Peak Energy and the Limits to Global Economic Growth

Annual Report 2011

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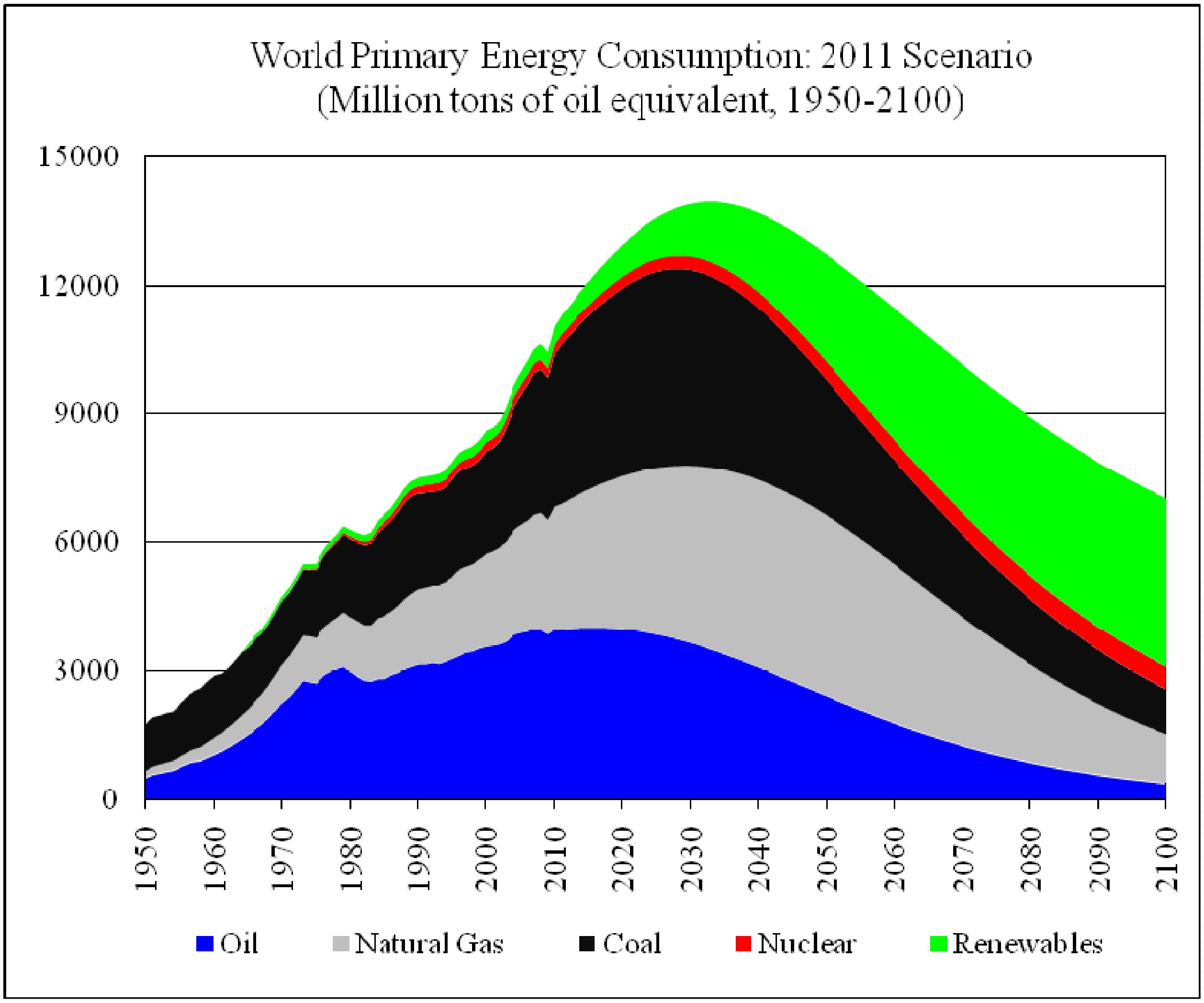
World Primary Energy Consumption: 2011 Scenario
(Million tons of oil equivalent, 1950-2100)
15000
12000
9000
6000
3000
0
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Oil
Natural Gas
Coal
Nuclear
Renewables

About the Author

Minqi Li was a political prisoner in China from 1990 to 1992. He received PhD in economics from University of Massachusetts Amherst in 2002. He taught political science at York University, Canada from 2003 to 2006. He has been teaching economics at University of Utah since 2006. He has published many articles on peak oil, climate change, and global economic crisis in journals such as *Monthly Review*, *Science & Society*, *Review*, *Journal of World Systems Research*, *Development & Change*, and *Journal of Contemporary Asia*. He has given invited talks on these subjects in US, Canada, China, and Europe on numerous occasions. His book *The Rise of China and the Demise of the Capitalist World Economy* was published by the Pluto Press and the Monthly Review Press in 2009.

Abstract

World oil production will peak before 2020; world coal production will peak before 2030; and world natural gas production will peak around 2040. World total energy supply will peak in the mid-2030s. As rising energy efficiency fails to offset declining energy supply, gross world output peaks around 2050 and declines over the second half of the 21st century. While the carbon dioxide emissions from fossil fuels consumption are projected to peak before 2030, the cumulative carbon dioxide emissions over the century imply a long-term global warming of 3.5-7°C, with potentially catastrophic consequences for the humanity.

Key Words

Peak Oil; Peak Energy; Limits to Growth; Global Economy; Climate Change

Introduction

Currently the world economy depends on fossil fuels for 94 percent of the total primary energy supply (based on the definitions used in this report, see the section on "conversion of nuclear and renewable electricity"). Fossil fuels are non-renewable energies. The consumption of fossil fuels results in the emission of carbon dioxide and other greenhouse gases that threaten to bring about dangerous climate change. Current evidence suggest that world oil production may peak in the near future. World coal and natural gas production may peak before the mid-21st century. The coming peak of the global supply of fossil fuels, along with the exhaustion of the global environmental space, will impose potentially insurmountable limits on global economic growth, with far reaching economic, social, and political implications.

This report attempts to examine the developments of global energy supply and consumption, project the future trajectories of global energy, and evaluate the energy impact on global economic growth and climate change over the course of the 21st century. The study will be updated and improved annually in the future.

The key findings of this year's report are the following. World oil production will peak before 2020; world coal production will peak before 2030; and world natural gas production will peak around 2040. Despite the rapid expansion of renewable energies, world total energy supply will peak in the mid-2030s. As rising energy efficiency fails to offset declining energy supply, gross world output peaks around 2050 and declines over the second half of the 21st century.

The carbon dioxide emissions from fossil fuels consumption are projected to peak before 2030 and decline through the rest of the 21st century. However, the cumulative carbon dioxide emissions over the century imply a long-term global warming of 3.5-7°C (degrees Celsius) relative to the pre-industrial time, with potentially catastrophic consequences for the humanity.

Sources of Data

Historical data of world production of oil, natural gas, and coal before 1965 are from Rutledge (2007). Historical data of world production and consumption of oil, natural gas, coal, nuclear electricity, and renewable energies from 1965 to 2010 are from BP (2011). Additional energy data are from the International Energy Agency (IEA), the US Energy Information Administration (EIA), and the World Energy Council (WEC).

Historical data of world economy are from Maddison (2003) and World Bank (2011). World economic projections for 2011 and 2012 are from the International Monetary Fund (IMF).

Conversion of Nuclear and Renewable Electricity

In this study, nuclear electricity, hydro electricity, and other renewable electricity are all measured by their electrical energy content (not "thermal equivalents"). They are all converted into oil equivalents based on the following conversion ratio: 1 million tons of oil equivalent = 11.63 terawatt-hours (billion kilowatt-hours).

This conversion formula allows one to define the total energy supply and consumption as well as energy efficiency in a consistent and straightforward manner.

Tables and Figures

All tables and figures (with the exception of the figure on page 1) are placed towards the end of the paper, after the bibliography section.

World Energy in 2010

2010 was the first year of global economic recovery after the deepest global economic crisis since the 1930s. From 2009 to 2010, world oil consumption (excluding biofuels) grew by 2.9 percent, natural gas consumption grew by 7.4 percent, and coal consumption grew by 7.6 percent. World consumption of nuclear electricity grew by 2.0 percent. World consumption of renewable energies (including hydro electricity, other renewable electricity, and biofuels) grew by 7.9 percent.

World total primary energy consumption reached 11,035 million tons of oil equivalent in 2010. World energy consumption grew by 5.7 percent from 2009 to 2010. In 2010, Oil, natural gas, and coal accounted for 36.0, 25.9, and 32.2 percent of the total world energy consumption respectively. Nuclear electricity accounted for 2.2 percent. All forms of renewable energies together accounted for 3.8 percent.

World economic output, measured by the Gross World Product (or world GDP) in constant 2005 international dollars, grew by 5 percent in 2010. It follows that world energy efficiency (the ratio of world GDP over world energy consumption) declined by 0.7 percent.

World carbon dioxide emissions from fossil fuels consumption (excluding emissions from biofuels) increased by 5.8 percent in 2010. It follows that world emission intensity of GDP (the ratio of world carbon dioxide emissions over world GDP) increased by 0.7 percent.

Peak Oil and the Global Economy

Oil is crucial for the normal functioning of the global economy, especially for transportation, agriculture, and chemical industries (Heinberg 2006: 35-64). According to IEA (2010), in 2008, oil accounted for 96 percent of the world energy consumption in the transportation sector, 29 percent in the industrial sector (including non-energy uses), and 15 percent in the residential and commercial sector. Oil provided the fuel for 6 percent of the world electricity generation.

In 2010, world oil production (excluding biofuels and coal derivatives) was 3,914 million tons (or 82.1 million barrels a day). Figure 1 shows the annual oil production of the world's five largest producers. Among the largest oil producers, the US clearly peaked in 1970 and Iran peaked in 1974. Both Russia and Saudi Arabia are currently producing at below their respective historical record levels (1987 for Russia and 2005 for Saudi Arabia). Only China has achieved sustained growth in production.

Figure 2 shows the observed world oil supply curve: the relationship between real oil price (in constant 2010 dollars) and the world oil production (broadly defined to include all liquid fuels in this figure). "Real oil price" measures the relative price between oil and the average price level of general goods and services.

Real oil price was very stable at about 10-12 dollars a barrel before 1973. Oil price surged after 1973 and surged again in 1980 during the two oil shocks caused by geopolitical conflicts. From 1986 to 2003, despite dramatically increased volatility, oil price had fluctuated within the range of 20-40 dollars a barrel, suggesting high "elasticity" in long-term oil supply. That is, from the mid-1980s to the early 2000s, world oil supply could expand relatively easily without forcing sustained rises in oil price. However, from 2003 to 2008, world oil production appeared to have completely lost the elasticity in supply. While the annual average oil price surged to 100 dollars a barrel in 2008, there was virtually no increase in oil production from 2004 to 2008.

World oil production increased significantly in 2010. But the observed oil supply curve remains very steep. Based on the EIA's current projections (EIA 2011), world daily oil supply in 2011 will be 3.3 million barrels above the 2009 level. If the world oil price averages 95-100 dollars a barrel in 2011, then world oil price this year would be approximately 35-40 dollars higher than in 2009. It follows that it would take an oil price increase of about 10 dollars a barrel to induce each additional one million barrels of oil supply.

Figure 3 shows the historical relationship between world oil spending and the growth rates of the global economy. Historically, whenever the world oil spending (the total market value of the world oil consumption) rises to more than 4 percent of world GDP (measured in current or nominal US dollars) over a sustained period (that is, over several years), the global economy had sunk into deep recessions. This happened in 1974-1975, 1980-1982, and 2008-2009.

The global economy now appears to be back into this dangerous territory. The world nominal GDP now stands at about 70 trillion dollars. World oil consumption is likely to average 88-89 million barrels a day in 2011. Given these conditions, it takes an annual average oil price of 90 dollars a barrel to keep the world oil spending at more than 4 percent of world GDP and an oil price of 110 dollars a barrel to keep the world oil spending above 5 percent of world GDP.

Figure 4 presents the evolution of world oil supply capacity (for all liquid fuels) from 2000 to 2010 and projections up to 2020. Data for world oil production by product type and OPEC surplus capacity as well as projections for 2011 and 2012 are from the US Energy Information Administration. After 2012, the daily supply of natural gas liquids and other liquids is assumed to rise by 500,000 barrels a year through 2020.

After 2012, change in crude oil supply capacity is estimated by calculating the difference between the newly added capacity and the depletion of the existing crude oil production. Existing crude oil production is assumed to deplete at an annual rate of 4 percent. Data for new additions of crude oil supply capacity are from the Wikipedia page on "Oil Megaprojects."

World oil supply capacity is projected to peak in 2012 (at about 93 million barrels a day) and stay on a plateau until 2015. OPEC surplus capacity is assumed to be depleted at a rate of one million barrels a year from 2013 to 2015. By 2015, the remaining OPEC surplus capacity would have been virtually exhausted.

Given these projections, the world oil price may experience a major surge between 2012 and 2015. It could take another deep global economic recession to stabilize the oil price.

