World Energy 2016-2050: Annual Report

by Ron Patterson Posted on 06/20/2016

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"Political Economist"

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The purpose of this annual report is to provide an analytical framework evaluating the development of world energy supply and its impact on the global economy. The report projects the world supply of oil, natural gas, coal, nuclear, hydro, wind, solar, and other energies from 2016 to 2050. It also projects the overall world energy consumption, gross world economic product, and energy efficiency from 2016 to 2050 as well as carbon dioxide emissions from fossil fuels burning from 2016 to 2100.

The basic analytical tool is Hubbert Linearization, first proposed by American geologist M. King Hubbert (Hubbert 1982). Despite its limitations, Hubbert Linearization provides a useful tool helping to indicate the likely level of ultimately recoverable resources under the existing trends of technology, economics, and geopolitics. Other statistical methods and some official projections will also be used where they are relevant.

Past experience with Hubbert Linearization suggests that Hubbert Linearization exercise tends to underestimate the ultimately recoverable oil and natural gas resources. To mitigate this "pessimistic" bias, I use the US Energy Information Administration (EIA)'s official projection to project US oil and natural gas production from 2016 to 2040, which may prove to be too optimistic.

About two years ago, I posted "World Energy 2014-2050" at Peak Oil Barrel (Political Economist 2014). The posts can be found here:

World Energy 2014-2050 (Part 1)

World Energy 2014-2050 (Part 2)

World Energy 2014-2050 (Part 3)

The 2014 report drew the following conclusion:

It finds that world production of oil, natural gas, and coal may peak between 2016 and 2031. As the supply of fossil fuels declines and the renewable energies do not grow sufficiently rapidly, the world energy consumption is projected to peak in 2035 and the world economy is projected to enter into a prolonged depression after 2040. World carbon dioxide emissions from fossil fuels burning are projected to peak in 2027. However, the cumulative carbon dioxide emissions from 2012 to 2100 are within the range of RCP 4.5 projected in the IPCC Fifth Assessment report, which may lead to long-term global warming of 3 degrees Celsius relative to the pre-industrial The summary statistics from the 2014 report are reported in the following table (Table 1).

These can be compared with the summary statistics reported towards the end of this report.

Since 2014, world energy conditions have significantly changed. Among the most important developments, the US production of oil and natural gas surged, leading to the collapse of world oil prices; China's coal consumption and production have declined since 2013, leading to growing hope that the world economic growth may begin to "decouple" from carbon dioxide emissions. This report will show that this hope may be premature.

Table 1 World Energy and Economy: 2000-2050 (2014 Scenario)

	2000	2010	2020	2030	2040	2050
World Energy Consumption						
(Mtoe):						
Oil	3,575	3,981	4,264	3,849	3,178	2,433
Natural Gas	2,177	2,868	3,424	3,627	3,390	2,895
Coal	2,343	3,469	4,322	4,755	4,514	3,797
Nuclear	584	626	673	825	950	1,052
Hydro	602	784	1,000	1,200	1,400	1,600
Wind	7	78	319	592	868	1,145
Solar	0	7	180	578	1,008	1,440
Geothermal and Biomass	45	83	145	195	245	295
Biofuels	9	60	100	150	200	250
Total	9,342	11,956	14,427	15,771	15,754	14,906
World GDP (billion $)	61,345	88,736	122,160	150,510	167,213	174,561
GDP per Capita ($)	10,053	12,888	15,912	17,957	18,595	18,371
Energy Efficiency ($/toe)	6,567	7,422	8,466	9,533	10,592	11,671
Carbon Dioxide Emissions (Mt)	25,931	32,876	38,253	39,169	35,600	29,309

"Oil" consumption excludes biofuels.
Mt: million metric tons; Mtoe: million metric tons of oil-equivalent; $: constant 2011 international dollars: $/toe: constant 2011 international dollars per metric ton of oil-equivalent.
Sources: See Political Economist (2014).

World Energy 2010-2015

According to BP's Statistical Review of World Energy, world primary energy consumption reached 13,147 million tons of oil equivalent in 2015 (BP 2016). From 2010 to 2015, world primary energy consumption grew at an average annual rate of 1.5 percent.

World oil consumption (including biofuels) was 4,331 million tons in 2015, accounting for 33 percent of the world energy consumption. From 2010 to 2015, world oil consumption grew at an average annual rate of 1.2 percent.

World natural gas consumption was 3,135 million tons of oil equivalent in 2015, accounting for 24 percent of the world energy consumption. From 2010 to 2015, world natural gas consumption grew at an average annual rate of 1.7 percent.

World coal consumption was 3,840 million tons of oil equivalent in 2015, accounting for 29 percent of the world energy consumption. From 2010 to 2015, world coal consumption grew at an average annual rate of 1.1 percent.

World consumption of nuclear electricity was 583 million tons of oil equivalent in 2015, accounting for 4 percent of the world energy consumption. From 2010 to 2015, world consumption of nuclear electricity declined at an average annual rate of 1.4 percent.

World consumption of hydro, geothermal and biomass electricity was 1,010 million tons of oil equivalent in 2015, accounting for 8 percent of the world energy consumption. From 2010 to 2015, world consumption of hydro, geothermal and biomass electricity grew at an average annual rate of 3.0 percent.

World consumption of wind and solar electricity was 248 million tons of oil equivalent in 2015, accounting for 2 percent of the world energy consumption. From 2010 to 2015, world consumption of wind and solar electricity grew at an average annual rate of 23.9 percent.

