declines in conventional oil production. The development of non-conventional oil production raises concerns about increased energy use, greenhouse gas emissions, and water issues. Due to the emerging fossil fuel resource constraints in coming decades, this study concludes that it is prudent to begin the development of hydrogen production and distribution systems in the near-term. The hydrogen gas is to be initially used by fuel cell vehicles, which will eliminate tailpipe greenhouse gas emissions. With a lowering of H_2 production costs through the amortization of system components, H_2 can be an economic fuel source for electricity generation post-2040.

Keywords: Oil; Hydrogen; Photovoltaics

1. Introduction

This study investigates world energy resource sustainability within the context of energy resource peak production, global economic growth, the adoption of advanced energy use technologies for transportation and electricity generation, and the production of alternative fuels including hydrogen gas (H_2). The current growth rate in world energy consumption is 2% per annum. If world energy consumption continues to grow at this rate, then it will double in 35 years, which raises concerns about energy resource sustainability. While world oil production is receiving widespread research attention, this study expands the scope of energy resource analysis by examining natural gas, coal, and uranium as well. The research is important because of the need to insure a sufficient supply of energy to sustain desired levels of global economic growth. The purpose of the research is to provide policy makers with timely information about the long-term effects of advanced energy technologies for transportation and electricity generation and alternative fuel production on energy resource production life-cycles. An important question is—Should the implementation of H_2 energy systems begin now or later?

The energy resource analysis is conducted within the framework of four energy paths and two theories. The four energy paths are: Path (1), continuation of current energy use technologies and fuel mixes; Path (2), universal adoption of advanced energy technologies for transportation and electricity generation; Path (3), the production of alternative fuels from non-conventional oil and biomass resources to supplement conventional oil production; and Path (4), the development of centralized H_2 production and distribution systems to provide H_2 for fuel cell vehicles (FCVs). The advanced energy technologies are listed in Table 1, which includes adoption timelines, adoption rates, and efficiency gains. The two theories informing the study are peak production theory from energy resource geology and capital conservation theory from resource economics.

Energy resource sustainability is evaluated in terms of peak production dates. When a particular energy resource attains its global peak production level, it can no longer support growth in energy demand, which impacts

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Table 1
Adoption schedules for advanced energy technologies

	Begin adoption date	End adoption date	Annual adoption rate (%)	Efficiency (%) or fuel economy (km/l)	Reduction in fuel use (%)
Energy Path 2					
A. Transportation					
1. Advanced fuel economy vehicles	2008	2027	5	20	50
B. Electricity generation					
1. Natural gas CC power plants	2007	2027	5	55%	38
2. Coal IGCC power plants	2007	2027	5	42%	24
3. Phase-out of oil power plants	2007	2027	5		100
4. PV 10% of total capacity	2007	2016	10		
5. Wind 10% of total capacity	2007	2016	10		
Energy Path 3					
A. Transportation					
1. Advanced fuel economy vehicles	2008	2027	5	20	50
B. Electricity generation					
1. Natural Gas CC power plants	2007	2027	5	55%	38
2. Coal IGCC power plants	2007	2027	5	42%	24
3. Phase-out of oil power plants	2007	2027	5		100
4. PV 10% of total capacity	2007	2016	10		
5. Wind 10% of total capacity	2007	2016	10		
Energy Path 4					
A. Transportation					
1. H_2 fuel cell vehicles (FCVs)	2011	2030	5		100
2. Advanced fuel economy vehicles	2008	2019	5	20	50
B. Electricity generation					
1. Natural Gas CC power plants	2007	2027	5	55%	38
2. Coal IGCC power plants	2007	2027	5	42%	24
3. Phase-out of oil power plants	2007	2027	5		100
4. PV 10% of total capacity	2007	2016	10		
5. Wind 10% of total capacity	2007	2016	10		

economic growth. An important assumption to this analysis is the desirability of maintaining a nominal 2% average annual growth rate in world energy demand.[1] A nominal 2% growth rate in energy use enables developing nations to continue their present economic growth trajectories. If the nominal growth rate in world energy demand is less than 2%, then current levels of world economic growth are disrupted, which most likely will lead to an increase in international political tensions.

The analysis is organized as follows. Section 2 presents the methodology and data sources for the analysis. The research findings are presented in Section 3 and include energy resource peak production date estimates, an evaluation of global oil supply/demand balances, and sensitivity analyses. A discussion of the findings is presented in Section 4. The study concludes in Section 5 with a brief summary of the findings and suggestions for further research.

2. Methods and data

2.1. Methods

The methodology for this study is informed by peak production theory from energy resource geology and capital conservation theory from resource economics. Peak production theory provides a model for the estimation of the peak production dates for energy resources. Peak production is the maximum annual production level of an energy resource and does not imply resource depletion. The concept of peak production is important because increases in demand for an energy resource cannot be supported post-peak, which will lead to dramatic price increases if alternative fuels or energy technologies are not available.

Peak production theory is premised on the assumption that the aggregate frequency distribution of annual production levels for an energy resource approximates a normal frequency distribution (Bentley, 2002; Laherrère,

[1]The 2% annual growth rate in world energy demand is modeled as a nominal growth rate. The growth rate is nominal in that while increases in the fuel efficiency of the modeled advanced energy technologies reduce energy resource consumption levels, the net amount of work, i.e. miles traveled and work hours of electricity generators, boilers, machinery, appliances, etc., continues to grow at an average of 2.0% per annum rate.

2005). Energy resource production life-cycles for single production units may deviate significantly from a normal distribution, but the aggregate or population-level frequency distribution of production units converges to a normal distribution, i.e., the central limit theorem. The peak production level of an energy resource occurs at the mode or midpoint of the normal frequency distribution. Hence, the peak production level of an energy resource can be predicted to occur when 50% of the economically recoverable reserves are extracted.

The precision of peak production date estimates is contingent on the accuracy of economically recoverable reserve estimates and resource demand growth rates. In an attempt to control for variation in these variables, this analysis includes a range in resource reserve estimates and demand growth rates, which factor in the effects of the adoption of advanced energy technologies for transportation and electricity generation and the production of alternative fuels. In addition, sensitivity analyses are preformed to evaluate the effects of variation in efficiency gains assigned to the advanced energy technologies and in the allocation of energy resources for alternative fuel production.

The second theory, capital conservation theory, defines economically recoverable reserves in terms of supply/demand economics. The energy resource supply/demand cycle is presented graphically in Fig. 1. The exploration for new energy reserves is driven by resource prices. Investors are not willing to invest in exploration for new reserves unless resource prices are sufficiently high to provide timely market returns on investments. If the investment risks for exploration increase, i.e., resources become more difficult to find and/or incur higher production costs, then higher resource prices are required to attract investors. The result is new energy resource supply/demand equilibrium albeit at a higher cost and price structure.

Peak production theory of resource geology is based on a narrow definition of economically recoverable reserves,

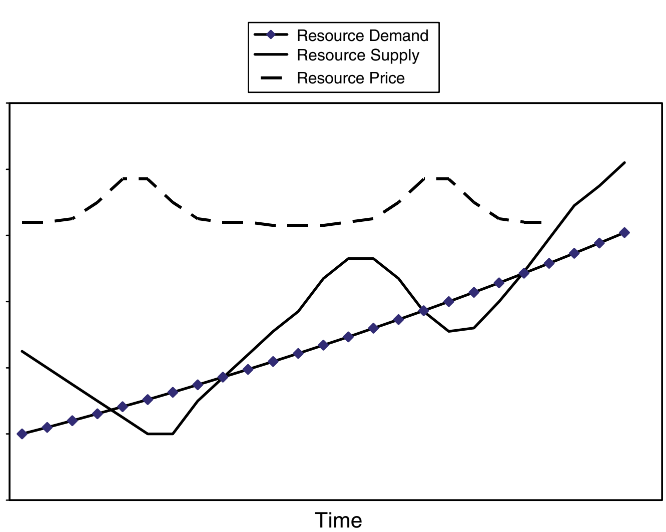

Fig. 1. Economics of resource supply (theory of capital conservation).

which are defined in terms of resource-specific physical and chemical properties and corresponding production costs. In contrast, resource economists have a much broader definition of resource reserves that is based on the relative cost structure of a market basket of substitutable energy resources. Since conventional oil production is a central variable in this analysis, the different conceptualization of conventional oil production by petroleum geologists and resource economists is explored in brief detail.