Figure 5 shows the historical growth rates of the world's cumulative production of oil (excluding biofuels and coal derivatives). By 2010, about 160 billion tons of oil has been produced in the entire history of world oil production. Applying linear trend to the cumulative production growth rates (the ratios of the current production to cumulative production) from 1993 to 2010, the result suggests that the world's ultimately recoverable oil resources will be about 370 billion tons and the remaining recoverable oil resources will be about 210 billion tons (regression R-square = 0.965; this is known as the "Hubbert Linearization" technique, named after the American geologist who successfully predicted the US oil production peak).

Figure 6 compares the historical oil production with the projected oil production trajectory. The projection is based on the linear regressions results shown in Figure 5. World oil production (excluding biofuels and coal derivatives) is projected to peak in 2016 with a production level of about 4 billion tons, which approximately corresponds to 84 million barrels of daily production of crude oil and natural gas liquids.

The projected world oil production presented in Figure 6 is used by this report for the total energy projection to be discussed later.

Natural Gas Uncertainties

Natural gas plays an important role in electricity generation in meeting the peak demands. It is the preferred fuel in the residential and commercial sector in the advanced capitalist countries. It also serves as an essential input in certain industrial sectors (for example, in the making of fertilizers). In 2008, natural gas accounted for 21 percent of the world energy consumption in the residential and commercial sector, 19 percent in the industrial sector (including non-energy uses), and 3 percent in the transportation sector. Natural gas accounted for 21 percent of the world's electricity generation (IEA 2010).

In 2010, world natural gas production was 3,193 billion cubic meters (1 billion cubic meters = 35 billion cubic feet; 1 billion cubic meters of natural gas = 0.9 million tons of oil equivalent). Figure 7 shows the annual natural gas production of the world's five largest producers.

World's proved natural gas reserves currently stand at 187 trillion cubic meters (about 170 billion tons of oil equivalent). According to the International Energy Agency's recent special report, the world's remaining recoverable natural gas resources amount to about 800 trillion cubic meters, including 400 trillion cubic meters of conventional natural gas, 204 trillion cubic meters of shale gas, 118 trillion cubic meters of coalbed methane, and 84 trillion cubic meters of tight gas (IEA 2011). However, some analysts believe that the development of unconventional natural gas resources, such as shale gas, involves high economic and environmental costs and their potentials have been greatly exaggerated (Hughs 2011).

This report uses the "creaming curve" approach to evaluate the ultimately recoverable natural gas resources. The approach estimates the ultimately recoverable resources by examining the historical trajectory of the "observed ultimately recoverable resources" and projecting the historical trend.

Figure 8 presents the historical growth rates of the world's observed ultimately recoverable natural gas resources (the growth rates are defined as the ratios of annual change in the observed ultimately recoverable resources to the current level). The observed ultimately recoverable natural gas resources are defined as the sum of the current proved reserves and the cumulative production. In 2010, the world's cumulative natural gas production was about 80 billion tons of oil equivalent and the world's proved natural reserves were 170 billion tons of oil equivalent. Thus, the observed ultimately recoverable natural resources as of 2010 were 250 billion tons of oil equivalent.

In Figure 8, regression over the historical growth rates for the period 1981-2010 leads to a downward linear trend suggesting the world's ultimately recoverable natural gas resources to be 374 billion tons of oil equivalent. Figure 9 compares the historical evolution of the observed ultimately recoverable natural gas resources and the projected trend (the "creaming curve"). In this report, it is assumed that the world's ultimately recoverable natural gas resources will be 400 billion tons of oil equivalent, approximately half the level of the IEA estimate.

Given the assumed ultimately recoverable resources, this author conducts a logistic fit to the historical world natural gas production levels. Figure 10 compares the historical world natural gas production with the projected production. The parameters are calibrated so that the predicted productions levels roughly correspond to the actual productions levels for the most recent years. World natural gas production is projected to peak in 2041 with a production level of about 4.4 billion tons of oil equivalent.

Peak Coal and China

Coal is mainly used for "base load" electricity generation (to meet the part of the electricity demand that requires constant flows) and is an essential input in the iron and steel industry. In 2008, coal accounted for 22 percent of the world's energy consumption in the industrial sector (including non-energy uses) and 4 percent of the energy consumption in the residential and commercial sector. Coal accounted for 41 percent of the world's electricity generation (IEA 2010).

In 2010, world coal production was 7,273 million tons (1 ton of coal = 0.5 ton of oil equivalent). Figure 11 shows the annual coal production of the world's largest five producers. The world coal production and consumption is dominated by China. In 2010, China accounted for 45 percent of the world coal production (by volume) and 48 percent of the world coal consumption (by energy content).

The BP *Statistical Review of World Energy* reports China's coal reserves to be 114.5 billion tons. This is the number that is widely cited by media and used by virtually all international energy institutions as China's "proved" coal reserves. In fact, the BP number has not been updated since 1992. Given the observed rapid growth of China's coal production, the reserves number reported by BP is likely to have substantially underestimated China's remaining recoverable coal resources. Some earlier studies that relied upon the BP number suggested that China's coal production could peak before 2020 and the peak production level would be less than 3 billion tons (see Heinberg 2009: 55-73). In fact, China produced 3.2 billion tons of coal in 2010.

Tao and Li (2007) used China's official coal reserves at the end of 2002 published by China's Ministry of Land and Natural Resources and estimated that China's coal production could peak between 2025 and 2032, and the peak production level was likely to be between 3.3 and 4.5 billion tons. However, the Chinese government does not regularly publish the official coal reserves. According to various news releases, at the end of 2001, 2002, and 2003, China's official coal reserves were 189.1, 188.6, and 189.3 billion tons respectively.

Since 2001, *The Statistical Yearbook of China* (published by China's National Bureau of Statistics) has published regularly China's coal "reserve base." While "reserves" refer to the economically recoverable coal that can be actually produced after mining losses have been subtracted, "reserve base" refers to the economically recoverable coal before the subtraction of mining losses. For 2001, 2002, and 2003, China's reserve base was reported to be 334.1, 331.8, and 334.2 billion tons respectively. A comparison of the two sets of numbers suggests that the implied recovery factor (the ratio between reserves and the reserve base) is about 57 percent.

In this study, a 60 percent recovery factor is applied to China's coal reserve base from 2001 to 2009 to derive a "standardized" estimate of China's remaining recoverable coal resources. The remaining recoverable coal resources in 2010 are assumed to be the same as in 2009 (the official data for 2010 are not yet available). From 1981 to 2000, *The Statistical Yearbook of China* published annually China's "identified coal resources." In 2001, the identified coal resources were 1.02 trillion tons or three times the reserve base. This study applies a 20 percent recovery factor to China's identified coal resources from 1981 to 2000 to estimate the remaining recoverable coal resources during the period.

The sum of the estimated remaining recoverable coal resources and the cumulative coal production is defined as the "observed ultimately recoverable coal resources." Figure 12 shows the historical growth rates of China's observed ultimately recoverable coal resources. Regression for the period 1991-2010 leads to a downward linear trend suggesting China's ultimately recoverable coal resources to be 257 billion tons. Figure 13 compares the historical evolution of the observed ultimately recoverable resources and the projected trend.

This report assumes that China's ultimately recoverable coal resources will be 260 billion tons. Given this assumption, China's future coal production can be projected by fitting a logistic curve to historical production levels. Figure 14 compares China's historical coal production and the projected production. China's coal production is projected to peak in 2027 with a production level of 5.1 billion tons.

In 2010, China overtook the United States to become the world's largest energy consumer. China now accounts for about 20 percent of the world's energy consumption and about 25 percent of the world's total carbon dioxide emissions. China's future development will have a major impact on the global economic, social, political, and ecological trajectories in the 21st century.

China depends on coal for 70 percent of the energy supply. If China's coal production slows down dramatically and eventually declines in the coming years, China's economic growth (and by implication global economic growth) will be severely constrained.

From 2000 to 2010, the Chinese economy expanded at an average annual rate of 10.4 percent and China's coal production grew at an average annual rate of 8.9 percent. The economic growth rate was higher than the coal production growth rate only by 1.5 percentage points. However, after 2005, China's energy efficiency improved rapidly. From 2005 to 2010, the economic growth rate accelerated to 11.1 percent and the coal production growth rate slowed down to 6.6 percent. The economic growth rate was higher than the coal production growth rate by 4.5 percentage points.

Taking the experience of 2005-2010 as a guide, this report generously assumes that China's future economic growth rates will be coal production growth rates plus five percentage points. According to this report's projection, China's average annual growth rate of coal production will slow down to 3.8 percent for 2010-2020, 0.7 percent for 2020-2030, -2.3 percent for 2030-2040, and -4.6 percent for 2040-2050. Simple calculation suggests that China's average annual economic growth rate could slow down to about 9 percent for 2010-2020, 6 percent for 2020-2030, 3 percent for 2030-2040, and 0 percent for 2040-2050. In other words, the Chinese economy will decelerate sharply after China's coal production peaks and approach complete stagnation by the 2040s.

According to the BP *Statistical Review of World Energy*, at the end of 2010, world (excluding China) had 746.4 billion tons of coal reserves. However, out of the total coal reserves, 403.9 billion tons were sub-bituminous and lignite coal, that is, coal with low energy content and economic value. Only 342.6 billion tons were anthracite and bituminous coal of relatively high quality.

Figure 15 shows the historical growth rates of world (excluding China)'s cumulative production of coal. A long-term downward linear trend can be established based on the growth rates from 1931 to 2010 (regression R-square = 0.724). The world (excluding China)'s ultimately recoverable coal resources will be about 660 billion tons and the remaining recoverable coal resources will be about 400 billion tons. The predicted remaining recoverable coal resources roughly correspond to the anthracite and bituminous coal reserves reported by BP.

Figure 16 compares the world (excluding China)'s historical coal production and the projected coal production. The world (excluding China)'s coal production is projected to peak in 2027, with a production level of 4.1 billion tons.

Nuclear Electricity

In 2010, the world consumed 2,767 terawatt-hours of nuclear electricity (11.63 terawatt-hours = 1 million tons of oil equivalent). Nuclear electricity accounted for 13 percent of the world's total electricity consumption (BP 2011).

Nuclear electricity has serious safety, security, and waste disposal concerns. Nuclear power plants construction in the future is likely to be slowed down by growing public resistance in the western world and potentially also in other parts of the world.

Nuclear electricity generation uses uranium, which is a nonrenewable resource. Unless in the future there are major technical breakthroughs in the development of breeder reactors and fusion reactors, nuclear electricity expansion will be limited by the available uranium resources in addition to the public concerns of other problems.

According to the World Energy Council, the world's total identified uranium resources were 6.3 million tons at the beginning of 2009. In addition, it was estimated that the world could have 10.4 million tons of undiscovered uranium resources (WEC 2010: 202-242). The world's cumulative uranium production up to 2010 was 2.5 million tons. The sum of cumulative production, identified resources, and undiscovered resources amounts to 19.2 million tons. This report assumes that the world's ultimately recoverable uranium resources will be 20 million tons.

Figure 17 shows the historical and projected world uranium production, and nuclear electricity generation. Nuclear electricity generation is assumed to grow in proportion with the uranium production in the future. Both uranium production and unclear electricity generation are projected to peak in 2088, when world nuclear electricity generation will rise to 6,300 terawatt-hours, more than double the present level.

Renewable Energies

Hydro electricity is currently the most important renewable energy. In 2010, the world consumed 3,428 terawatt-hours of hydro electricity and 701 terawatt-hours of other renewable electricity (11.63 terawatt-hours = 1 million tons of oil equivalent). Hydro electricity accounted for 16 percent of the world's total electricity consumption, other renewable electricity accounted for about 3 percent. In 2010, the world' total biofuels production was 59 million tons of oil equivalent (or 1.9 million barrels of daily production) (BP 2011).

Among the renewable energies, hydro electricity, tide, wave, and geothermal have limited physical potentials and are unlikely to become a worldwide dominant source of energy. Wind, solar, and biomass are the three renewable sources that have a physical potential to make a very large contribution to the future world energy supply (Trainer 2007: 107-111; Smil, 2010: 105-153).

The expansion of the renewable energies faces short-term, medium-term, and long-term obstacles. In the short-term and medium-term, the growth of renewable energies is limited by their relatively high economic costs. Table 1 compares the electricity generating cost of conventional and renewable power plants using the latest cost estimates from EIA (2010). Solar and wind electricity remains more expensive than conventional electricity. Solar electricity (in the form of stand-alone power plant) is currently about five times as costly as coal-fired electricity and wind electricity is about 50 percent more expensive than coal-fired electricity. Nuclear electricity appears to be cheap, but the potentially high cost of nuclear power plant decommissioning has not been taken into account.

The world currently has a total installed electricity generating capacity of about 5,000 giga-watts with an average capacity utilization rate of about 50 percent. Assuming the coal-fired power plant sets the standard (about 3 billion dollars per giga-watt), then the 5,000 giga-watts currently represent a total capital investment of about 15 trillion dollars, approximately 20 percent of world GDP. If the 5,000 giga-watts were to be entirely replaced by solar power plants, given the solar power plants' comparatively low capacity utilization rates, it would take about 15,000 giga-watts of solar power plants. At the cost of 5 billion dollars per giga-watt, the total capital investment of the 15,000 giga-watts of solar power plants would amount to 75 trillion dollars, or great than the world's current GDP. Clearly this would represent a forbidding economic cost for the current global economy.