According to World Bank and IMF data, gross world product (global economic output) was 107.0 trillion dollars (in 2011 constant international dollars) in 2015. From 2010 to 2015, global economic output grew at an average annual rate of 3.4 percent.

World average energy efficiency was 8,136 dollars per ton of oil equivalent in 2015. From 2010 to 2015, world average energy efficiency grew at an average annual rate of 1.8 percent.

World carbon dioxide emissions from fossil fuels burning were 33.5 billion tons in 2015. From 2010 to 2015, world carbon dioxide emissions grew at an average annual rate of 1.2 percent.

World average emissions intensity of gross world product was 0.313 kilogram of carbon dioxide emissions per dollar of gross world product. From 2010 to 2015, world average emissions intensity of gross world product declined at an average annual rate of 2.1 percent.

World average emissions intensity of primary energy consumption was 2.55 tons of carbon dioxide emissions per ton of oil equivalent. From 2010 to 2015, world average emissions intensity of primary energy consumption declined at an average annual rate of 0.3 percent.

Figure 1 compares the historical world economic growth rates and the primary energy consumption growth rates from 1991 to 2015. The primary energy consumption growth rate has an intercept of -0.011 at zero economic growth rate and a slope of 0.904. That is, primary energy consumption has an “autonomous” tendency to fall by 1.1 percent a year when economic growth rate is zero. When economic growth rate rises above zero, an increase in economic growth rate by one percentage point is associated with an increase in primary energy consumption by 0.9 percent. R-square for the linear trend is 0.751.

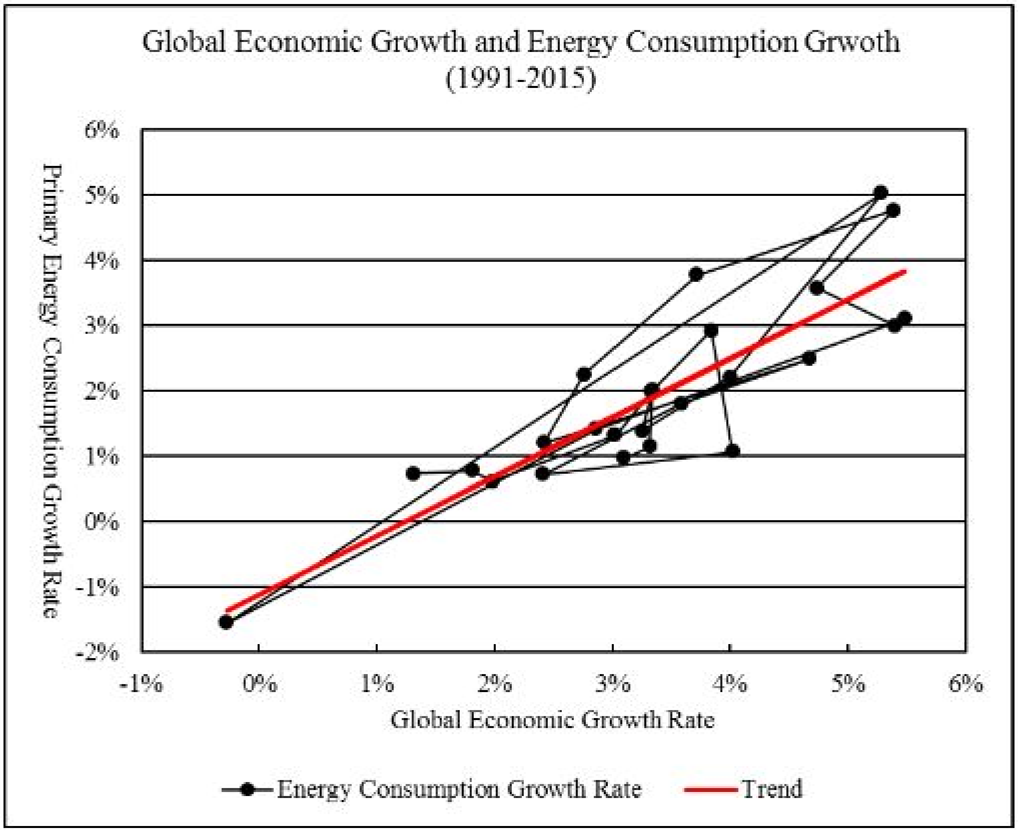

Figure 1
Sources: Gross world product in constant 2011 international dollars is from World Bank (2016); world primary energy consumption is from BP (2016).

Oil

World oil production (including crude oil and natural gas liquids) was 4,362 million tons (91.7 million barrels per day) in 2015, 3.2 percent higher than world oil production in 2014.

In 2015, Saudi Arabia was the world's largest oil producer by energy content; Saudi Arabia produced 569 million tons of crude oil and natural gas liquids (12.0 million barrels per day), accounting for 13 percent of the world oil production.

The United States was the world's largest oil producer by volume; the US produced 567 million tons of crude oil and natural gas liquids (12.7 million barrels per day), accounting for 13 percent of the world oil production.

The Russian Federation was the world's third largest oil producer; Russia produced 541 million tons of crude oil and natural gas liquids (11.0 million barrels per day), accounting for 12 percent of the world oil production.