Petroleum geologists define conventional oil as liquid hydrocarbons of light and medium gravity and viscosity with an $API > 25$, deposited in porous and permeable reservoirs. Non-conventional oil resources are defined as oil deposits with densities greater than water, high viscosities, and deposited in tight formations. In contrast, resource economists distinguish between conventional and non-conventional oil resources in terms of oil production costs. For example, oil sands were classified as a non-conventional oil resource just a few years ago, but today syncrude produced from oil sands is included in conventional oil production reports since syncrude is competitively priced with conventional crude oil.

The key difference between the peak production and capital conservation perspectives is the forecast regarding whether or not the rate of increase in oil production from non-conventional oil resources will be sufficient to offset both declines in post-peak conventional oil production and increases in global oil demand. Peak production theory predicts that the rate of increase in oil production from non-conventional oil resources will not be able to compensate for declines in post-peak conventional oil production because the oil production rate of non-conventional oil resources is constrained by "technological readiness, energy content, investment limits, water requirements and emissions" (Bentley, 2002). The water and emissions constraints entail institutional factors in the form of air and water regulations. The effect of greenhouse gas (GHG) emissions policies is expected to have a growing influence on the selection of energy fuel sources and technologies in coming years (Schellnhuber et al., 2006). In contrast, capital conservation theory predicts that oil futures market provide investors with price signals regarding the profitability of investments in non-conventional oil production. If the expected long-term price of conventional oil is sufficiently high to support non-conventional oil production, then the emerging market basket of oil supplies, which includes conventional and non-conventional oil resources, will maintain an oil supply/demand balance. In essence, the central issue is whether or not the combination of conventional and non-conventional oil production can sustain the global oil supply/demand balance after conventional oil production peaks.

2.2. Data

The energy resource reserve estimates are presented in Table 2 and are the total of past consumption, proved, and

Table 2
Peak production estimates for oil, natural gas, coal and uranium

	Oil (Exajoules)		Natural gas (Exajoules)		Coal (Exajoules)		Uranium (Exajoules)	
	Low	High	Low	High	Low	High	Low	High
Consumed through 1998	4865	4865	2347	2347	5984	5984	157	157
Recoverable reserves	6951	14,104	8530	17,231	22,201	78,569	1565	2504
Total recoverable reserves	12,850	18,969	10,877	19,579	28,184	85,333	1722	2661
1. Year 2000 technology	Oil (peak year)		Natural gas (peak year)		Coal (peak year)		Uranium (peak year)	
	Low	High	Low	High	Low	High	Low	High
1.5% average annual growth	2006	2021	2024	2050	2048	2117	2051	2071
2.0% average annual growth	2006	2020	2023	2046	2044	2101	2047	2064
2.5% average annual growth	2006	2019	2022	2042	2041	2089	2043	2058
2. Advanced technology								
	Low	High	Low	High	Low	High	Low	High
1.5% average annual growth	2006	2022	2026	2056	2049	2121	2051	2071
2.0% average annual growth	2006	2021	2025	2051	2045	2104	2047	2064
2.5% average annual growth	2006	2021	2024	2047	2042	2091	2043	2058
3. Syncrude and biofuel								
	Low	High	Low	High	Low	High	Low	High
1.5% average annual growth	2006	2022	2026	2054	2046	2111	2039	2053
2.0% average annual growth	2006	2021	2025	2050	2043	2098	2038	2050
2.5% average annual growth	2006	2020	2023	2046	2040	2088	2036	2058
4. H_2 and fuel cell vehicles								
	Low	High	Low	High	Low	High	Low	High
1.5% average annual growth	2006	2023	2025	2049	2044	2107	2030	2037
2.0% average annual growth	2006	2022	2024	2045	2041	2092	2029	2036
2.5% average annual growth	2006	2021	2023	2042	2038	2082	2028	2034

unproved reserves. Low and high estimates of economically recoverable reserves for oil, natural gas, coal, and uranium are presented. The high-reserve estimates are derived from a review of the US Energy Information Administration's (EIA) *International Energy Outlook* (2005), the United Nation's World Energy Assessment (2000) and Nakićenović et al. (1998). The low-reserve estimate for oil is from Deffeyes (2001); for natural gas and coal from the EIA (2005) and Laherrère (2005); and for uranium from Kidd (2005). The past consumption estimates are from the World Energy Assessment (2000). The unproved coal-reserve estimate is derived from an estimate of the total coal resource base adjusted by a factor of 0.54, which conforms to the estimation method of the United States Geological Survey. The total coal-reserve estimate excludes 2943 billion metric tons of coal from remote Siberia because it is unlikely that these coal reserves are economically recoverable.

The energy resource peak production analysis is conducted within the context of four energy technology and fuel paths. Energy Path 1 is based on the continuation of year 2005 energy use technologies and fuel mixes. A listing of the Path 2 advanced energy technologies for transportation and electricity generation are presented in Table 1 and includes adoption timelines, adoption rates, efficiency gains, and reductions in fuel use. The advanced energy technologies introduced in Path 2 are also included in energy Paths 3 and 4.

Energy Path 2 assumes the universal adoption by 2027 of advanced light-duty vehicles and light commercial trucks with an average fuel economy a factor of two greater than the 2005 average fuel economy. In addition, Path 2 assumes the universal adoption of advanced electricity generating technologies: coal integrated gasification combined-cycle (IGCC) power plants; natural gas combined-cycle power plants; wind power plants; and photovoltaic (pv) power plants. Coal IGCC and natural gas combined-cycle power plants completely replace all single-cycle coal and natural gas power plants by 2027, and the efficiency gains are 31% and 62%, respectively. Wind and pv provide 20% of total electricity generating capacity by 2021.[2] A final technology transition adopted in Path 2 is the complete phase-out of all oil power plants by 2027, and the displaced oil electricity generating capacity is replaced by coal IGCC power plants.

It is important to note that the results of this analysis are driven by choice of assumptions. The assumption having the greatest effect on results is the nominal 2% average annual growth rate in demand for each of the energy

[2]The pv displacement of fossil fuel generating capacity estimates are derived from the average effective load carrying capacity estimates of Perez et al. (1997). The percentage reduction differential for natural gas and coal electricity generation are best-guess estimates. The wind displacement of fossil fuel generating capacity estimates are from the European Wind Energy Association (European Wind Energy Association (EWEA), 2005). With pv 10% and wind 10% of capacity; the reduction in electricity generating capacity is 7% for natural gas and 5% for coal.

resources. The nominal growth rate is a function of the choice of efficiency gains assigned to the advanced energy technologies. The intended purpose in modeling the selected range of advanced energy technologies is to construct a meaningful framework to evaluate effects of reductions in energy resource consumption levels on energy resource sustainability. The advanced energy technologies for transportation and electricity generation modeled in this study reduce the projected 2027 annual consumption level of oil by 36%, of natural gas by 15%, and of coal by 15%, while enabling 2% per annum growth in energy use applications. The efficiency gains of the advanced energy technologies modeled in this study are technologically feasible, but it is highly improbable that universal adoption will occur within the assumed 20-year transition period, particularly in developing countries. The expected shortfall in energy savings between the modeled and realizable can serve as a proxy for potential energy savings achieved through the adoption of un-modeled energy use technologies.