In the long run, renewable energies are limited by the physical availability of land and various nonrenewable mineral resources. Green, Baski, and Dilmaghani (2007) estimated the long-term physical potential of renewable energies. Using the same assumptions regarding land availability as those used by the Working Group III of the IPCC (Intergovernmental Panel on Climate Change), assuming that 1 percent of the world's total unused land (or 390,000 square kilometers) is used to produce solar electricity, 4 percent of the world's total land with wind speed higher than 5.1 meters per second (or 1.2 million square kilometers) is used to produce wind electricity, and 100 percent of the word's cropland that is not used for crops (8.9 million square kilometers or 890 million hectares) is used to produce biomass, the long-term physical potential is estimated to be 326-481 EJ (exa-joule, or 10^{18} joules, 1 EJ = 23.88 million metric tons of oil equivalent).

In an earlier paper, Lightfoot and Green (2002) pointed out that the assumed available land could be significantly too high. Much of the land is in very remote areas. The land may not be suitable and may not allow access for maintenance. In deserts, sand storms and large amounts of dust can be particularly serious problems.

Solar and wind are intermittent energy resources. Given the existing electric grids, wind and solar electricity can penetrate up to 20 percent of the installed electricity generating capacity or 10 percent of the actual electricity production without causing serious problems. Beyond these limits, further increase in solar and wind electricity will have to require large-scale storage of electricity (Lightfoot and Green 2002). There are serious difficulties to store electricity on very large scales and substantial energy loss will occur due to conversion inefficiencies (Green, Baski, and Dilmaghani 2007).

The manufacturing of the solar and wind equipment consumes massive amounts of nonrenewable mineral resources (Prieto 2008). Biofuels production is highly water intensive and may be limited by the availability of fresh water. It also requires large energy inputs and the net energy output of biofuels is much smaller than the gross output (Green, Baski, and Dilmaghani 2007).

Renewable energies other than biofuels are mainly used to generate electricity and cannot serve as liquid, gaseous, or solid fuels. In 2008, electricity and direct uses of non-biomass renewable energies accounted for 20 percent of the world final energy consumption; liquid, gaseous, and solid fuels accounted 80 percent (IEA 2010).

In the future, as fossil fuels and uranium deplete, the world will have to completely rely on renewable resources to meet energy demand. Suppose biofuels production potential, due to water and land constraints, is limited to 60 EJ or approximately 1,500 million tons of oil equivalent. If half of the total energy demand can be met from electricity and the rest has to be from biofuels, then the long-term potential of renewable electricity would be limited to 1,500 million tons of oil equivalent.

When resource, storage, and grid constraints are taken into account, the long-term potential of the renewable energies could be reduced to 150-175 EJ (Green, Baski, and Dilmaghani 2007).

This report assumes that the long-term potential of renewable energies will be 4,000 million tons of oil equivalent. This roughly corresponds to the high end of the resource-constrained renewable energy potential estimated by Green et al. Figure 18 shows the historical and projected world renewable energy production.

World renewable energy production is projected to rise to 2,500 million tons of oil equivalent by 2050 and keep rising over the second half of the 21st century as it approaches the long-term potential. The projected renewable energy production in 2005 roughly corresponds to the world natural gas consumption before the 2008-2009 global economic crisis.

If biofuels production can provide 500 million tons of oil equivalent in 2050, then the remaining renewable energy production (2,000 million tons of oil equivalent) will have to be provided by electricity. 2,000 million tons of oil equivalent equal about 23,300 terawatt-hours of electricity (or 110 percent of the world's electricity generation in 2010). This represents an increase of 19,100 terawatt-hours of renewable electricity generation from 2010.

19,100 terawatt-hours correspond to electricity generation from about 2,200 giga-watts of full-capacity power plants. Assume that the future renewable power plants have an average capacity utilization rate of 25 percent, 2,200 giga-watts of full-capacity power plants correspond to 8,800 giga-watts of renewable power plants.

In other words, for the projected increase in renewable energy to be materialized, the world needs to build in average 220 giga-watts of renewable power plants a year from 2010 to 2050. By comparison, according to the EIA data, from 2005 to 2008, the world in average built about 170 giga-watts of all types of power plants a year (including about 60 giga-watts of hydro and other renewable power plants).

Peak Energy and Peak Economy

Figure 19 compares the historical and projected world primary energy consumption from 1950 to 2100. The projected world energy consumption from 2011 to 2100 is based on the sum of the projected world oil production, world natural gas production, world coal production, world nuclear electricity generation, and world renewable energy production discussed in the previous sections. World primary energy consumption is projected to peak in 2033, at a level of about 14,000 million tons of oil equivalent, and decline thereafter.

World energy efficiency (defined as the ratio of the gross world product over world energy consumption) grew at an average annual rate of 1.4 percent from 1980 to 1990, 1.5 percent from 1990 to 2000, and 1.0 percent from 2000 to 2010. These results are based on world

GDP measured in purchasing power parity. If world GDP is measured by market exchange rates (which give the stagnating western economies a greater weight), world energy efficiency growth rates would be lowered by about one percentage point for recent years.

Lightfoot and Green (2001) studied the long-term physical potential for world energy efficiency improvement and concluded that in the long run, the global economy's energy intensity could be reduced to 40 percent of the 1990 level, implying that the long-run maximum world energy efficiency would be about 250 percent of the 1990 level. Baski and Green (2007) developed the study by taking into account economic structural changes and found that long-run world energy efficiency could be increased to 300-450 percent of the 1990 level.

In 1990, the world energy efficiency was about 4,800 dollars per ton of oil equivalent (in 2005 international dollars). This report assumes that the long run maximum world energy efficiency will be four times the 1990 level or 20,000 dollars per ton of oil equivalent.

Figure 20 presents the historical and projected world energy efficiency from 1980 to 2050. World energy efficiency for 2011 and 2012 is calculated based on IMF projections of world economic growth in the two years. World energy efficiency is projected to rise to about 10,000 dollars per ton of oil equivalent by 2050. By comparison, currently the most energy efficient economies, such as Japan and European Union, have energy efficiency levels at about 8,000 dollars per ton of oil equivalent.

Gross world product can be calculated as the product of the projected world primary energy consumption and the projected world energy efficiency. Figure 21 shows the historical and projected world economic growth rates from 1951 to 2100. World economic growth rates are projected to trend down from now to 2050. Around 2050, gross world product will peak and decline over the second half of the 21st century.

Table 2 summarizes the historical and projected average annual rates of change of world energy consumption, carbon dioxide emissions from fossil fuels burning, world GDP, world energy efficiency, and world emission intensity of GDP for every decade from 1950 to 2050.

Table 3 summarizes the historical and projected share of oil, natural gas, coal, nuclear energy, and renewable energies in the world's total primary energy consumption from 1950 to 2050.

The 21st Century: Path to Climate Catastrophe?

It is now widely understood that human economic activities have led to emissions of greenhouse gases, mainly carbon dioxide emissions from fossil fuels consumption, which contribute to long-term global warming and threaten to bring about global ecological catastrophes.

In 2010, the global average land and ocean surface temperature was 14.6°C, which was 0.9°C higher than in 1880 and 0.3°C higher than in 2000 (NASA 2011).

If global warming rises above 2°C (relative to the pre-industrial time), dangerous climate feedbacks may be triggered, leading to the release of more greenhouse gases from soil and ocean. For this reason, 2°C warming is generally considered by scientists as the "safe limit" beyond which global warming may be out of human control.

A 3°C warming would destroy the Amazon rainforest, leading to a further warming of 1.5°C. Southern Africa, Australia, Mediterranean Europe, and Western US would turn into deserts. Sea level could rise by 25 meters and billions of people could become environmental refugees.

With a 4°C warming, the melting of the Arctic permafrost could release massive amount of carbon dioxide and methane. Algae, the main carbon sinker in the ocean, would die out. The world is set for runaway global warming that could lead to additional temperature rises by several degrees.

If global warming rises to 5°C and above, much of the world would cease to be inhabitable and global human population could suffer a catastrophic decline. Table 4 summarizes the potential consequences of various degrees of global warming. It is not exaggerating to say that the very survival of the human civilization for centuries to come is at stake.

In the pre-industrial time, the amount of greenhouse gases, measured by atmospheric concentration of CO_2-equivalent was about 280 parts per million (ppm). According to the Intergovernmental Panel on Climate Change (IPCC), the "climate sensitivity" or the extent of global warming that would result from a doubling of the greenhouse gases in the atmosphere is estimated to be 3°C. Thus, according to the IPCC climate sensitivity, if the atmospheric concentration of CO_2-equivalent rises to 550 ppm, it should lead to an increase in global average temperature by 3°C from the pre-industrial time (IPCC 2007).

However, new developments in climate science suggest that IPCC is likely to have underestimated the potential of global warming. Based on the study of paleoclimate data, James Hansen, one of the world's leading climate scientists, concludes that when "slow" climate feedbacks (such as ice sheet disintegration and vegetation migration) are taken into account, the long-term climate sensitivity is about 6°C rather than 3°C (Hansen 2009). Given the Hansen climate sensitivity, an atmospheric concentration of CO_2-equivalent of 550 ppm would lead to a long-term global warming of about 6°C.

In 2010, the atmospheric concentration of CO_2 (which measures only carbon dioxide in the atmosphere, not including other greenhouse gases) rose by 2.4 ppm and reached 389.8 ppm (NOAA 2011). According to the European Environment Agency (2010), the total greenhouse gases regulated by the Kyoto Protocol reached 438 ppm CO_2-equivalent in 2008, which was 2 ppm higher than in 2007. Without any further increase in greenhouse gases, the current level of greenhouse gases already implies a long-term warming of 2-4°C.

Table 5 summarizes the various scenarios of climate stabilization. Under Scenario I, atmospheric concentration of CO_2 eventually stabilizes at 350 ppm and the total greenhouse gases stabilize at 450 ppm CO_2-equivalent. This will lead to a long-term global warming of about 2°C under the IPCC climate sensitivity but a 4°C warming under the Hansen climate sensitivity.

As more than 2°C global warming would significantly increase the risk of dangerous climate feedbacks and anything beyond 3°C warming would be devastating for human civilization, a responsible global climate policy should really aim at an atmospheric concentration of CO_2-equivalent at no more than 450 ppm. To achieve this objective, the cumulative carbon dioxide emissions from fossil fuels burning over the entire 21st century needs to be less than one trillion tons.

However, over the first decade of this century, about 300 billion tons of carbon dioxide has already been emitted from fossil fuels burning. For all practical purposes, it is no longer possible to keep long-term global warming at less than 2°C (Anderson and Bows 2011).

According to IPCC (2007), to keep atmospheric concentration of CO_2-equivalent at no more than 550 ppm (which implies long-term global warming of 3-6°C), the cumulative carbon dioxide emissions from fossil fuels burning over the entire 21st century need to be less than two trillion tons.

Figure 22 compares the historical world carbon dioxide emissions, the future carbon dioxide emissions based on the fossil fuels consumption projected by this report, and the emission trajectory that would be consistent with an atmospheric concentration of CO_2-equivalent at no more than 550 ppm.

According to BP (2011), world carbon dioxide emissions from fossil fuels consumption increased from 25.6 billion tons in 2000 to 33.2 billion tons in 2010. After correcting for emissions from biofuels (in the BP statistics, biofuels are not subtracted from oil consumption when emissions are calculated), world carbon dioxide emissions were 33.0 billion tons in 2010.

World carbon dioxide emissions are projected to peak in 2027 and decline thereafter. The peak emissions will be 38.8 billion tons. The cumulative carbon dioxide emissions from fossil fuels burning over the 21st century will amount to 2.6 trillion tons.

If a 50 percent "airborne" ratio (that is, the proportion of carbon dioxide emissions that end up in the atmosphere) is assumed, then 1.3 trillion tons of the emitted carbon dioxide will stay in the atmosphere. One "ppm" of carbon dioxide equals roughly 8 billion tons. Thus, over the course of the 21st century, about 160 ppm of carbon dioxide will be added to the atmosphere. In 2000, the atmospheric concentration of CO_2 was 370 ppm. The projected emission trajectory therefore implies a long-term atmospheric concentration of CO_2 of 530 ppm. In the long run, the non-CO_2 greenhouse gases are likely to rise to 100-150 ppm CO_2-equivalent. When all greenhouse gases are included, the atmospheric concentration of CO_2-equivalent will rise to about 650 ppm, leading to a long-term global warming of about 3.5-7°C.

To keep the cumulative carbon dioxide emissions over the 21st century at less than two trillion tons, the world needs to immediately start reducing the absolute levels of emissions and achieve an annual reduction rate of 1.5 percent a year from now to 2100. By comparison, in 2009, during the deepest global economic crisis since the 1930s, the world carbon dioxide emissions declined by 1.9 percent.