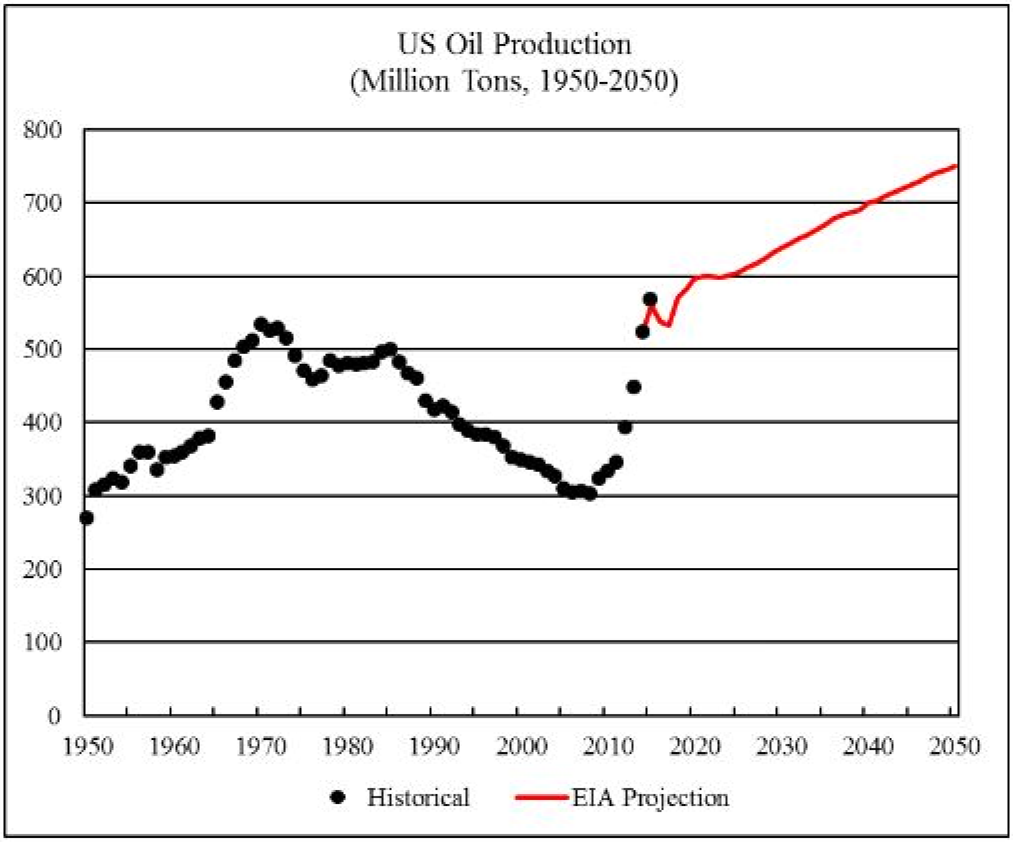

Figure 2
Sources: US historical oil production from 1950 to 1964 is from Rutledge (2008); US oil production from 1965 to 2015 is from BP (2016). Projected US oil production from 2014 to 2040 is from EIA (2016a), reference case, extended to 2050 by this author.

Figure 2 shows the historical and projected US oil production from 1950 to 2050. Theprojection is based on the US Energy Information Administration's reference case scenario of the US oil production from 2014 to 2040 (EIA 2016a), extended to 2050 based on the trend from 2031 to 2040.

The US cumulative oil production up to 2015 was 32 billion tons. EIA's current projection implies that the US cumulative oil production will be 48 billion tons by 2040 and the US ultimately recoverable oil resources will be 160 billion tons. Hubbert linearization applied to the EIA projection from 2031 to 2040 implies that the US oil production will not peak until 2081 when production rises to 833 million tons.