Energy Path 3 incorporates the large-scale production of synfuels from non-conventional oil and biomass resources to supplement conventional oil production. The production schedule for non-conventional oil production is presented in Table 3. Oil produced through the application of enhanced or tertiary oil recovery methods, which involve the injection of oil thinning agents such as CO_2, N_2, and polymers, is a special case category of oil production and can be classified as either conventional or non-conventional oil. For the purposes of this analysis, oil produced with enhanced oil recovery methods is defined as non-conventional oil production because the method is not applicable in all oil fields. The application of enhanced oil recovery methods is dependent on the geology of oil fields, oil type, and access to oil diluents and large volumes of water. Primary and secondary oil extraction technologies are able to extract only 25–30% of the oil in an oil reservoir. Enhanced oil recovery methods can increase the proportion of oil extracted from an oil reservoir by an additional 5–15% (Gielen and Unander, 2005). This is a large potential source of oil production. However, oil production by enhanced oil recovery methods is applicable only after oil fields are well past peak production. Therefore, oil production by enhanced oil recovery methods is expected to have little impact on the peak production date for oil, but it is expected to reduce the rate of decline in post-peak oil production. It is assumed that oil production from enhanced oil recovery projects will be 10 million barrels of oil equivalent energy per day (Mboe/d) by 2030. This level of oil production from enhanced oil recovery methods

Table 3
Production schedule of non-conventional fuels to supplement conventional oil

	2010	2015	2020	2025	2030	Capital costs per Mboe/d (billion $)	Capital costs 2030 (billion $)
Enhanced oil recovery[a]	3.0	4.8	6.6	8.3	10.0		
A. Path 3—Alternative fuels							
1. Non-conventional synfuels							
a. Coal-to-liquids	0.1	0.5	1.0	2.0	3.0	65	195
b. Heavy oil and oil sands[b]	2.0	3.0	4.0	5.0	6.0	25	150
c. Gas-to-liquids (stranded NG)	0.1	1.0	2.0	3.0	4.0	35	140
d. Oil shale (in situ)	0.0	0.0	1.0	2.0	3.0	50	150
Total syncrude production[c]	2.2	4.5	8.0	12.0	16.0		635
2. Biofuels from biomass							
a. Ethanol—Corn	0.1	0.3	0.5	0.5	0.5	35	18
b. Ethanol—cellulosic biomass	0.3	1.0	3.0	5.0	7.0	65	455
c. Biodiesel—soybean	0.1	0.3	0.5	0.5	0.5	35	18
Total biofuel production	0.5	1.5	4.0	6.0	8.0		490
Total Path 3	2.7	6.0	12.0	18.0	24.0		1125
B. Path 4—Hydrogen production							
1. Cellulosic biomass gasification	0.0	1.4	2.7	4.2	6.0	79	474
2. Coal gasification	0.0	1.4	2.7	4.2	6.0	79	474
3. Nuclear electrolysis	0.0	1.4	2.7	4.2	6.0	145	870
4. PV electrolysis	0.0	1.4	2.7	4.2	6.0	259	1554
5. Wind electrolysis	0.0	1.4	2.7	4.2	6.0	261	1566
Total Path 4	0.0	7.0	13.6	21.1	30.0		4938

Million barrels of oil equivalent per day (Mboe/d).

[a]Oil production by enhanced oil recovery methods totaled 1.3 Mboe/d in 2004.

[b]Syncrude production in 2005 was 1.0 Mboe/d from Canadian oil sands and 0.6 Mboe/d from Venezuelan heavy oils.

[c]The capital costs of Path 3 fuel production plants do not include GHG emissions capture and storage systems, while the capital costs of Path 4 coal gasification plants do include GHG emissions capture and storage costs.

Table 4
Alternative fuels production primary energy and GHG emissions

	Energy use (MJ_{prim}/MJ_e)[a]	GHG emissions (g CO_2 Eq/MJ_e)
A. Gasoline production from conventional oil		
1. Gasoline production	0.24	17
B. Synfuels production from non-conventional oil		
1. Coal-to-liquids	0.78	72
2. Tar sands	0.42	30
3. Heavy oil	0.39	28
4. Gas-to-liquids	0.55	22
5. Oil shale (in-situ)	0.53	38
C. Biofuels production from biomass		
1. Ethanol—Corn	0.79	81
2. Ethanol—Cellulosic biomass	0.10	11
3. Biodiesel—Soybean	0.44	22
D. Hydrogen production		
1. H_2 by coal gasification	0.48	44
2. H_2 by electrolysis with nuclear	0.24	15
3. H_2 by electrolysis with PV	0.23	15
4. H_2 by electrolysis with wind	0.15	12
E. Gasoline combustion (ICE vehicles)	1.24	83

[a]Primary energy is the energy input per unit of energy output. Primary energy includes the energy to extract and transport the energy resource.

reduces the decline in post-peak oil production from an expected decline rate of 2% per annum to 1.3% per annum.[3]

Other sources of non-conventional oil are oil sands, heavy oil, and oil shale. Also categorized as non-conventional oil resources are coal-to-liquids, gas-to-liquids from stranded natural gas reserves, and biofuels. Data on oil sands and heavy oil production are from Gielen and Unander (2005), Woynillowicz et al. (2005), CAPP (2005), and Bauquis (1998). The recoverable reserves of oil sands and heavy oil are substantial, 310 Gboe from Canadian oil sands, 270 Gboe from Venezuelan heavy oil, and 3000 Gboe from US oil shale (EIA, 2005). The primary concerns with syncrude production from non-conventional oil resources are large increases in energy use, GHG emissions, and water issues. A comparison of energy and GHG emissions to produce fuels is presented in Table 4.

The current syncrude production level from heavy oils and oil sands is 0.67 Mboe/d from Venezuelan heavy oil and 1.0 Mboe/d from Canadian oil sands (EIA, 2005). These production levels indicate that heavy oil and oil sands production technologies are relatively mature and that the production projections presented in Table 3 are technologically feasible and can be increased if required. Canada is preparing the infrastructure for roads and housing to support a large scale-up in Alberta oil sands development, and pipelines are being built to distribute the syncrude to refineries in Canada and the USA.

[3]The decline rate in global post-peak oil production assumes that oil production remains at the peak level for 3 years and then begins to decline progressively to the 2% per annum decline rate over 9 years. The decline rate of 2% per annum is derived from the symmetrical shape of the normal distribution.

The data on oil shale production are from Bartis et al. (2005) and Johnson et al. (2004). Oil shale production technologies are still in the development stage. In the 1980s mining extraction methods were tested, but today in-situ oil recovery methods appear more promising and less costly. Royal Dutch Shell is expected to make a decision as to whether to pursue large-scale, in-situ production of syncrude from oil shale by 2010. The projected production of 1 Mboe/day of syncrude from oil shale in 2020 is considered technologically feasible. However, environmental concerns about high energy use, GHG emissions, and water issues could hinder the development of oil shale. The world's largest oil shale reserves are in the Green River Basin of Wyoming, USA, and the large amounts of water required are a cause of concern because of projected long-term water supply reductions in the western US due to the effects of global warming-induced climate change (Cook et al., 2004). Ground-water pollution is another serious concern.