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Table 1. US Electricity Generating Cost (standard one giga-watt power plant)

	Coal	Natural Gas	Nuclear	Wind	Solar
Capacity Utilization[a]	0.65	0.25	0.9	0.25	0.15
Annual Generation[b]	5,700	2,200	7,900	2,200	1,300
Capital Cost[c]	2,800	1,000	5,300	2,400	4,700
Annual Fixed Cost[d]	280	100	530	240	470
Annual Fuel Cost[e]	120	90	40	0	0
Annual Total Cost[f]	400	190	570	240	470
Average Cost[g]	0.070	0.086	0.072	0.109	0.362

[a] Based on the observed capacity utilization rates of US power plants in 2009.

[b] In million kilowatt-hours; calculated by using the capacity utilization rates; one giga-watt power plant generates 8,760 million kilowatt-hours with 100 percent capacity utilization.

[c] In million 2010 dollars; data are from EIA (2010).

[d] In million 2010 dollars; assumed to be 10 percent of the capital cost (5 percent for depreciation and maintenance and 5 percent for interests).

[e] In million 2010 dollars; for coal-fired and gas-fired plants, 40 percent generating efficiency is assumed; coal price is assumed to be $50/ton; natural gas price is assumed to be $5/million BTU; nuclear fuel cost is assumed to be $0.005/kilowatt-hour.

[f] In million 2010 dollars; equals the sum of annual fixed cost and annual fuel cost.

[g] In dollars per kilowatt-hour; equals annual total cost divided by annual generation.

Table 2. World Energy Consumption, Carbon Dioxide Emissions from Fossil Fuels Burning, and World GDP, 1950-2050 (average annual rates of change, %)

	Energy Consumption	CO_2 Emissions	Gross World Product	Energy Efficiency	Emission Intensity[a]
Historical:					
1950-1960	5.0	4.6	4.7	-0.3	-0.1
1960-1970	5.1	5.1	5.0	-0.1	0.1
1970-1980	2.8	2.6	3.8	1.0	-1.2
1980-1990	1.8	1.6	3.2	1.4	-1.5
1990-2000	1.4	1.2	2.9	1.5	-1.7
2000-2010	2.5	2.6	3.5	1.0	-0.9
Projected:					
2010-2020	1.6	1.4	3.1	1.5	-1.6
2020-2030	0.7	0.3	1.9	1.2	-1.6
2030-2040	-0.2	-0.9	0.9	1.1	-1.8
2040-2050	-0.7	-1.8	0.3	1.0	-2.0

[a] Negative values indicate favorable change.

Table 3. Structure of World Primary Energy Consumption, 1950-2050 (share in total, %)

	Oil[a]	Natural Gas	Coal	Nuclear Energy	Renewable Energies[a]
Historical:					
1950	30	9	61	*	*
1960	37	14	49	*	*
1970	47	19	31	1	2
1980	47	21	29	1	2
1990	42	24	30	2	3
2000	41	25	28	3	3
2010	36	26	32	2	4
Projected:					
2020	31	28	34	2	6
2030	26	30	33	2	9
2040	22	32	29	3	14
2050	19	33	25	3	20

[a] Biofuels are excluded from oil and included in the renewable energies.

Table 4. Global Warming Scenarios

Global Warming Scenarios	1-2°C	3-4°C	5-6°C
Drought and Desertification	**Frequent heat waves**	**Widespread drought and desertification**	**Much of the world ceases to be inhabitable**
Sea Ice and Ice Sheets	**Disappearing of Arctic sea ice**	**Melting of Greenland ice sheets**	**Melting of Antarctic ice sheets**
Sea Level Rise	**Several meters**	**25 meters**	**75 meters**
Eco-systems	**One third of species become extinct**	**Amazon rainforest burns down**	**Massive species extinction**
Human Impact	**Half a billion people at risk of starvation**	**Billions become environmental refugees**	**Catastrophic decline of global population**
Climate Feedbacks	**Possible initiation of soil and ocean carbon feedbacks**	**Arctic permafrost and ocean algae endangered**	**Runaway global warming**

Sources: Spratt and Sutton (2008); Hansen (2009).

Table 5. Climate Stabilization Scenarios (Gt: billion tons)

Climate Stabilization Scenarios	Scenario I	Scenario II	Scenario III
Atmospheric CO_2	350 ppm	450 ppm	550 ppm
Atmospheric CO_2-equivalent	450 ppm	550 ppm	700 ppm
Global Warming:[a]			
IPCC Climate Sensitivity	2°C	3°C	4°C
Hansen Climate Sensitivity	4°C	6°C	8°C
Approximate 21st Century Carbon Budget:			
Cumulative CO_2 Emissions Budget	1,000 Gt	2,000 Gt	3,000 Gt
Less: early 21st century emissions	300 Gt	300 Gt	300 Gt
Remaining CO_2 Emissions Budget	700 Gt	1,700 Gt	2,700 Gt

[a] Long-term equilibrium temperature increase relative to pre-industrial time.

Sources: IPCC (2007); Hansen (2009).

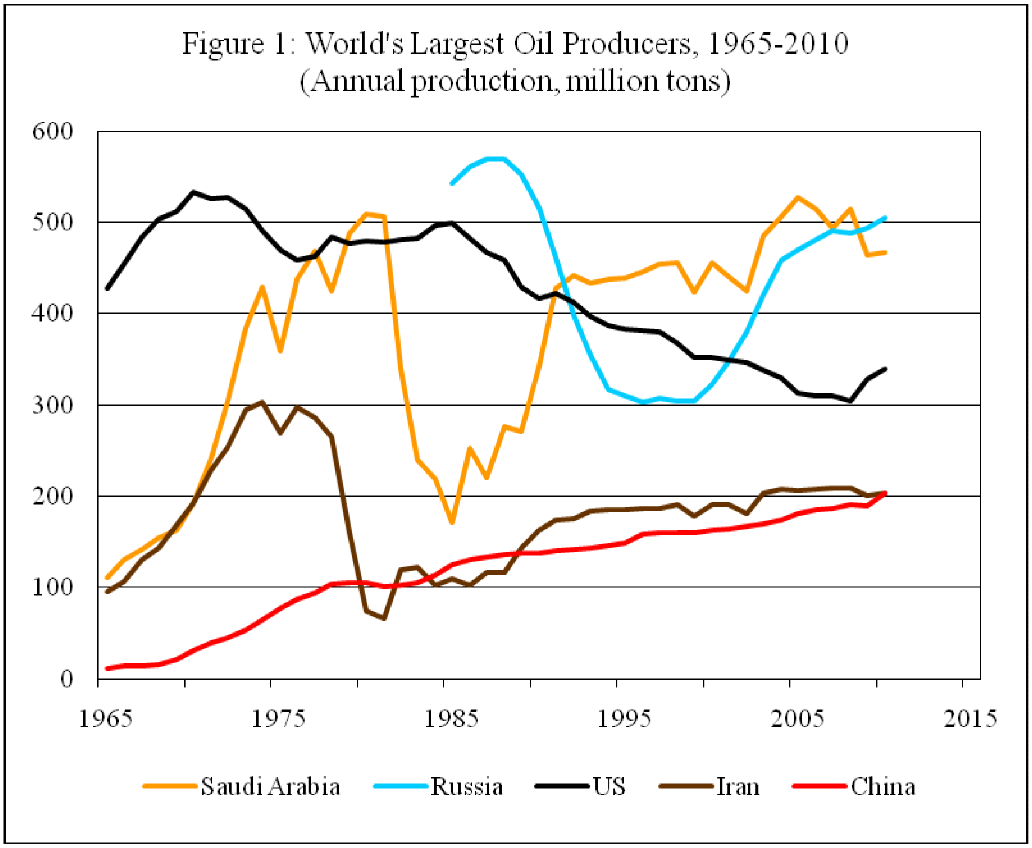
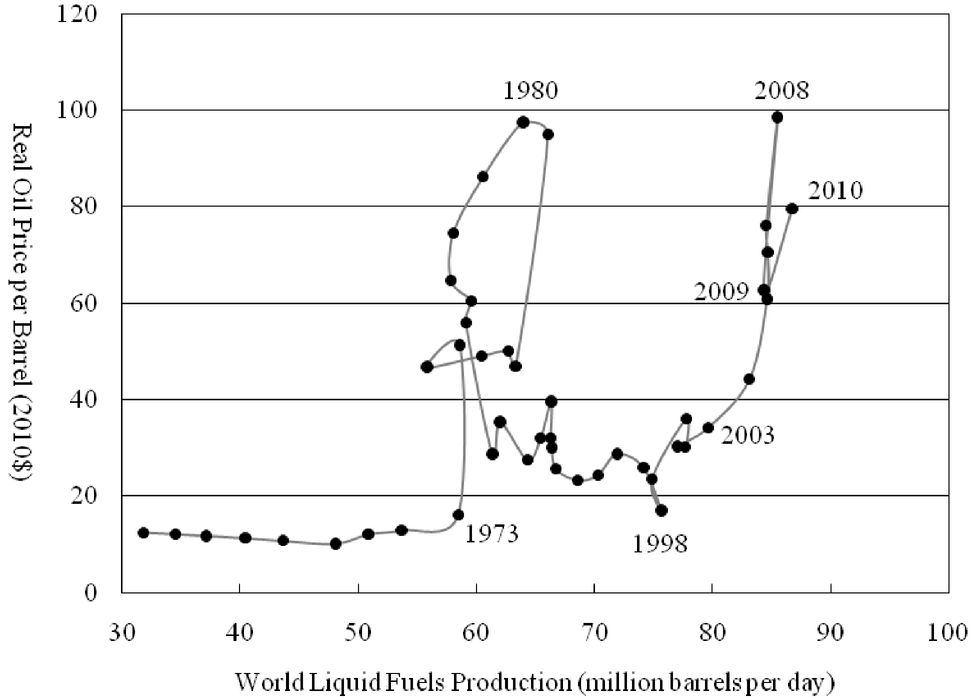


Figure 1: World's Largest Oil Producers, 1965-2010
(Annual production, million tons)
600
500
400
300
200
100
0
1965
1975
1985
1995
2005
2015
Saudi Arabia
Russia
US
Iran
China

Figure 2. World Oil Supply Curve
(1965-2010)



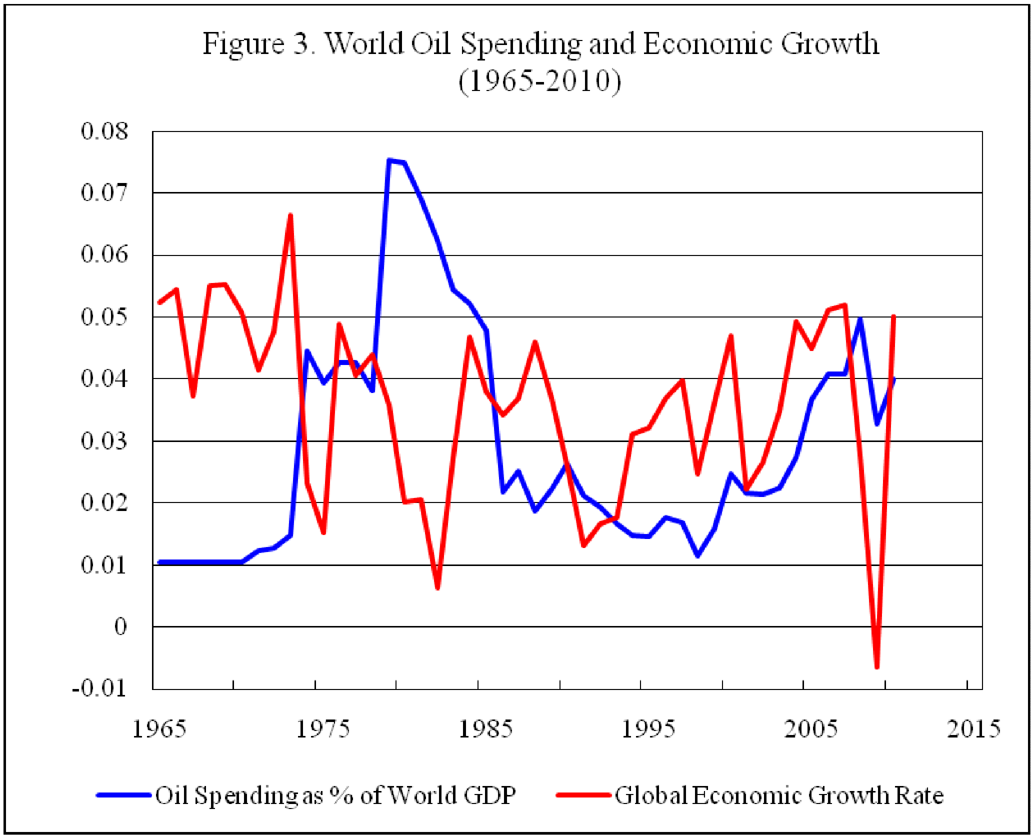
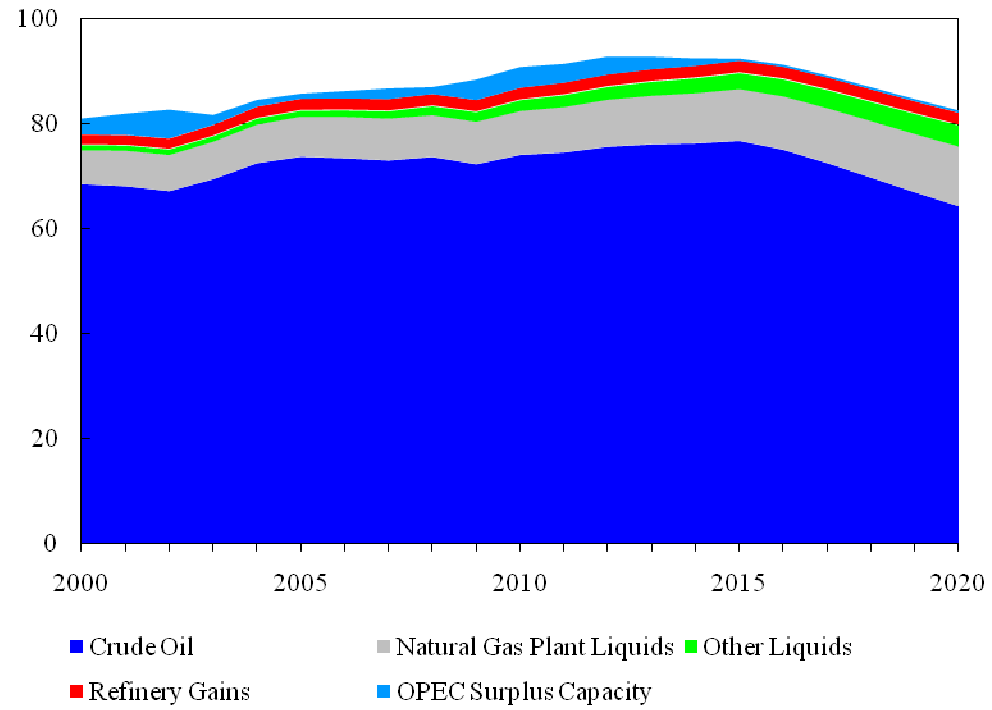