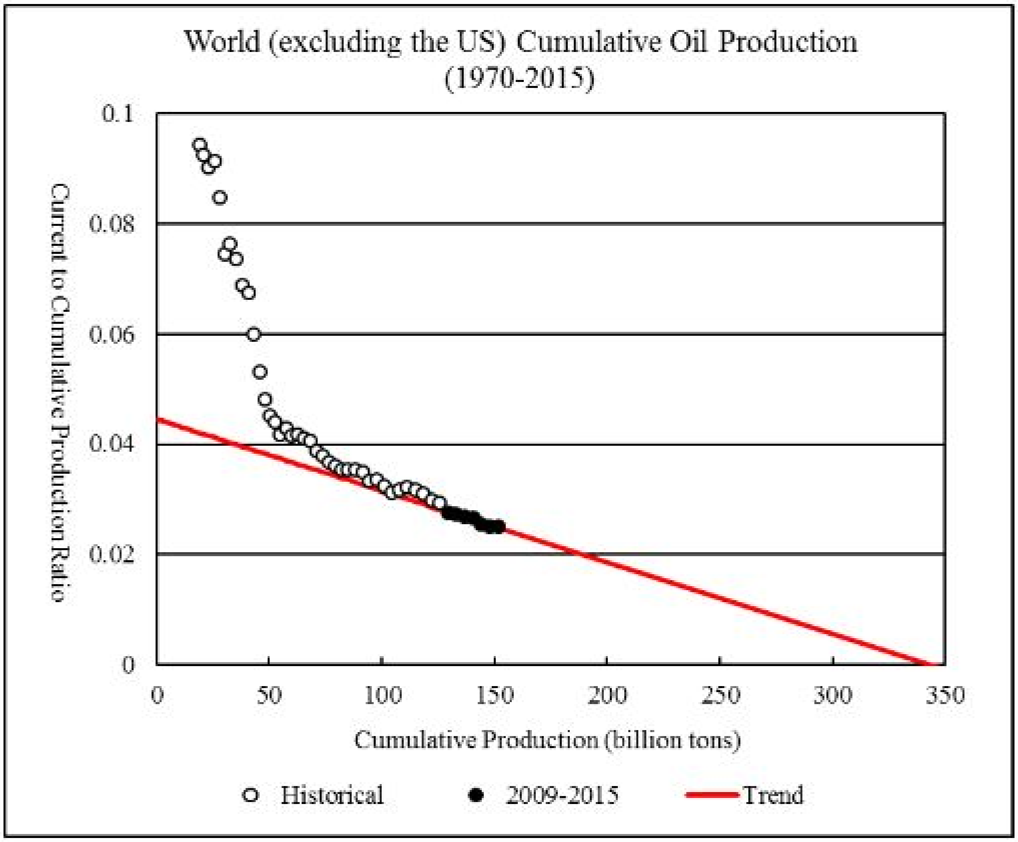

Figure 3
Sources: World historical cumulative oil production is from Rutledge (2008); world oil production from 1965 to 2015 is from BP (2016).

Figure 3 applies the Hubbert Linearization analysis to the world (excluding the US) oil production. The world (excluding the US) cumulative oil production up to 2015 was 152 billion tons. The linear trend from 2009 to 2015 indicates that the world (excluding the US) ultimately recoverable oil resources will be 343 billion tons. Regression R-square is 0.956. Year 2009 is selected as the beginning year in estimating the linear trend because it was a year of global economic recession. Other things being equal, a recession year tends to have a lower current production to cumulative production ratio and result in a larger amount of estimated ultimately recoverable resources.

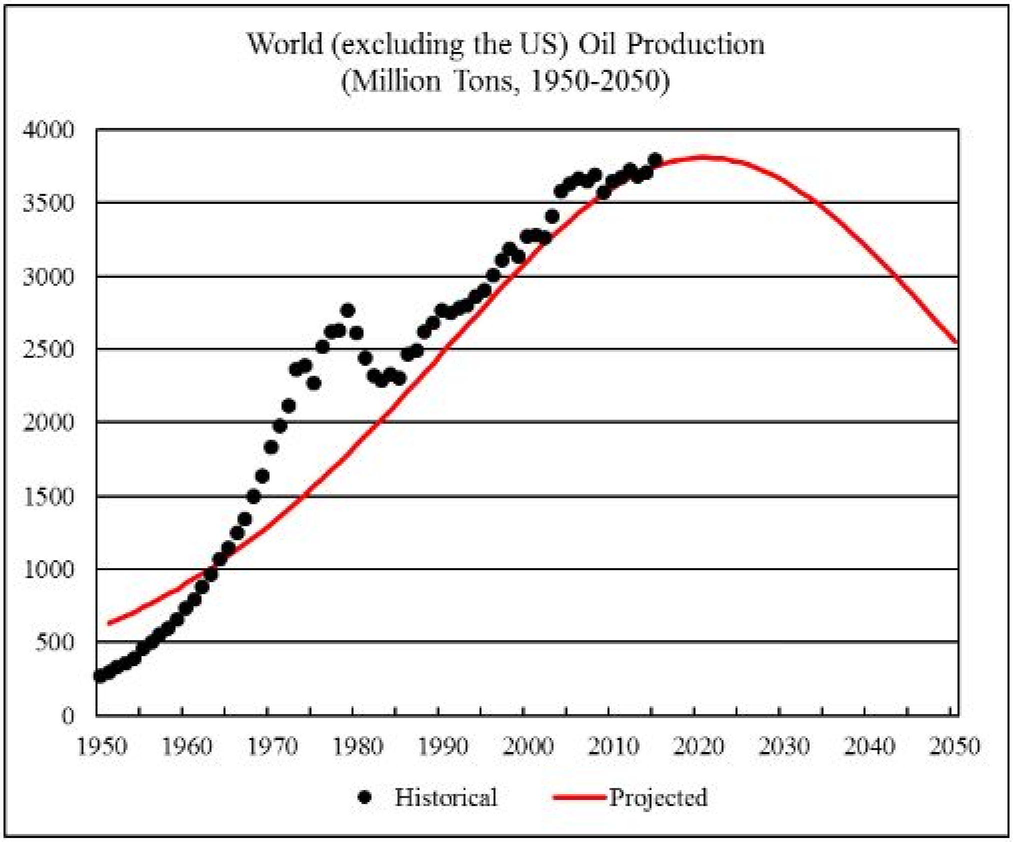

Figure 4
Sources: World historical oil production from 1950 to 1964 is from Rutledge (2008); world oil production from 1965 to 2015 is from BP (2016).

Figure 4 shows the historical projected world (excluding the US) oil production from 1950 to 2050. The world (excluding the US) oil production is projected to peak in 2021, with a production level of 3,811 million tons.