Other sources of liquid fuels to supplement conventional oil are coal-to-liquids, gas-to-liquids, and biofuels from biomass. The data for coal-to-liquids and gas-to-liquids are from Gielen and Unander (2005), EIA (2005), and Ogden (2002). The data for biofuel production are from Farrell et al. (2006), Perlack et al. (2005), and GREET 1.6 (Wang and Michael, 2001). The coal-to-liquids and gas-to-liquids production projections in Table 3 are based on established technologies and are technically achievable. This study projects a 2030 biofuel production level that is ~30% of world gasoline production.[4]

[4]A potentially large source of biofuel, not considered in this study, is the production of biodiesel from algae ponds. The process is still in the experimental stages of development.

Energy Path 4 is the development of centralized H_2 production and distribution systems. The H_2 is produced by coal and biomass gasification plants and by water electrolysis plants using nuclear, pv, and wind electricity.[5] The costs estimates for a centralized pv H_2 production and distribution system are derived from the H_2 systems research of Ogden (1993, 2002), Cloumann et al. (1994), Dietsch (1996), Szyszka (1998), Amos (1998), Ivy (2004), Mason et al. (2006), and Mason (2003; 2006). The construction of a H_2 production and distribution system is coupled to the mass-marketing of FCVs. The average fuel efficiency of FCVs is a factor of 2.2 greater than the average fuel efficiency of the ICE vehicles replaced (General Motors Corporation et al., 2001).

The energy values applied in this analysis are: 6.1 GJ/barrel of oil; 38.4 MJ/m^3 of natural gas; 23.9 GJ/metric tonne of coal, which is an average over the grades of coal; 156.5 TJ/metric tonne of uranium;[6] 34.8 MJ/l of gasoline; and 10.8 MJ/m^3 of H_2. Energy values are also reported in terms of Mboe/d. Energy values are reported at the gross heat value. All monetary values are in 2005 US dollars.

3. Findings

3.1. Energy resource peak production dates

The estimates for peak production dates are presented in Table 2, which report peak production estimates for low- and high-reserve estimates and 1.5–2.5% demand growth rates. The findings reported in this section are the results for the nominal 2.0% demand growth rate. The findings for Paths 3 and 4 are based on the assumption that the energy used to produce alternative fuels is from one energy source. This assumption is relaxed in the sensitivity analyses, which present findings for 33% and 50% energy source allocations for alternative fuel production.

Energy Path 1 is a continuation of current energy technologies and fuel mixes, and the projected energy resource peak production dates are presented in Table 2(1). For oil, the peak production dates range from 2006 to 2020 for the low- and high-reserve cases, respectively. For natural gas, the peak production dates range from 2023 to 2046 for the low- and high-reserve cases, respectively. For coal, the peak coal production dates range from 2044 to 2101 for the low- and high-reserve cases, respectively. For uranium, the peak production dates range from 2047 to 2064 for the low- and high-reserve cases, respectively.

Energy Path 2 assumes a reduction in energy resource demand through the universal adoption of advanced energy technologies in the transportation and electricity energy use sectors. The peak production dates for Path 2 are presented in Table 2(2). For oil, the peak production dates are 2006 and 2021 for the low- and high-reserve cases, respectively. There is only a 1 year extension in the peak production date for the high-reserve case compared to Path 1 because of the high initial consumption level, an extended adoption schedule for the advanced energy technologies, and exponential demand growth. This finding indicates that increases in vehicle fuel economy will not delay the peak in conventional oil production. The natural gas finding is another cause of concern. Even with the universal adoption of combined-cycle natural gas power plants and a reduction in natural gas demand from pv/wind power plants, the natural gas peak production dates range from 2025 to 2051 for the low and high-reserve cases, respectively. The projected peak production dates for coal range from 2045 to 2104 for the low- and high-reserve cases, respectively. There is no change in the projected peak production dates for uranium since nuclear power production was not changed in this scenario.

Energy Path 3 reduces demand for conventional oil by supplementing conventional oil supplies with syncrude produced from non-conventional oil resources and biofuels produced from biomass. The production of syncrude and biofuel requires energy, which increases demand for natural gas, coal, and uranium resources. The peak production dates for Path 3 are presented in Table 2(3). The peak production dates for Path 3 in the low and high-reserve cases, respectively, are: oil—2006 and 2021; natural gas—2025–2050; coal—2043–2098; and uranium—2038–2050. The peak production dates for oil and natural gas are basically the same as the Path 2 estimates, while the peak production dates for coal and uranium are accelerated. These findings suggest a limited role for the application of natural gas and nuclear power for syncrude and biofuel production. The peak production date estimates for coal suggest that coal reserves are sufficient to support large-scale production of synfuels and biofuels.

Energy Path 4 models centralized H_2 production and distribution systems with the H_2 produced with natural gas, coal, and uranium energy sources. The peak production date estimates are presented in Table 2(4). The peak production dates in the low- and high-reserve cases, respectively, are: oil—2006 and 2022; natural gas—2024 and 2045; coal—2041–2092; and uranium—2029 and 2036. The findings indicate that the coal resource base is the only

[5]Other sources of H_2 production not considered in this analysis are natural gas by steam reformation and off-peak electricity generation. Natural gas resource constraints are the reason for not including natural gas, but in some regions it may be a suitable source of limited H_2 production. If excess off-peak electricity generation is available, it is a good source of low-cost electricity for electrolytic H_2 production. Hydropower is not included because it is more appropriate, in terms of GHG emissions reduction, to use off-peak hydro-electricity for pumped storage of water to increase production of zero-GHG emissions peak-period electricity production. Other methods of producing H_2 with nuclear energy are in the experimental stage of development such as utilizing the heat of nuclear power plants to produce H_2 from sulfuric acid and hydrogen iodide. Still another oft mentioned sources of H_2 production in the experimental stage of development are biological H_2 production systems such as algae ponds.

[6]The energy content of uranium is based on the net U energy used to generate 1 kW h of electricity. It is assumed that it takes 0.023 g U/kW h of electricity, which is derived from 365 GW of nuclear power plant capacity using 68,000 tonnes of uranium with a nuclear power plant operating capacity factor of 0.9 (Uranium Information Centre (UIC), 2005).

energy resource base sufficient to sustain large-scale H_2 production.

In summary, peak production of conventional oil reserves will occur within 20 years. This will be followed by peak production of natural gas reserves 10–15 years later. Peak production of both oil and natural gas will dramatically increase the demand for coal and uranium. The coal resource base is large, but in many regions of the world the reserves of high-grade, low-sulfur anthracite and bituminous coal are already past peak production. This implies greater utilization of lower-grade lignite coals and a greater reliance of coal supplies from more remote regions of the world. The findings indicate that the resource base of uranium is not sufficient to support the large-scale expansion of conventional nuclear power without the adoption of fast-breeder reactors. Also, it should be noted that variation in the 1.5–2.5% range in the resource demand growth rates have little impact on resource peak production dates.

3.2. *The effects of energy paths on oil supply/demand balances*

This section evaluates the effects of energy Paths 2–4 on global supply/demand balance for conventional oil at a nominal 2.0% growth rate in demand. The oil supply/demand balance with the adoption of Path 2 advanced energy technologies and Path 3 alternative fuels is presented in Fig. 2. The top curve in Fig. 2 is the real 2.0% growth rate in oil demand. The real demand curve is reduced to the second curve, which represents the Path 2 reduction in conventional oil demand through the adoption of advanced energy technologies. Demand for conventional oil is further reduced to the third curve with the addition of Path 3 alternative fuels. Paths 2 and 3 demand curves represent the nominal 2% growth rate in oil demand. The supply curves for conventional oil are presented at three peak production dates, 2006, 2015, and 2022. The conventional oil supply curves include oil production from enhanced oil recovery methods. In Fig. 2, if the peak production date for conventional oil is 2006, then the combination of Path 2 advanced energy technologies and Path 3 alternative fuels is not sufficient to maintain an oil supply/demand balance. On the other hand, if the oil peak production date is 2015, then the combination of Paths 2 and 3 is sufficient to maintain an oil supply/demand balance.