Figure 3. World Oil Spending and Economic Growth
(1965-2010)
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
-0.01
1965
1975
1985
1995
2005
2015
Oil Spending as % of World GDP
Global Economic Growth Rate

Figure 4. World Oil Production and Capacity
(Million barrels per day, 2000-2020)



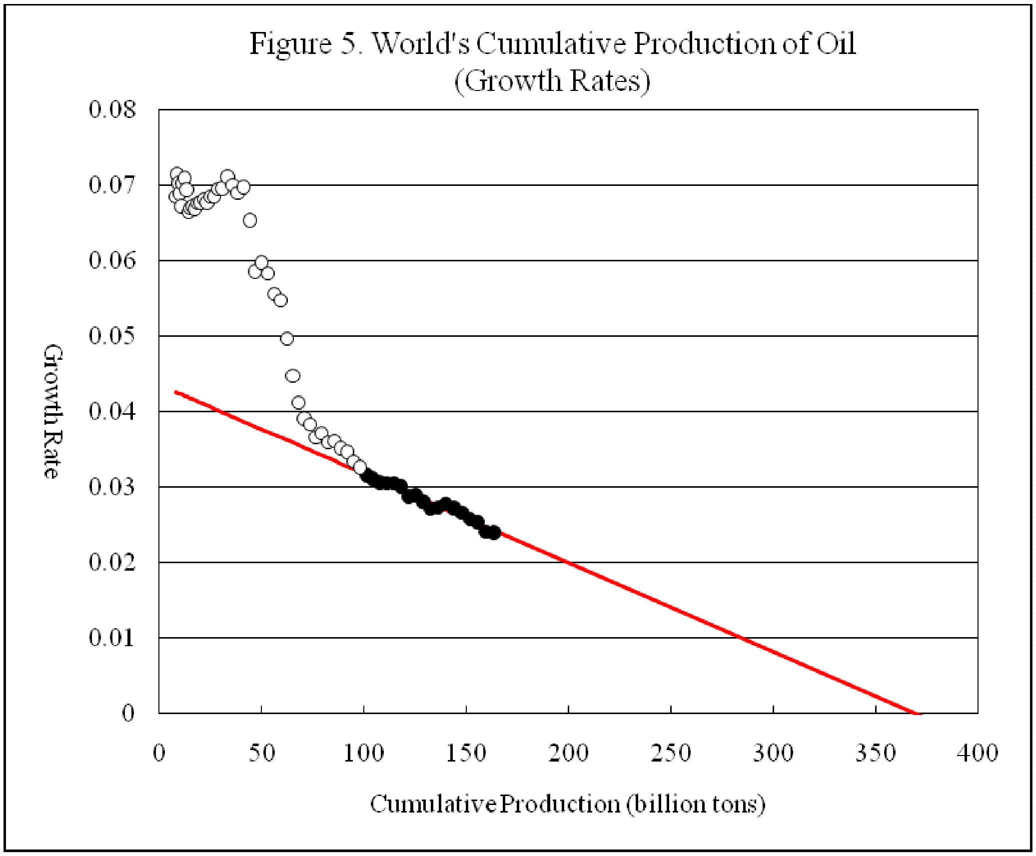


Figure 5. World's Cumulative Production of Oil
(Growth Rates)
Growth Rate
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0
0
50
100
150
200
250
300
350
400
Cumulative Production (billion tons)

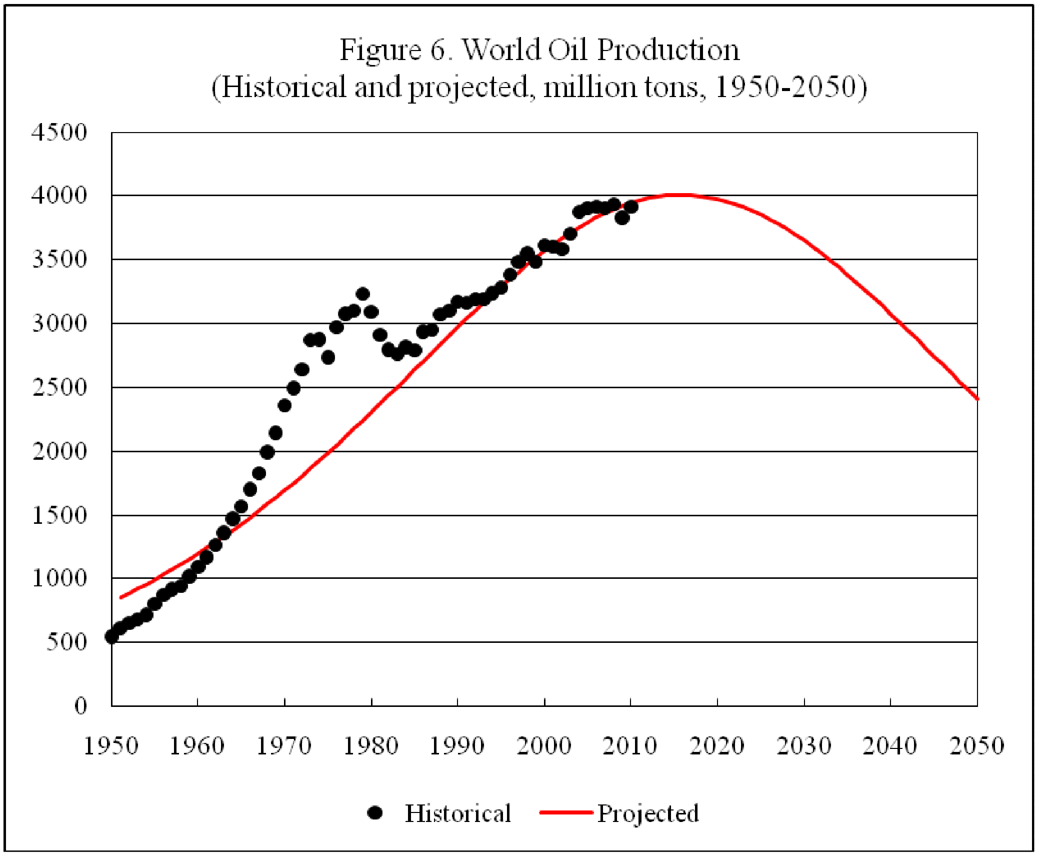


Figure 6. World Oil Production
(Historical and projected, million tons, 1950-2050)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
Historical
Projected

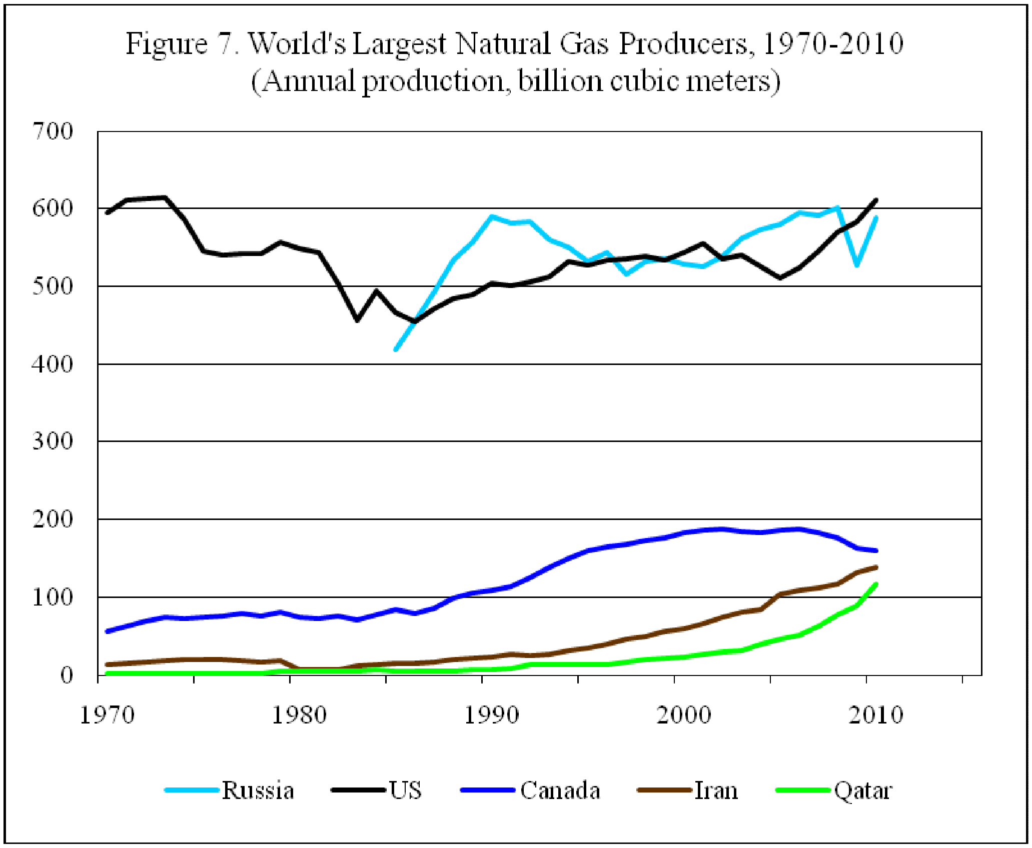


Figure 7. World's Largest Natural Gas Producers, 1970-2010
(Annual production, billion cubic meters)
700
600
500
400
300
200
100
0
1970
1980
1990
2000
2010
Russia
US
Canada
Iran
Qatar

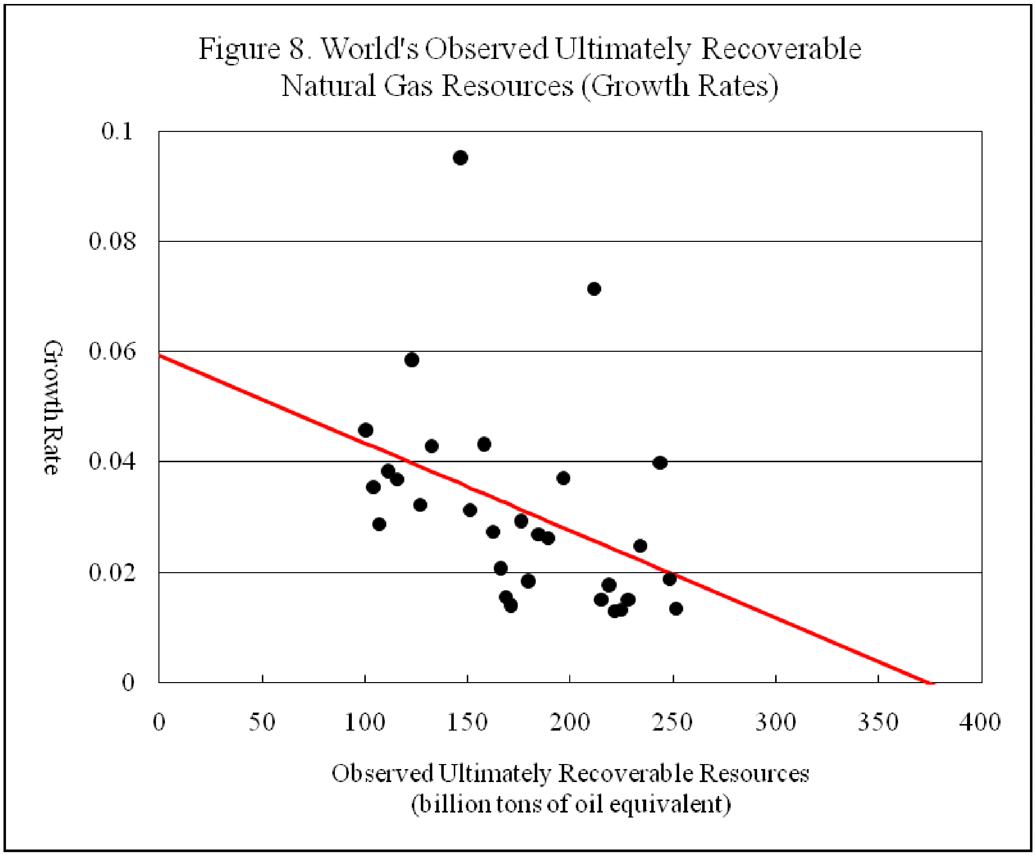


Figure 8. World's Observed Ultimately Recoverable
Natural Gas Resources (Growth Rates)
Growth Rate
0.1
0.08
0.06
0.04
0.02
0
0
50
100
150
200
250
300
350
400
Observed Ultimately Recoverable Resources
(billion tons of oil equivalent)