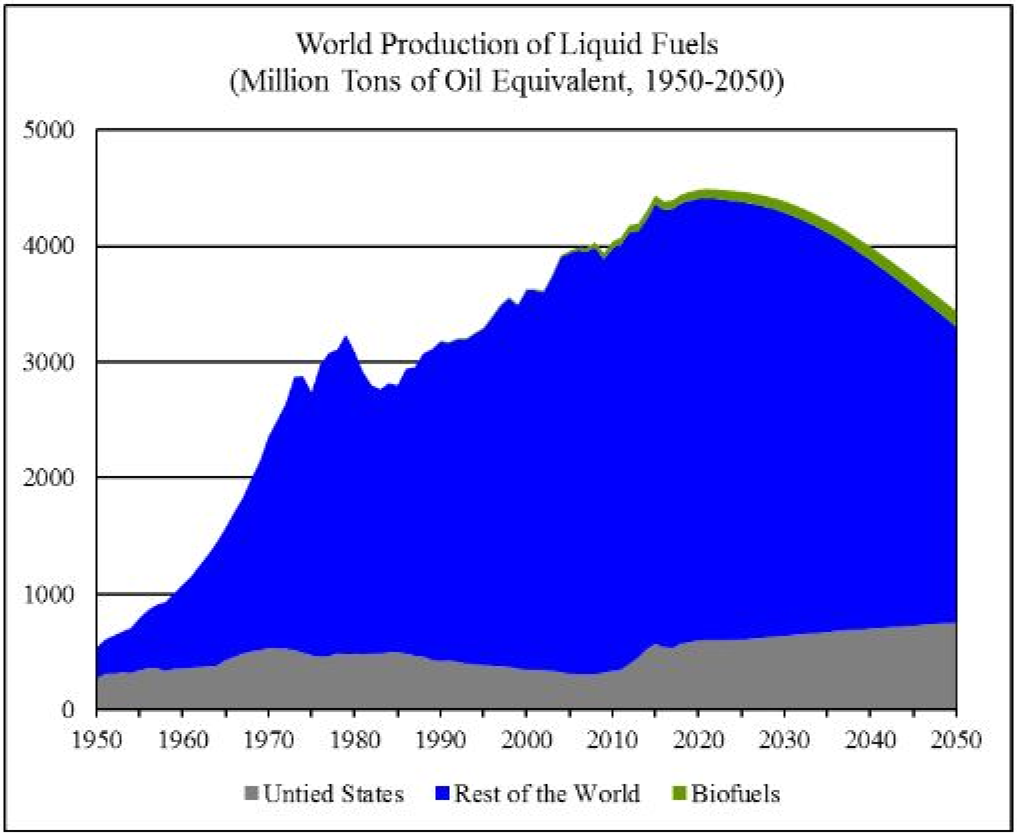

Figure 5
Sources: See Figure 2 and 4 for the US and the world (excluding the US) oil production. World biofuels production from 1990 to 2015 is from BP (2016). Projection of world biofuels production from 2016 to 2040 is from EIA (2016b), extended to 2050 based on the linear trend from 2030 to 2040.

Figure 5 shows the historical and projected world production of liquid fuels. The world production of liquid fuels is the sum of the US oil production, the world (excluding the US) oil production, and the biofuels production. Projection of world biofuels production from 2016 to 2040 is from EIA (2016b), extended to 2050 based on the linear trend from 2030 to 2040. World production of liquid fuels is projected to peak in 2021, with a production level of 4,491 million tons.

Natural Gas

World natural gas production was 3,539 billion cubic meters (3,200 million tons of oil equivalent) in 2015, 2.2 percent higher than world natural gas production in 2014.

In 2015, the United States was the world's largest natural gas producer; the US produced 767 billion cubic meters of natural gas (705 million tons of oil equivalent), accounting for 22 percent of the world natural gas production.

The Russian Federation was the world's second largest natural gas producer; Russia produced 573 billion cubic meters of natural gas (516 million tons of oil equivalent), accounting for 16 percent of the world natural gas production.

Iran was the world's third largest natural gas producer; Iran produced 193 billion cubic meters (173 million tons of oil equivalent), accounting for 5 percent of the world natural gas production.