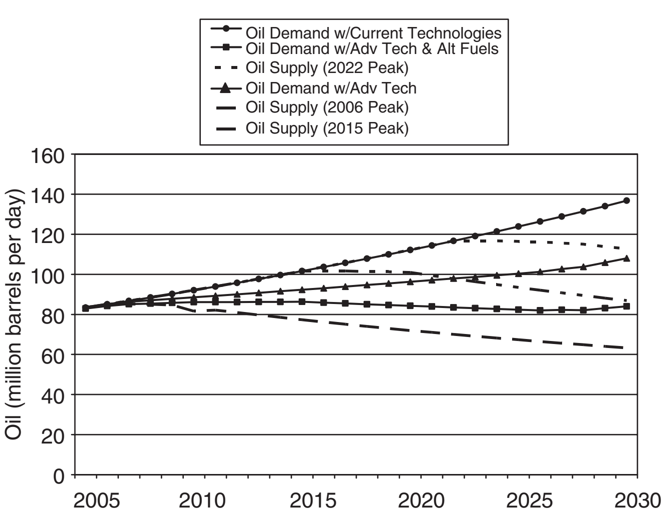

Fig. 2. Oil supply/demand balance with adoption of energy Paths 2 and 3.

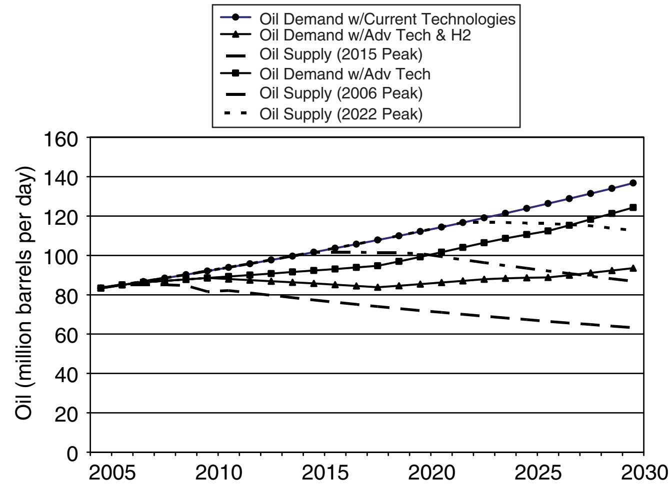

Fig. 3. Oil supply/demand balance with adoption of energy Paths 2 and 4.

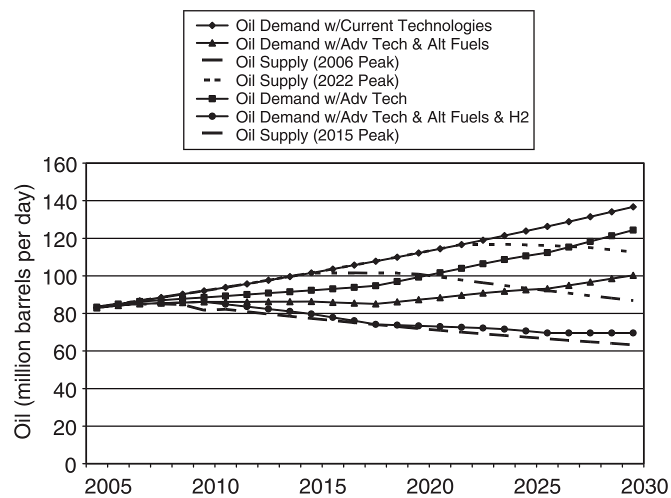

Fig. 4. Oil supply/demand balance with adoption of energy Paths 2, 3, and 4.

The effects of Path 4 H_2 and Path 2 advanced energy technologies on global oil supply/demand balances are presented in Fig. 3. As in the previous case, if the peak production date for conventional oil is 2006, then the combination of Path 4 H_2 and Path 2 advanced energy technologies is not sufficient to satisfy global oil demand. On the other hand, if the oil peak production date is 2015, then the combination is sufficient to maintain an oil supply/demand balance. The effect of Path 2 advanced energy technologies is greater in Fig. 2 than in Fig. 3, which is attributable to the fact that the full effect of demand reductions from increased fuel economy of vehicles is realized in Fig. 2. Note in Fig. 3 that there is an inflection in the Path 2 curve in year 2019, which corresponds to the date when FCVs begin to dominate the light-duty vehicle market and Path 2 demand reduction is transferred to Path 4 H_2.

The effects of a combination of all three energy paths on oil supply/demand balances are presented in Fig. 4. A combination of the three energy paths maintains a global oil supply/demand balance throughout the 2006–30 timeframe. This result highlights the large degree of change in energy use technologies and alternative fuel production that will be required to sustain 2% per annum growth in global energy use applications if there is a near-term peak in conventional oil production. The findings of this study indicate that if there is a near-term peak in conventional oil production, then alternative fuel production will need to be on the order of 44 Mboe/d by 2030 to maintain a global supply/demand balance with a nominal 2% growth rate.

3.3. Sensitivity analysis for peak production estimates

The results presented in Table 2 are premised on the assumptions regarding the efficiency gains of a specified range of advanced energy technologies and on the assumption that the energy for alternative fuel production is provided by only one energy source. Sensitivity analyses are performed to evaluate the change in energy resource peak production dates by increasing vehicle fuel economy by 400%, increasing natural gas and coal electricity generating efficiency by 100%, and by applying a 50% and 33% allocation of energy sources for the production of alternative fuels. The sensitivity results for Path 3 alternative fuel production are presented in Fig. 5, and the sensitivity results for Path 4 H_2 production are presented in Fig. 6.

The sensitivity results indicate that energy resource peak production dates are basically inelastic. For Paths 3 and 4, the large changes in advanced energy technology efficiencies coupled with variation in the allocation of energy sources for alternative fuel production result in small changes in energy resource peak production dates. A surprising result is the finding that a 400% increase in vehicle fuel economy has virtually no impact on extending the peak production date of oil in the high-reserve case. The sensitivity findings for natural gas are similar to the oil findings in that there is very little change in peak production dates. The largest changes in peak production dates, ~10 years, are for coal and uranium in the high-reserve cases.

The sensitivity findings demonstrate the inertia built into global energy resource systems by the current high levels of production and consumption. The sensitivity findings indicate that efficiency gains from the adoption of advanced energy technologies will not delay the timing of energy resource peak production events. However, the pursuit of efficiency improvements in energy use technologies is important to sustain energy supply/demand balances through alternative fuel production after resource production levels peak and then decline.