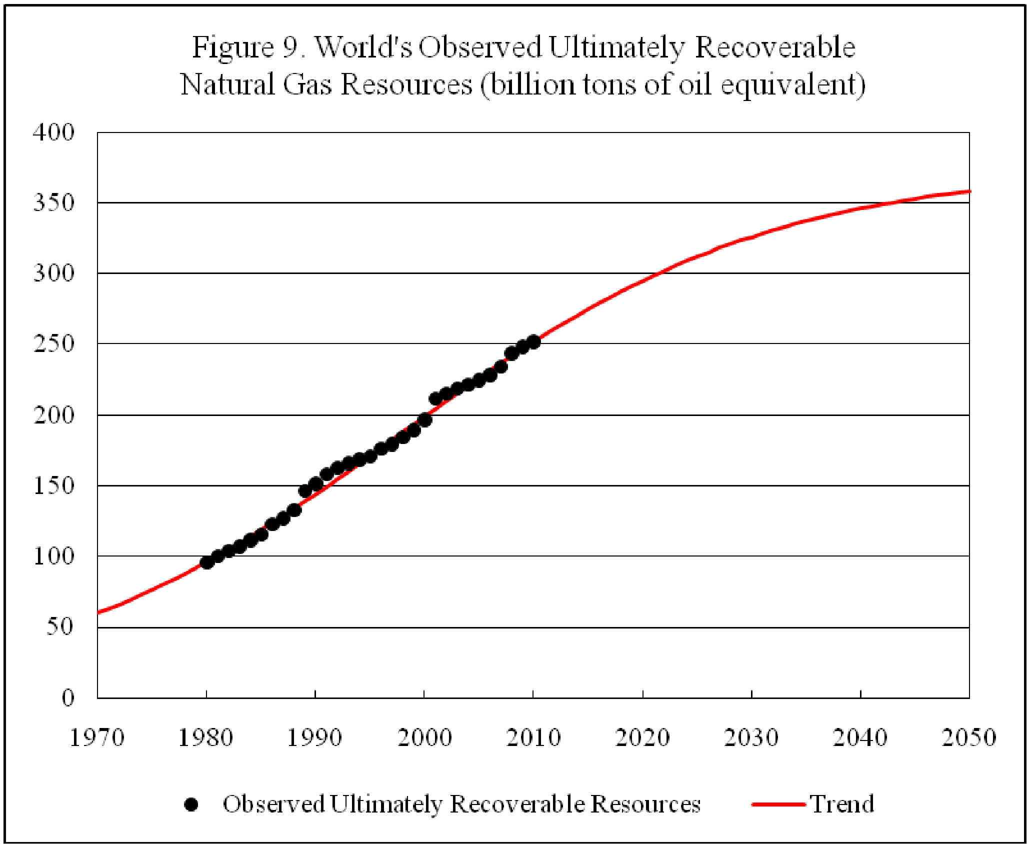


Figure 9. World's Observed Ultimately Recoverable
Natural Gas Resources (billion tons of oil equivalent)
400
350
300
250
200
150
100
50
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Observed Ultimately Recoverable Resources
Trend

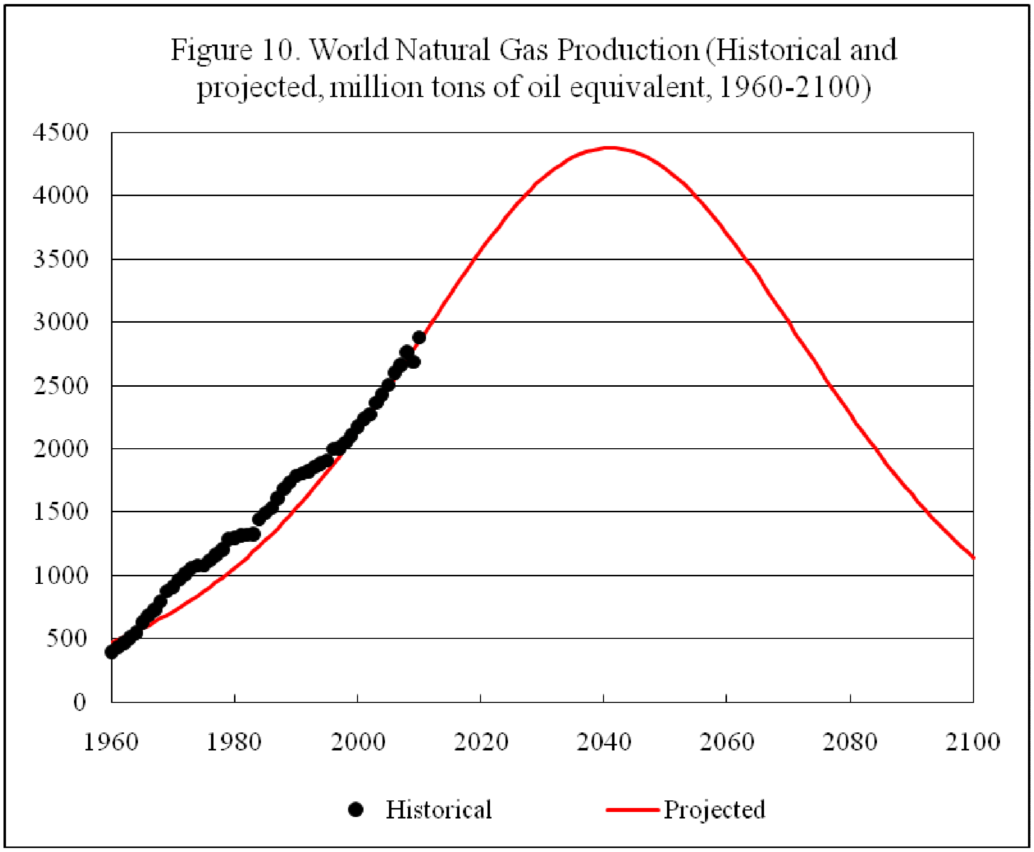


Figure 10. World Natural Gas Production (Historical and projected, million tons of oil equivalent, 1960-2100)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1960
1980
2000
2020
2040
2060
2080
2100
Historical
Projected

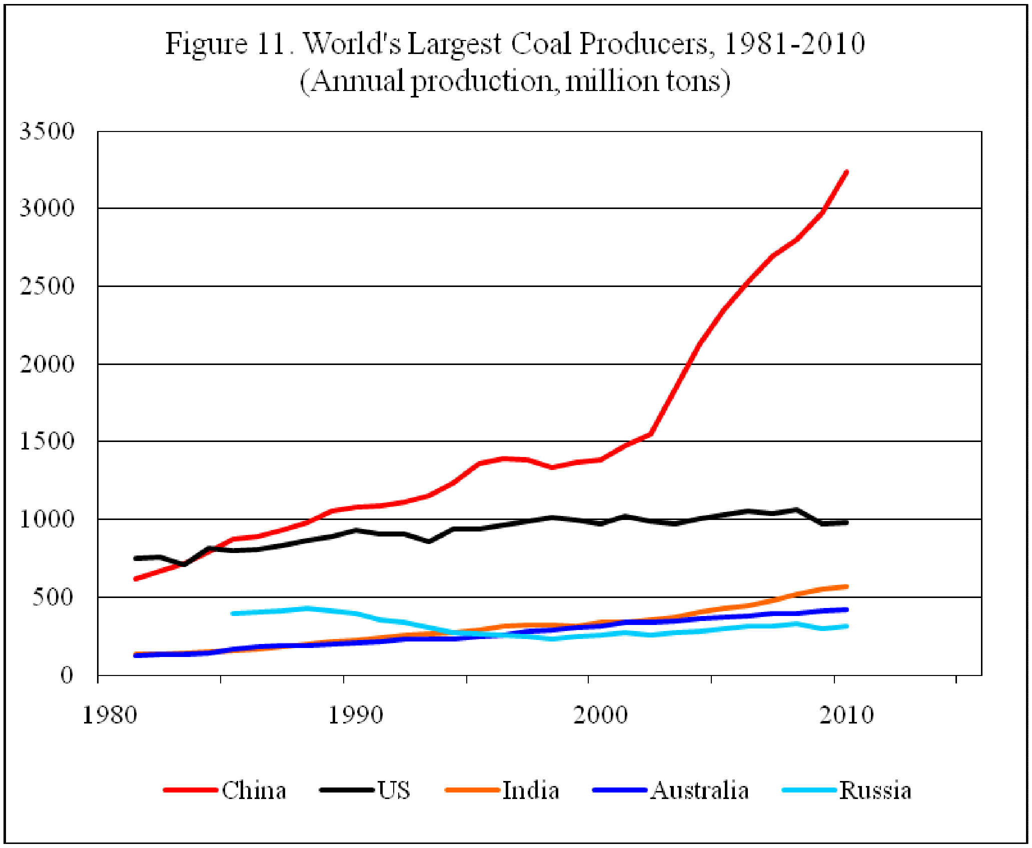


Figure 11. World's Largest Coal Producers, 1981-2010
(Annual production, million tons)
3500
3000
2500
2000
1500
1000
500
0
1980
1990
2000
2010
China
US
India
Australia
Russia

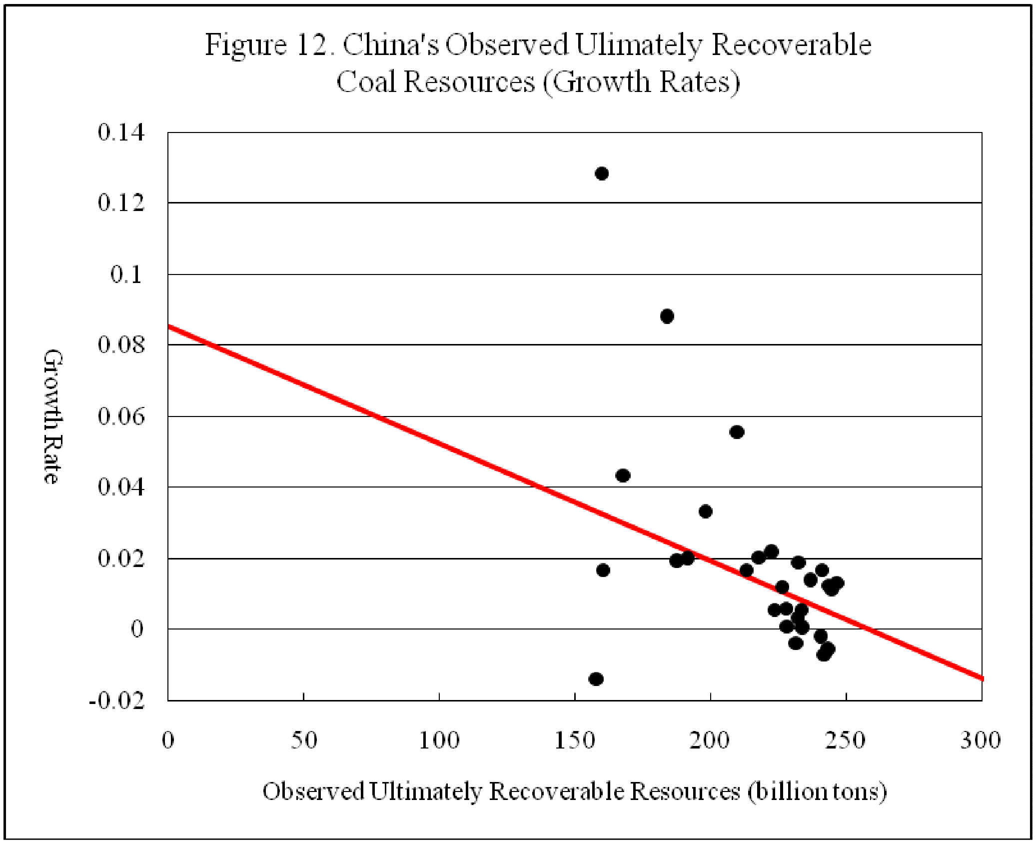


Figure 12. China's Observed Ulimately Recoverable
Coal Resources (Growth Rates)
Growth Rate
0.14
0.12
0.1
0.08
0.06
0.04
0.02
0
-0.02
0
50
100
150
200
250
300
Observed Ultimately Recoverable Resources (billion tons)