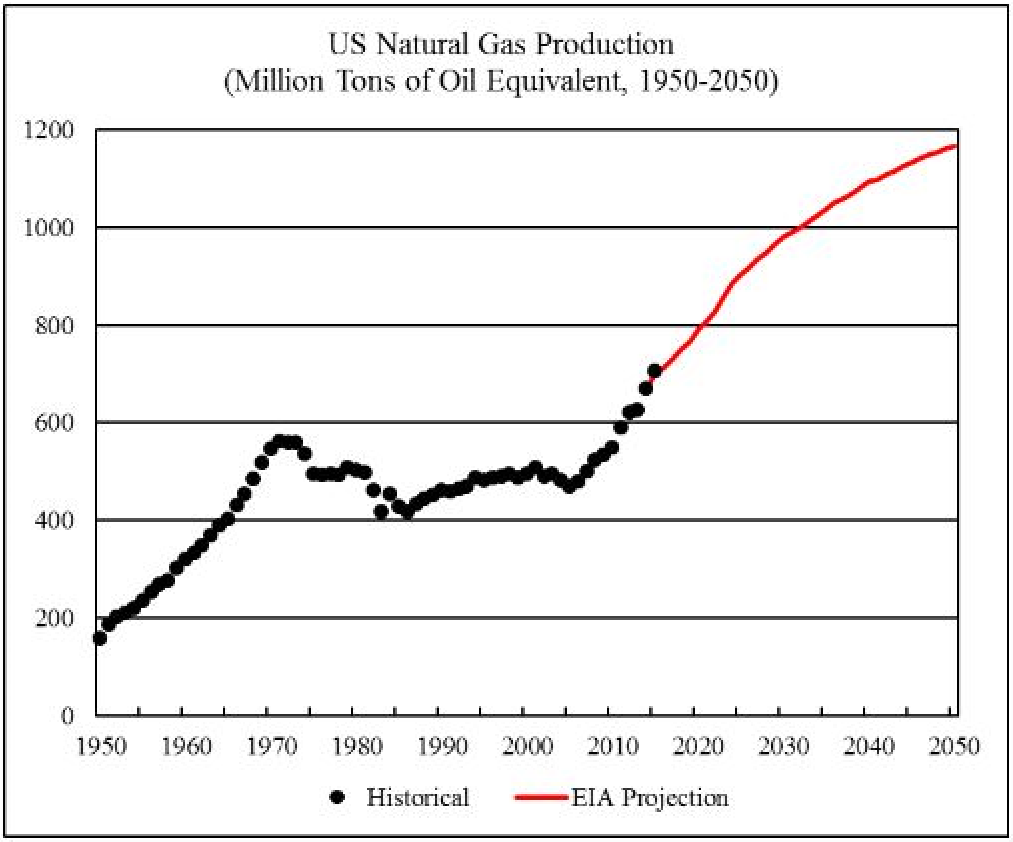

Figure 6
Sources: US historical natural gas production from 1950 to 1969 is from the US Energy Information Administration, "U.S. Natural Gas Marketed Production," 1900-2015; US natural gas production from 1970 to 2015 is from BP (2016). Projected US natural gas production from 2014 to 2040 is from EIA (2016a), reference case, extended to 2050 by this author.

Figure 6 shows the historical and projected US natural gas production from 1950 to 2050. The projection is based on the US Energy Information Administration's reference case scenario of the US natural gas production from 2014 to 2040 (EIA 2016a), extended to 2050 based on the trend from 2031 to 2040.

The US cumulative natural gas production up to 2015 was 32 billion tons of oilequivalent. EIA's current projection implies that the US cumulative natural gas production will be 55 billion tons of oil equivalent by 2040 and the US ultimately recoverable natural gas resources will be 156 billion tons of oil equivalent. Hubbert linearization applied to the EIA projection from 2031 to

2040 implies that the US natural gas production will peak in 2060 with aproduction level of 1,198 million tons of oil equivalent.

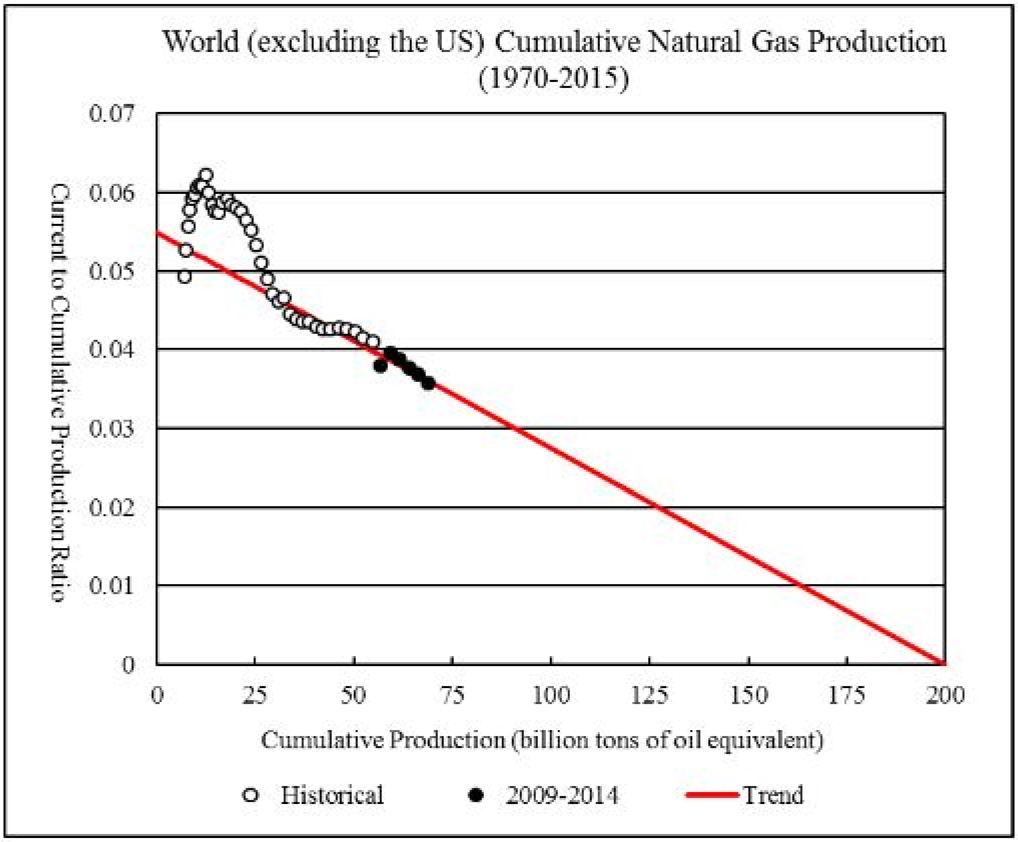

Figure 7

Sources: World historical cumulative natural gas production is from Rutledge (2008); world natural gas production from 1970 to 2015 is from BP (2016).

Figure 7 applies the Hubbert Linearization analysis to the world (excluding the US) natural gas production. The world (excluding the US) cumulative natural gas production up to 2015 was 72 billion tons of oil equivalent. The linear trend from 2009 to 2015 indicates that the world (excluding the US) ultimately recoverable natural gas resources will be 200 billion tons ofoil equivalent. Regression R-square is 0.777.