4. Discussion of findings

4.1. Evaluation of peak production date estimates

Because of the variation in peak production dates between the low- and high-reserve cases, an evaluation of

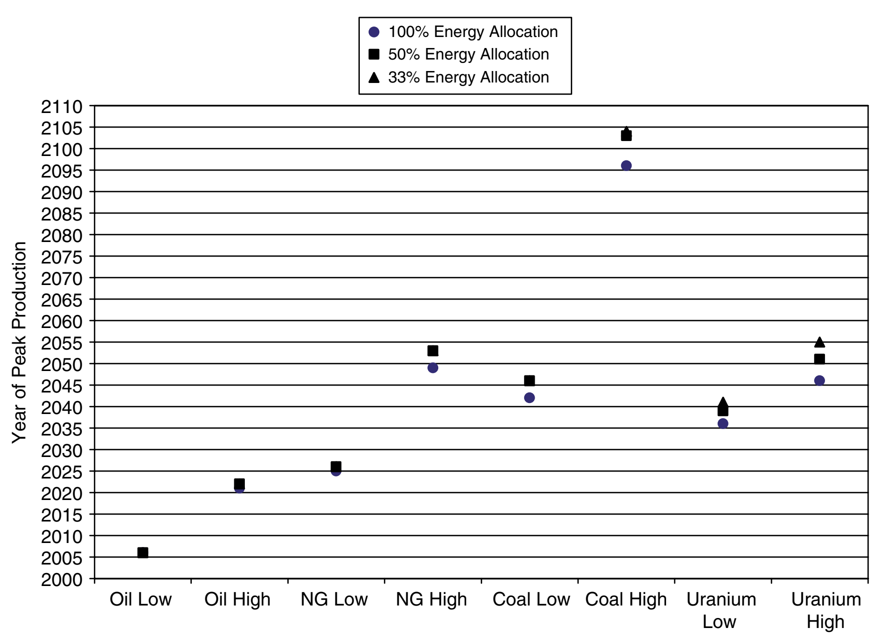

Fig. 5. Path 3 sensitivity analysis—peak production dates with a 400% increase in vehicle fuel economy and a 100% increase in electricity generating efficiencies.

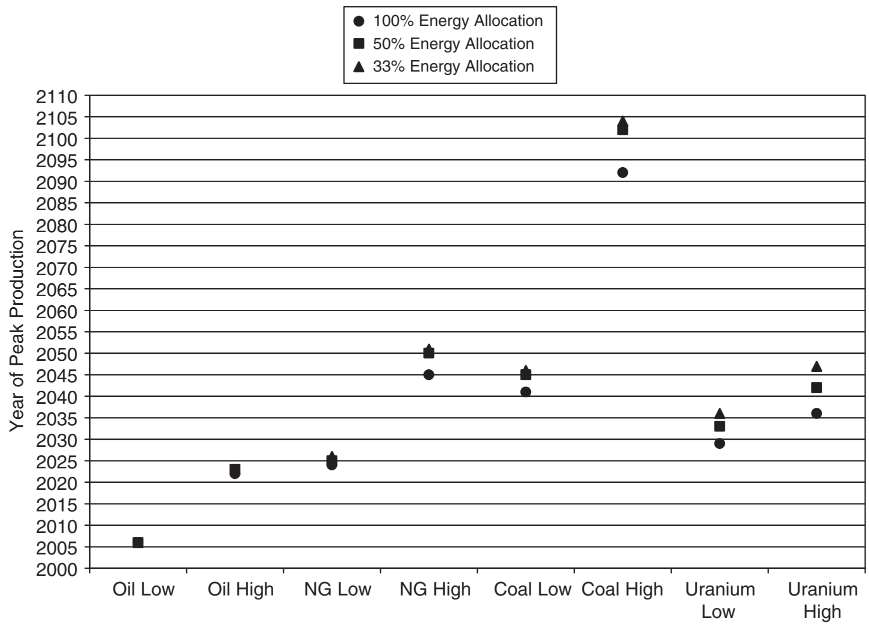

Fig. 6. Path 4 sensitivity analysis—peak production dates with a 400% increase in vehicle fuel economy and a 100% increase in electricity generating efficiencies.

whether the low- or high-reserve case estimates is the more accurate is needed. Since a global energy resource peak production event has never occurred, the only guidelines to evaluate whether the peak production estimates for the low or high-reserve cases are the more accurate are country and regional energy resource peak production events. The peaks in US and North American oil production, in US and North American natural gas production, in North Sea oil production, and in US Appalachian coal production correspond to the peak production dates for the low-reserve estimates. Also, recent analysis of the US Alaskan Prudhoe Bay, North Sea Forties, North Sea Brent and Oman Yibal giant oil fields indicate that oil recovery from these fields is less than 10% greater than the initial estimates of ultimate oil recovery, and these oil fields have utilized the most advanced oil recovery technologies (Simmons, 2003). Hence, the peak production projections based on the low estimates of economically recoverable energy reserves should be taken seriously.

There are indications that we are nearing the peak in global conventional oil production. From 2000 to 2004, the production of light-grade crude oil declined by 3.9% (OPEC, 2005). In addition, there is an increase in the proportion of oil with ‘‘sour’’ or high sulfur content in the light and medium grades of crude oil being produced. OPEC in their projections for 2006–10 state, ‘‘OPEC capacity expansion is likely to be overwhelmingly medium and heavy and predominantly sour’’ and goes on to state that world refiners are going to have to adjust future refining capacity to take into account the lower quality of oil being produced (OPEC, 2005).

The OPEC projections are in contrast to Cambridge Energy Research Associates (CERA) projections, which project a 10 Mboe/d increase in light crude production through 2010 (Jackson and Esser, 2005). A critic of the CERA report claims that the optimistic CERA projections fail to fully account for depletion rates in aging oil fields (Skrebowski, 2005). The CERA and Skrebowski projections are based on transparent, bottom-up listings of world oil projects scheduled to be brought into production through 2010. Whether the CERA or the Skrebowski projection is the more accurate should become apparent with the release of 2008 oil production reports, which is the year when the two projections begin to diverge.

Another indication that global conventional oil production is at or near peak is the high level of investments going into the development of non-conventional oil resources. The Canadian Association of Petroleum Producers (CAPP) reports that $36 billion is being invested in oil sands development to increase syncrude production from the current 1.0 to 2.7 Mboe/d by 2012 (CAPP, 2005). This brings total investments in Canadian oil sands to $70 billion with additional expansion being planned through 2015. In the case of gas-to-liquids production, nine projects with total investments of $20 billion are in various stages of planning and development in Qatar and Nigeria and have the capacity to produce 0.58 Mboe/d by 2012 (EIA, 2005). Nineteen additional gas-to-liquids plants are proposed but are on hold at present. Proposed investments in the production of ethanol from cellulosic biomass (corn husks, wood chips, and agricultural residues) total approximately $3 billion in the USA alone. The large investments in oil production from non-conventional oil resources are an indication of a perception by financial institutions that conventional oil prices will remain high due to increasing supply scarcity. This is another indication that the peak in conventional oil production is close at hand.

4.2. Issues related to the production of synfuels from non-conventional oil resources

While the oil production schedule from non-conventional oil resources presented in Table 3 appears to be achievable in terms of technological readiness and capital investments, the oil production totals are not sufficient to prevent a global oil supply/demand imbalance if the early oil peak production estimate is accurate. If peak production of conventional oil occurs from 2006 to 2012, then an additional 20 Mboe/d of oil production from non-conventional oil resources, above the Path 3 levels presented in Table 3, will be required to maintain a global oil supply/demand balance through 2030. In the case of an early peak in oil production, it appears to be technically and economically feasible to double or even triple the syncrude production schedule presented in Table 3 for oil sands, heavy oil deposits, and coal-to-liquids. However, the large-scale syncrude production from non-conventional oil resources raise concerns about energy use, GHG emissions, and water issues, which may hinder their timely scale-up.

Oil production from non-conventional oil resources increases energy use and GHG emissions. The primary energy and GHG emissions factors for the range of non-conventional oil production used in this study are presented in Table 4. The increase in energy to produce non-conventional fuels compared to conventional gasoline ranges from a high of a 225% increase for coal-to-liquids production to a low of a 63% increase for heavy oil production. Increases in GHG emissions range from a high of a 324% increase for coal-to-liquids production to a low of a 30% increase for gas-to-liquids production. Proposed solutions to the GHG emissions problem associated with non-conventional oil production are to institute carbon capture and storage (CCS) systems and to use nuclear power plants.