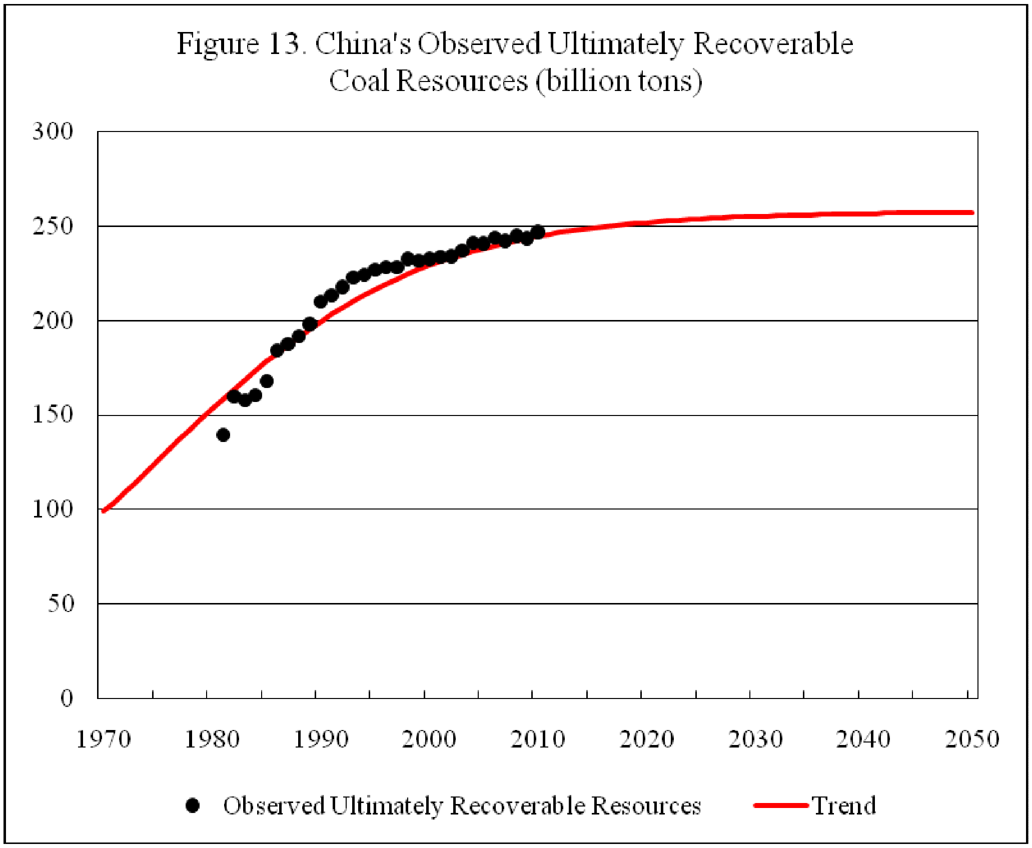


Figure 13. China's Observed Ultimately Recoverable
Coal Resources (billion tons)
300
250
200
150
100
50
0
1970
1980
1990
2000
2010
2020
2030
2040
2050
Observed Ultimately Recoverable Resources
Trend

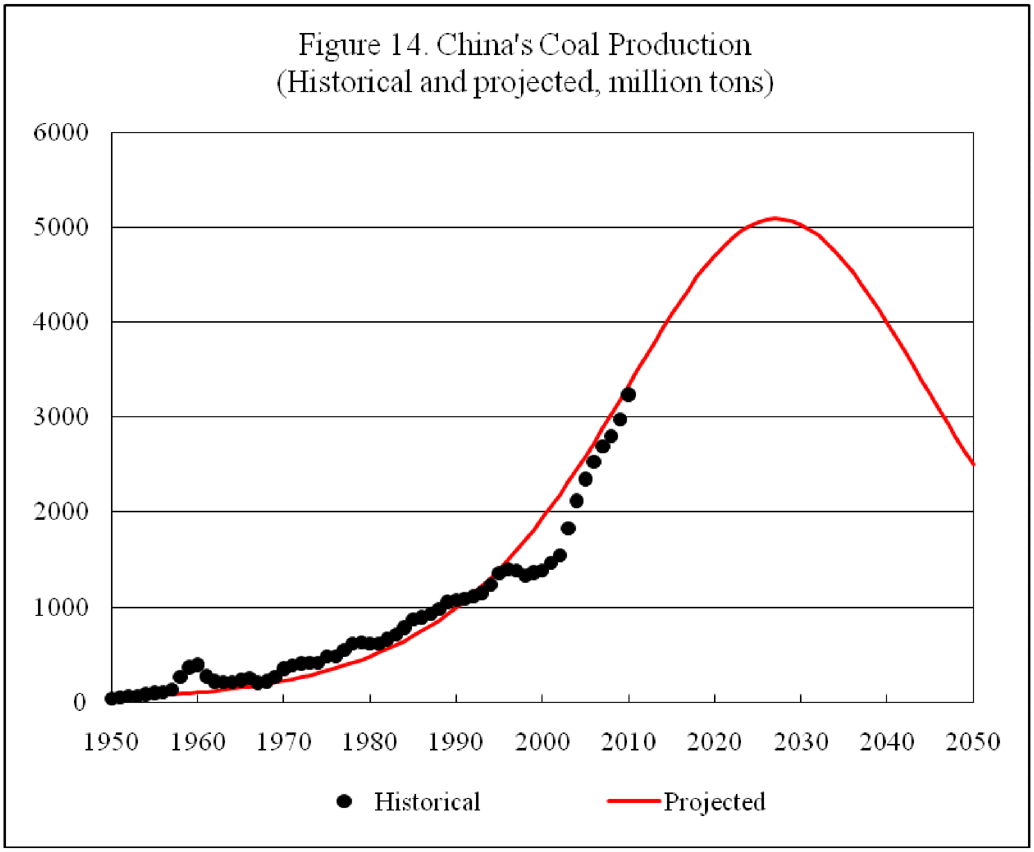


Figure 14. China's Coal Production
(Historical and projected, million tons)
6000
5000
4000
3000
2000
1000
0
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
Historical
Projected

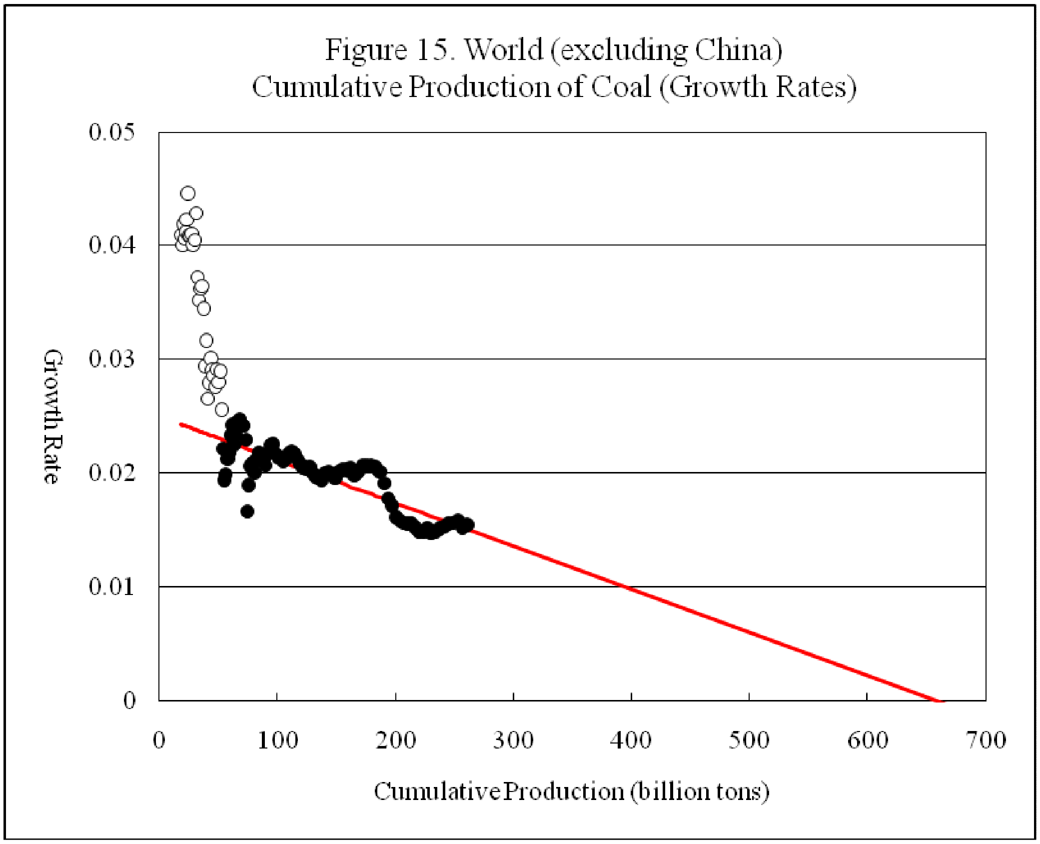


Figure 15. World (excluding China)
Cumulative Production of Coal (Growth Rates)
0.05
0.04
0.03
0.02
0.01
0
Growth Rate
0
100
200
300
400
500
600
700
Cumulative Production (billion tons)

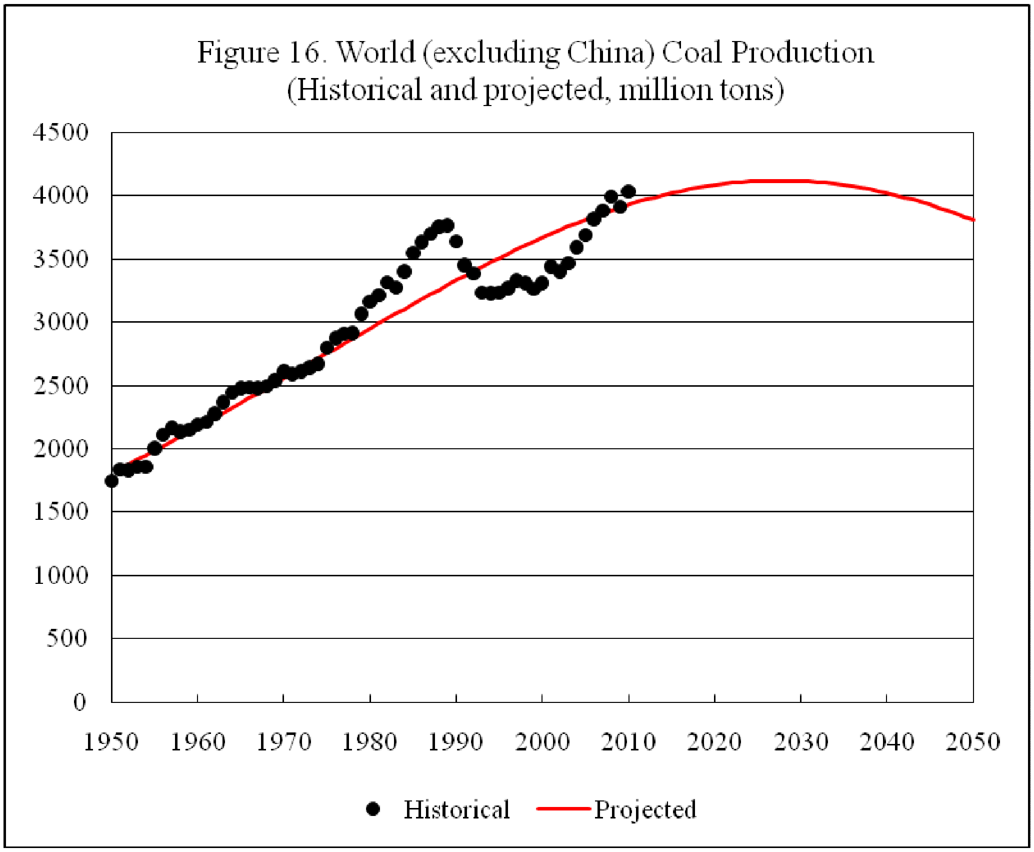
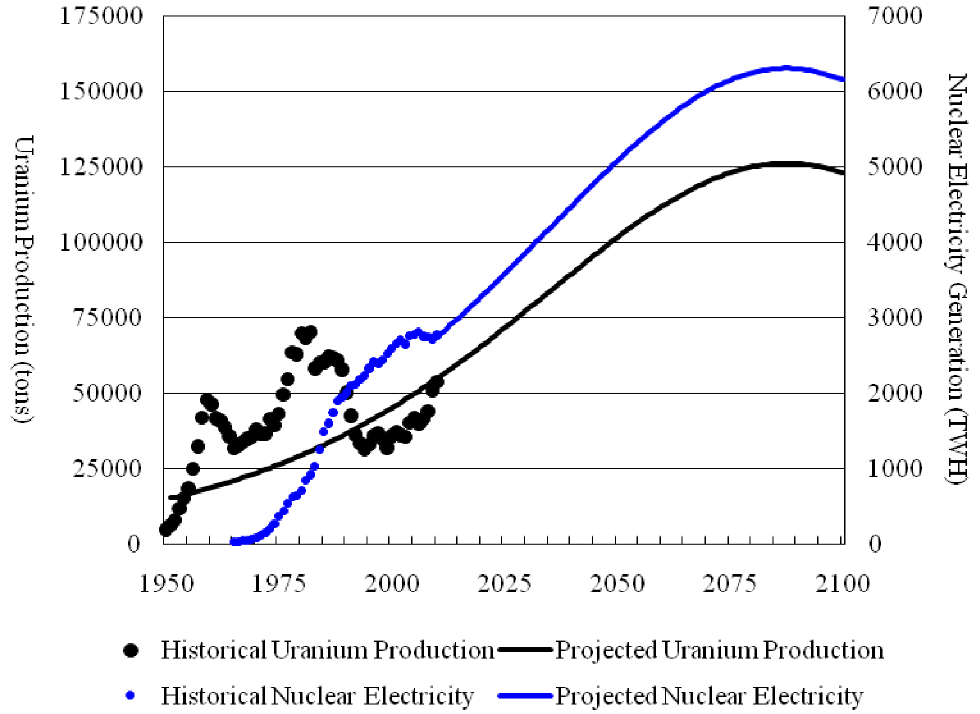