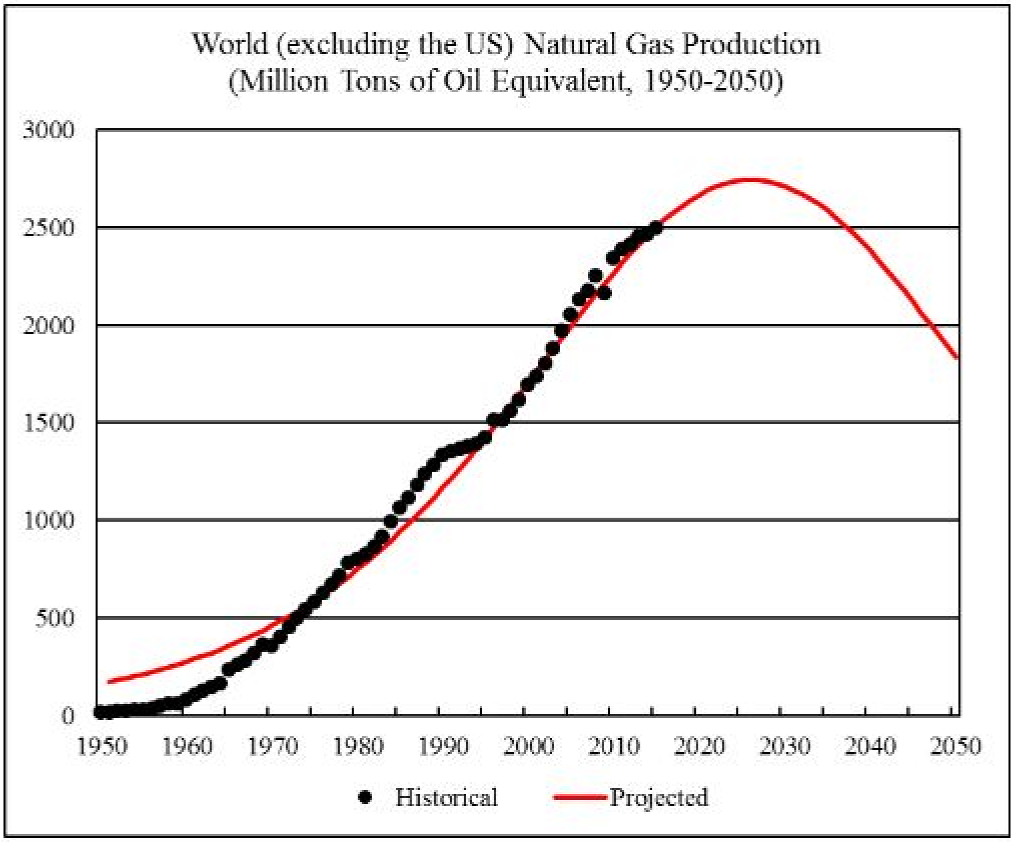

Figure 8
Sources: World historical natural gas production from 1950 to 1959 is estimated using carbon dioxide emissions from natural gas consumption (EPI 2015); world historical natural gas production from 1960 to 1969 is from Rutledge (2008); world natural gas production from 1970 to 2015 is from BP (2016).

Figure 8 shows the historical and projected world (excluding the US) natural gas production from 1950 to 2050. The world (excluding the US) natural gas production is projected to peak in 2026, with a production level of 2,743 million tons of oil equivalent