While CCS systems reduce GHG emissions, they create additional concerns. The installation and operation of CCS systems at coal and natural gas power plants increase capital costs, energy use, and GHG emissions. The increase in energy use for CCS systems results in efficiency losses of 14% for coal IGCC plants and 16% for natural gas combined-cycle plants (Herzog and Golomb, 2004). CCS systems increase the capital costs of coal plants by 20–25% and natural gas plants by 70–75% (Griffiths et al., 2005). The incremental cost of pre-combustion CO_2 capture systems at new coal IGCC plants and natural gas combined-cycle plants ranges from \$15 to \$24/tCO_2 avoided (Griffiths et al., 2005). The incremental cost of retrofitting existing coal and natural gas plants with post-combustion CO_2 capture systems ranges from \$53 to \$90/ton CO_2 avoided (Griffiths et al., 2005). Because of the substantial costs of CCS systems, they are unlikely to be voluntarily adopted without incentives/penalties in the form of carbon tax policies. Based on the CCS costs presented above in terms of avoided CO_2, carbon taxes of \$20–30/ton CO_2 are required as an incentive to induce the installation of CCS systems at new plants, and carbon taxes of >\$50/ton CO2 are required to induce the retrofitting of pre-existing plants with CCS systems. Because of the high capital costs to retrofit power plants with CO_2 capture systems compared to the capital costs of new plant CO_2 capture systems, it is important to ensure that all new power plants built in coming years are prepared for CO_2 capture systems even if the technology is not used initially. The challenge for policy makers is to design carbon tax policies with an incentive structure to facilitate high CCS system compliance rates. This will be a particularly challenging task for new power plants built in developing countries. Growing concerns about the effects of global warming increase uncertainty regarding the imposition of carbon taxes, which may discourage or cause delay in investments for the timely development of non-conventional oil resources.

Nuclear energy is one of the proposed solutions to the energy use and GHG emissions problems caused by non-conventional oil production. If expansion in nuclear power plants occurs at a 2% per annum rate, then the current 365 GW of nuclear power plant capacity will increase to 660 GW of capacity in 30 years. The estimated peak production dates for uranium at a 2% growth rate are 2047 and 2064 for the low- and high-reserve cases, respectively. Therefore, the uranium resource base should be sufficient to sustain a 2% growth rate in nuclear power plant capacity through 2030. While the findings related to uranium peak production dates for Paths 3 and 4 indicate that the uranium resource base is not sufficient to support 100% of the energy for alternative fuel production, the uranium resource base is sufficient for nuclear power to provide a reduced, yet still significant, level of energy for alternative fuel production. If nuclear power is to play an expanded role in meeting future energy needs, then fast-breeder reactors will be required to extend the uranium resource base. Fast-breeder nuclear reactors are in the experimental stage of development and have to overcome significant performance, safety, cost, and nuclear weapon proliferation problems.

A new generation of fast-breeder reactors is being proposed with advanced reprocessing of spent nuclear fuels that pose less of a proliferation risk and significantly reduce the amount of radioactive waste requiring long-term disposal. Current plans for the global expansion of nuclear power plant capacity is contingent on advanced nuclear countries selling reactors and nuclear fuel to developing nations, and the spent fuel is then to be returned to the host country and recycled. The relevant question concerns the effectiveness of international spent fuel monitoring systems. At present there is approximately 365 GW of global nuclear power plant capacity, but even with this relatively small nuclear power plant capacity and international regulatory scrutiny, there is enough highly

Table 5
H_2 levelized pump prices

	Coal H_2[a] (\$/GJ H_2)	Nuclear H_2[b] (\$/GJ H_2)	PV H_2[c] (\$/GJ H_2)	Wind H_2[d] (\$/GJ H_2)
H_2 production plant	11.71	17.67	20.32	21.65
H_2 plant administration facilities	0.07	0.16	0.16	0.07
Compression station	0.79	1.12	1.66	1.53
Pipeline	0.23	0.23	0.23	0.23
Pipeline booster compressors	0.01	0.01	0.01	0.01
Underground storage	0.03	0.03	0.03	0.10
City Gate distribution facilities	0.15	0.15	0.15	0.15
City Gate metal hydride H_2 containers	2.00	2.00	2.00	2.00
City Gate compression	0.52	0.52	0.52	0.52
City Gate H_2 delivery trucks	1.09	1.09	1.09	1.09
Filling station H_2 dispensing costs	0.70	0.70	0.70	0.70
H_2 levelized pump price w/o fuel tax (\$/GJ)	17.29	23.67	26.87	28.04
H_2 gasoline equivalent pump price (\$/GJ)	7.78	10.65	12.09	12.62
Characteristics of a H_2 production and distribution system per 1-million FCVs				
Capital costs (billion \$)	2.30	4.21	7.53	7.60
Size of electrolyser plant (GW)		1.41	4.70	3.88
Size of electricity power plant (GW)		1.61	5.49	5.41
Annual fuel consumption (metric tons)	2 046 183	331	0	0
Land area (km^2)	2	2	39	282
Electricity power plant				
Levelized cost of electricity (\$/kW h)	0.050	0.045	0.051	0.049

[a]The capital costs of a coal gasification plant are assumed to be \$1000/kW.
[b]The capital costs of a nuclear power plant is assumed to be \$1500/kW with a 90% operating capacity factor.
[c]The capital costs of a pv power plant is \$917/kW with 12% efficient pv and sited at a location with a minimum average solar insolation of 271 W/m^2.
[d]The capital costs of wind power plant is \$900/kW and sited at a location with a minimum average wind power density of 500 W/m^2. The average annual capacity factor of the wind turbines are assumed to be 34%.

enriched uranium unaccounted for to build numerous nuclear bombs the size and type of the Hiroshima nuclear bomb (Glaser and von Hippel, 2006). Because of the apparent intractability of the nuclear weapons proliferation problem, it is likely that proposals to significantly increase nuclear power plant capacity internationally will meet with opposition, which may prove problematic for the timely expansion of nuclear power plant capacity to meet the energy requirements of energy Paths 3 and 4.

4.3. H_2 production and distribution systems

The development of centralized H_2 production and distribution systems is another means of offsetting declines in conventional oil production. The primary concerns about H_2 production and distribution systems are the high capital costs compared to other energy sources, refer to Table 3, and the need to construct a H_2 distribution system. Coal is a good feedstock for large-scale H_2 production, but the optimum scale of coal use for H_2 production needs to be evaluated since the Path 4 findings indicate that coal production will peak within 40 years in the low-coal-reserve case. Also, it is important to keep in mind that the demand for coal will increase significantly when natural gas production peaks. Another mature technology for H_2 production is electrolysis of water. A comparative analysis of the levelized cost components of H_2 produced by coal gasification and water electrolysis using nuclear, pv, and wind electricity is presented in Table 5.[7] The H_2 gasoline equivalent pump price for each of the H_2 production methods presented in Table 5 is lower than the 2005 US gasoline pump price of approximately \$14.00/GJ.[8]

Electrolytic H_2 produced with pv and wind electricity is a clean, safe, sustainable, and weapon- free energy source. Electrolytic H_2 produced with pv and wind electricity reduces fuel cycle energy use and GHG emissions by $>90\%$ without the need for CCS systems (Mason, 2006). Post-2040, second-generation pv and wind electrolysis plants can produce H_2 as a fuel substitute for electricity

[7]The levelized production cost of electrolytic H_2 using intermittent energy sources such as pv and wind electricity is only 10–20% greater than the production cost of electrolytic H_2 using energy sources with higher electrolyser capacity factors. Electricity price, not electrolyser cost, drives the production cost of electrolytic H_2. Electricity price accounts for 70–80% of the production cost of electrolytic H_2, while the electrolyser cost component contributes less than 20% to the production cost of electrolytic H_2.