Figure 16. World (excluding China) Coal Production
(Historical and projected, million tons)
4500
4000
3500
3000
2500
2000
1500
1000
500
0
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
Historical
Projected

Figure 17. World Uranium Production and Nuclear Electricity Generation (Historical and projected, 1950-2100)



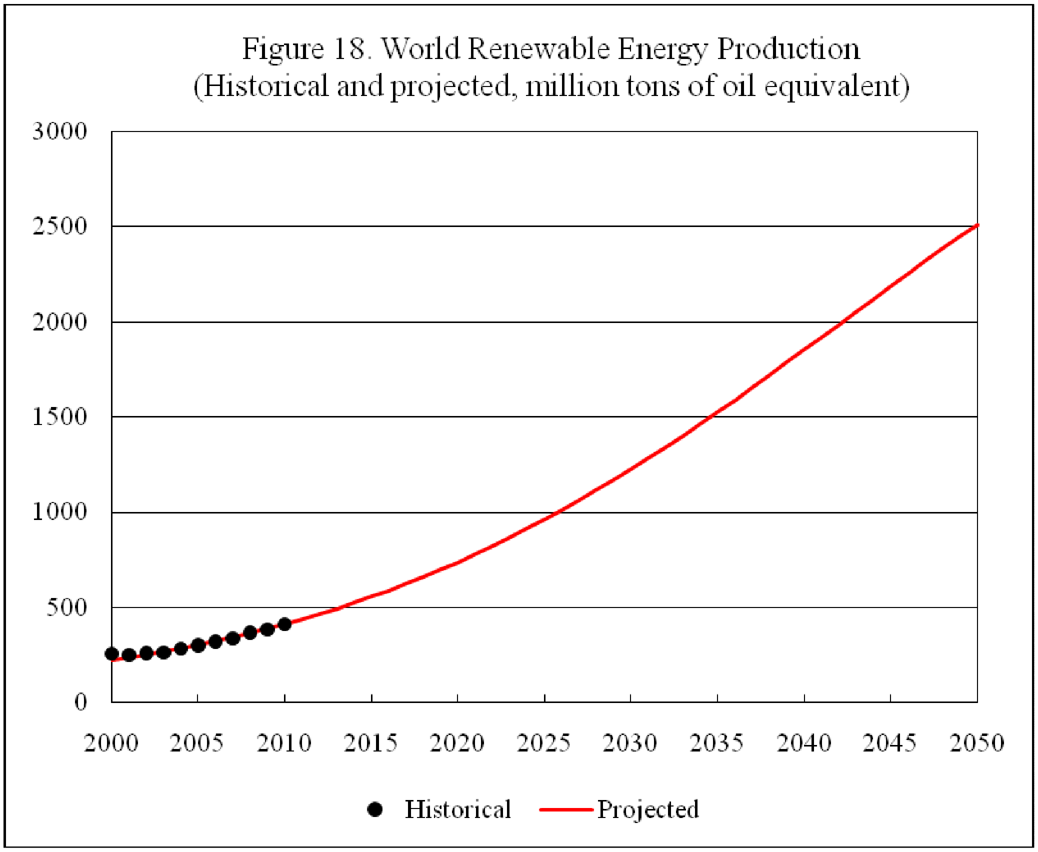


Figure 18. World Renewable Energy Production
(Historical and projected, million tons of oil equivalent)
3000
2500
2000
1500
1000
500
0
2000
2005
2010
2015
2020
2025
2030
2035
2040
2045
2050
Historical
Projected

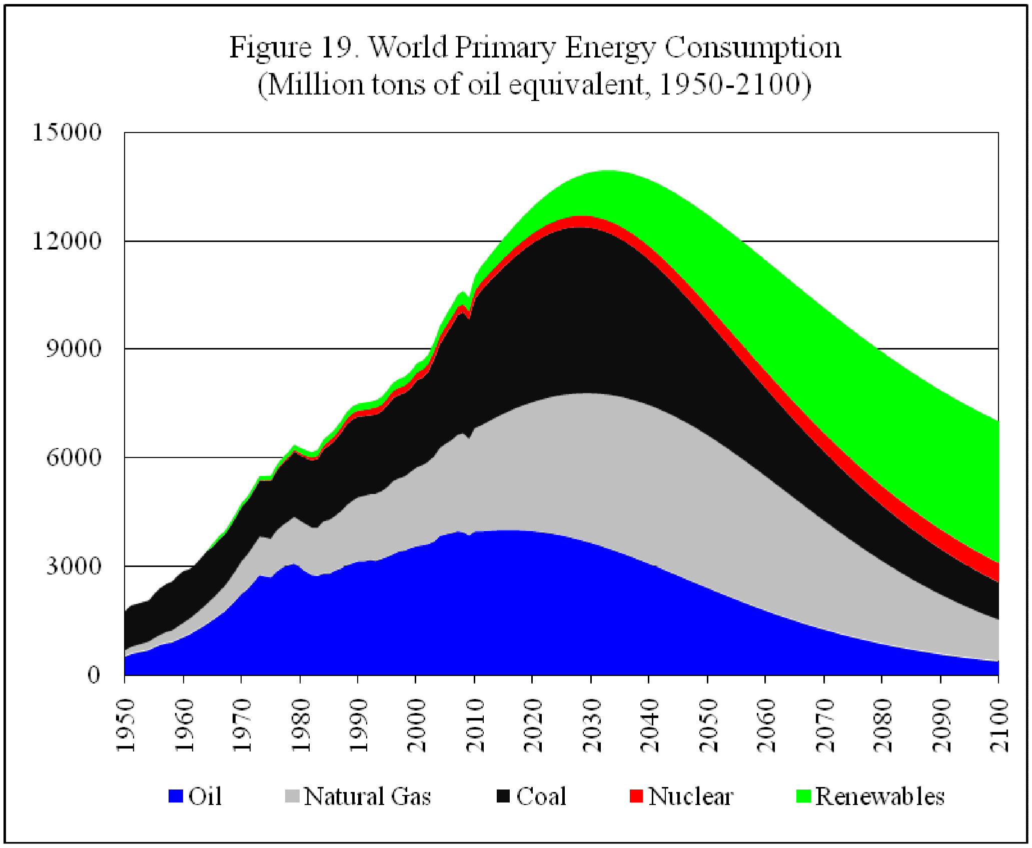
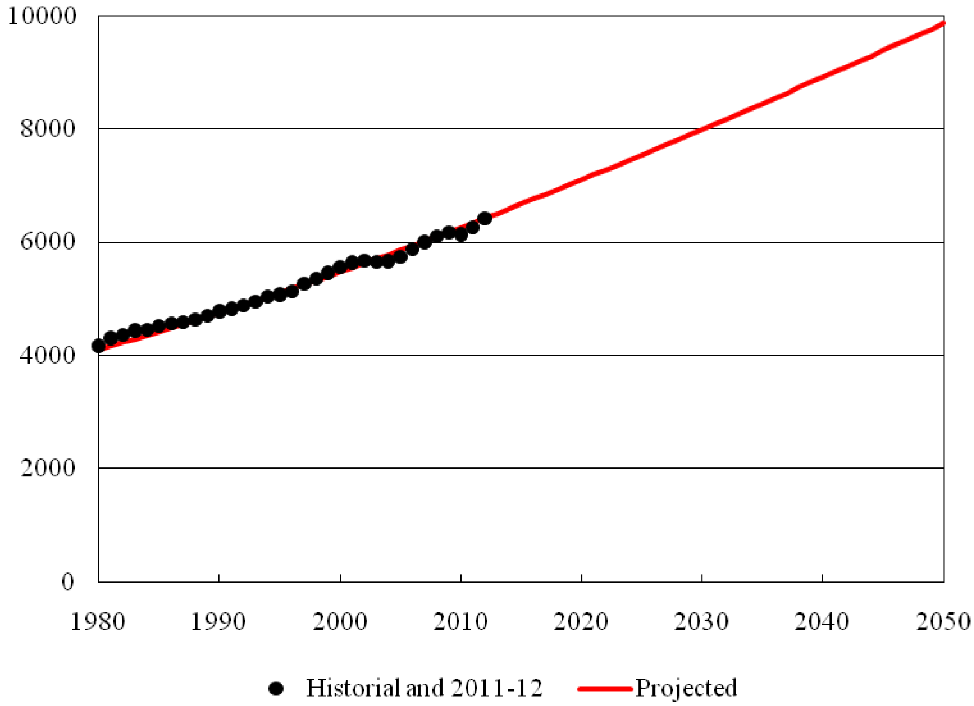


Figure 19. World Primary Energy Consumption
(Million tons of oil equivalent, 1950-2100)
15000
12000
9000
6000
3000
0
1950
1960
1970
1980
1990
2000
2010
2020
2030
2040
2050
2060
2070
2080
2090
2100
Oil
Natural Gas
Coal
Nuclear
Renewables

Figure 20. World Energy Efficiency (Historical and projected, dollars per ton of oil equivalent, 1980-2050)



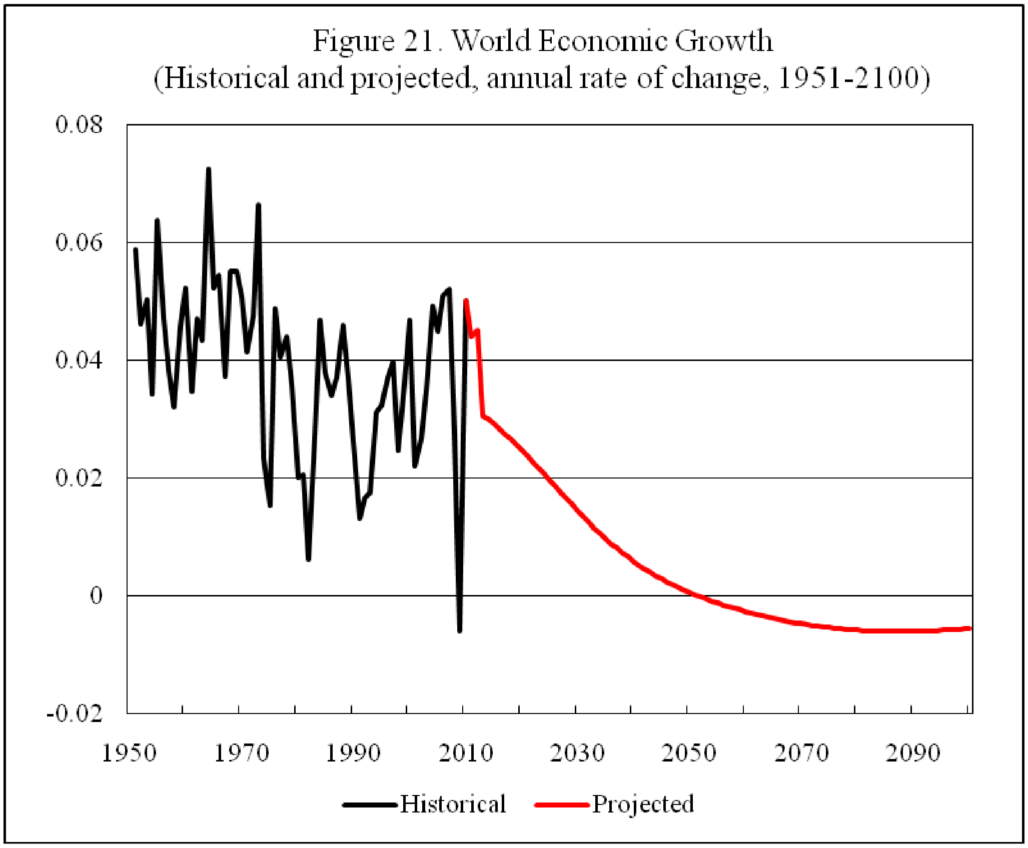


Figure 21. World Economic Growth
(Historical and projected, annual rate of change, 1951-2100)
0.08
0.06
0.04
0.02
0
-0.02
1950
1970
1990
2010
2030
2050
2070
2090
Historical
Projected

Figure 22. World CO_2 Emissions from Fossil Fuels Burning
(Historical and projected, billion tons, 2000-2100)