[8]The fuel economy of FCVs is a factor of 2.2 greater than that of conventional ICEs, therefore the gasoline equivalent pump price of H_2 is calculated by adjusting the levelized pump price of H_2 by a factor of 0.45.

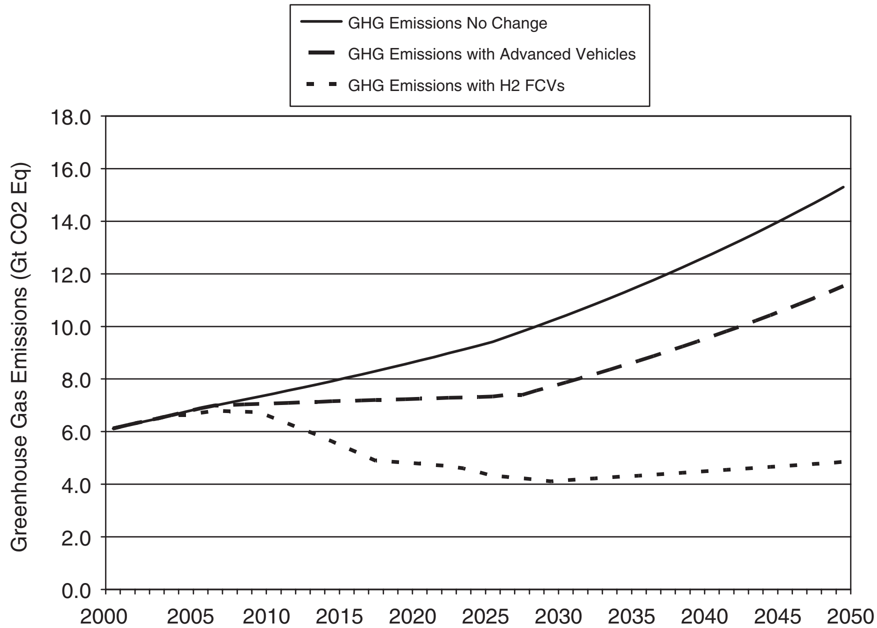

Fig. 7. Greenhouse gas emissions for transportation comparing Paths 1, 2, and 4.

generation at combined-cycle power plants.[9] The cost of H_2 produced at first-generation pv and wind electrolysis plants is too expensive to be considered as a fuel for electricity generation. However, the construction of second-generation plants post-2040 will result in significant reductions in pv and wind electrolytic H_2 production costs due to the amortization of many H_2 system components including manufacturing plants. The projected cost of second-generation pv/wind electrolytic H_2 delivered to combined-cycle power plants is \$12–\$14/GJ, which translates into a levelized wall-outlet electricity price of \$0.12–\$0.14/kW h (Mason, 2006). The electricity prices are comparable to current US high-end electricity prices.

The negative aspect to pv and wind electrolytic H_2 production is high capital costs. However, the evaluation of the capital costs for pv and wind electrolytic H_2 production systems need to take into account labor market dynamics. PV and wind electrolytic H_2 production is manufacturing intensive. Job creation in the manufacturing sector for pv, wind, and electrolyser components will far outweigh job losses in the current liquid fuels production sectors. The job creation will result in economic growth and capital formation, which will help support the high level of capital investments. The benefits of a pv and wind electrolytic H_2 system are higher-performance vehicles, zero-GHG emissions, and stable fuel prices.[10]

On a final note, if GHG emissions reduction becomes the primary issue, then H_2 is the best path to zero-GHG emissions in the transportation sector. Transportation GHG emissions for Paths 1, 2, and 4 are presented in Fig. 7.[11] The inflection point in the GHG emissions curves for Paths 2 and 4 represent the universal adoption of advanced vehicles in 2027, and the upward GHG emissions trend post-2027 is caused by aggregate growth in transportation fuel consumption. It is a cause of concern that the universal adoption of advanced fuel economy light-duty vehicles and light commercial trucks and the application of zero-GHG emissions biofuels for 30% of total gasoline consumption does not reduce GHG emissions below current GHG emissions levels in the transportation energy use sector. From the information provided in Fig. 7, it is obvious that if there are to be significant reductions in the current level of GHG emissions from transportation then zero-GHG emissions H_2 will need to be utilized by additional modes of transportation.

[9]This analysis does not include electricity generation by stationary fuel cells. Stationary fuel cells may prove to be a lower cost source of electricity produced with H_2. The purpose of utilizing combined-cycle electricity generating plants is this analysis is to demonstrate the applicability of H_2 as an economical source of electricity in the future.

[10]Larry Burns of GM states that FCVs will sell because they are "better cars" rather than because of the price of gasoline, and he states that GM is on pace to meet its goal to have FCVs market ready by 2010 (Motavalli, 2005). Significant advances are occurring in fuel cell performance, fuel cell production costs, and hydride storage systems.

(*footnote continued*)

[11]The GHG emissions for Path 1 are based on 2005 vehicle technology and fuels mixes. The GHG emissions for Path 2 are based on a doubling in the average fuel economy of light-duty vehicles and light commercial trucks, and zero-emission biofuels account for 17% of all transportation fuel by 2027. It is assumed that transportation accounts for 55% of total oil production and that the light-duty vehicles and light commercial trucks account for 49% of transportation fuel consumption. The GHG emissions estimates are based on 66 g CO_2 Eq/MJ_e of fuel combusted. The life cycle GHG emissions for transportation fuels include only 1.2 g CO_2 Eq/MJ_e for fuels production since it is assumed that 90% of CO_2 emissions are captured and sequestered in fuel production stages.

5. Conclusions

This study finds that conventional oil production will peak within 20 years and that natural gas production will peak 10–20 years later. These two events will dramatically increase demand for coal and uranium, which implies that the world will be confronted with serious fossil fuel resource constraints by 2050. The problem is further aggravated by the uneven geographical distribution of fossil fuel resources.

Of immediate concern is the approaching peak in global conventional oil production. Two distinct paths of supplementing conventional oil supply are (1) a continuation of liquid fuels use through the large-scale development of non-conventional oil resources such as oil sands, heavy oils, biofuels, coal-to-liquids, and oil shale, and (2) the beginning of a break with liquid fuels for transportation through the development of H_2 production and distribution systems and the introduction of mass-produced fuel cell vehicles (FCVs). The capital costs of developing non-conventional oil resources are much less than the development of a H_2 production and distribution system. However, there are significant unresolved issues regarding the large-scale development of non-conventional oil resources to supplement declines in conventional oil production. The primary concerns are increased energy use, vehicle tailpipe greenhouse gas (GHG) emissions, and water issues.

Due to the evolving global energy resource constraints in coming decades, the need for a H_2 production and distribution system is inevitable. The strongest argument for the near-term development of H_2 production systems and a transition to FCVs is the elimination of tailpipe GHG emissions, which lowers the risk of experiencing the most severe consequences of global warming. The development of an H_2 system is a large and costly task, and the sooner the process is begun, the less the economic burden on future generations.

In conclusion, this study raises five important research questions. What are the environmental risks of super large-scale development of oil shale, oil sands, and heavy oils? What are the risks of nuclear weapon proliferation from the large-scale, international expansion of nuclear power plants? What is the optimum level of coal production for alternative fuel production to minimize the risks of coal supply/demand imbalance when coal production peaks? What is the potential of using off-peak hydro- or nuclear electricity capacity for electrolytic H_2 production? What are the macro-economic effects of pv and wind electrolytic H_2 production and distribution systems?

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