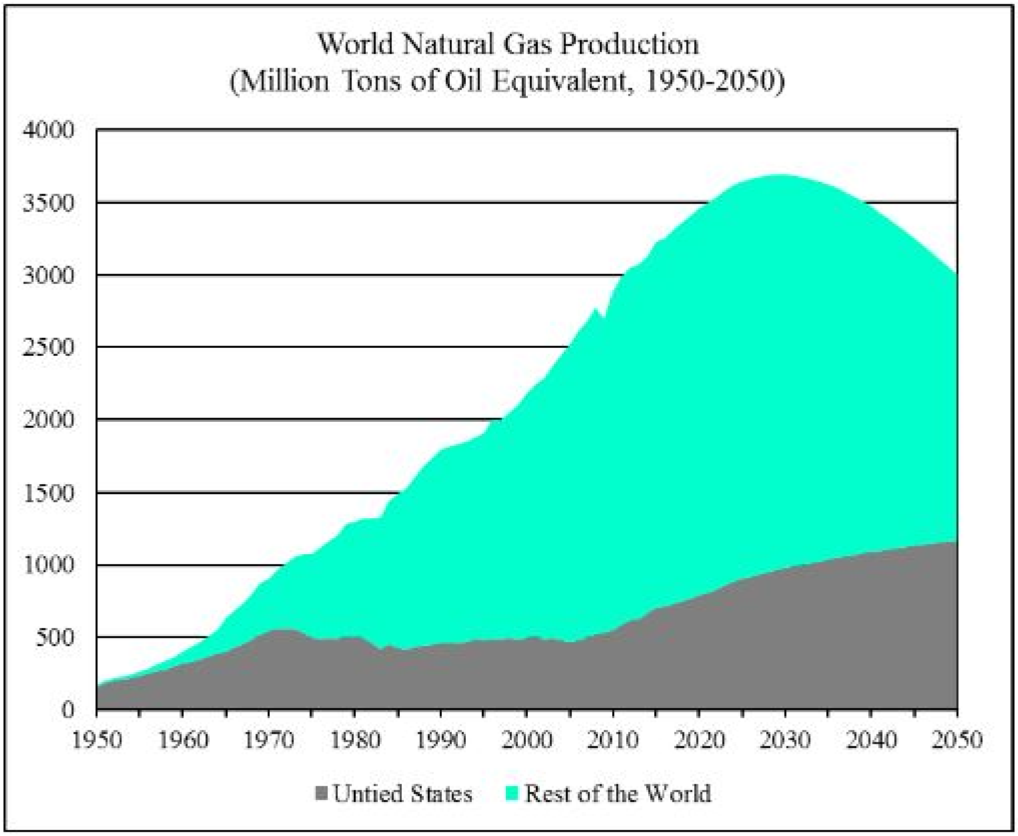

Figure 9
Sources: See Figure 6 and 8 for the US and the world (excluding the US) natural gas production.

Figure 9 shows the historical and projected world natural gas production. World natural gas production is projected to peak in 2030, with a production level of 3,694 million tons of oil equivalent.

Coal

World coal production was 7,861 million tons (3,830 million tons of oil equivalent) in 2015, 4 percent lower than world coal production in 2014.

In 2015, China was the world's largest coal producer; China produced 3,747 million tons of coal (1,827 million tons of oil equivalent), accounting for 48 percent of the world coal production.

The United States was the world's second largest coal producer; the US produced 813 million tons of coal (455 million tons of oil equivalent), accounting for 12 percent of the world coal production.

India was the world's third largest coal producer; India produced 678 million tons of coal (284 million tons of oil equivalent), accounting for 7 percent of the world coal production.

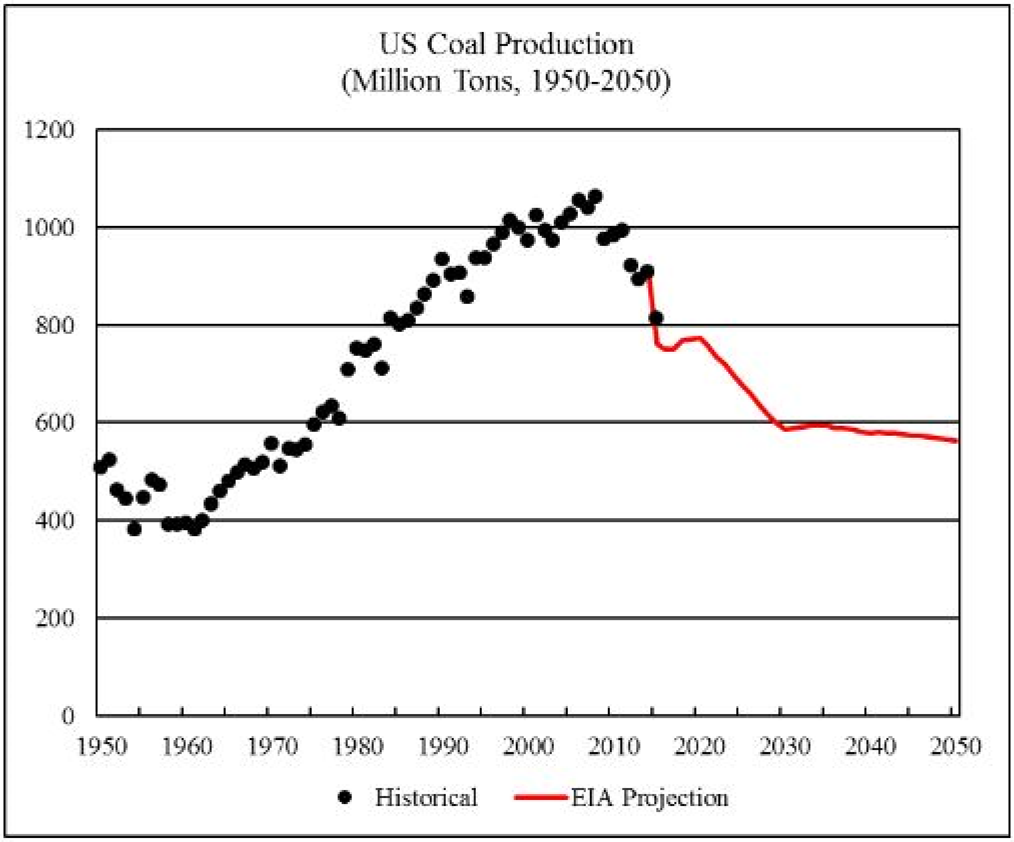

Figure 10
Sources: US historical coal production from 1950 to 1980 is from Rutledge (2011); US coal production from 1981 to 2015 is from BP (2016). Projected US coal production from 2014 to 2040 is from EIA (2016a), reference case, extended to 2050 by this author.

Figure 10 shows the historical and projected US coal production from 1950 to 2050. The projection is based on the US Energy Information Administration's reference case scenario of the US coal production from 2014 to 2040 (EIA 2016a), extended to 2050 based on the trend from 2031 to 2040.

The US cumulative coal production up to 2015 was 75 billion tons. EIA's current projection implies that the US cumulative coal production will be 91 billion tons by 2040 and the US ultimately recoverable coal resources will be 155 billion tons. The US coal production peaked in 2008, with a production level of 1,063 million tons.

The world (excluding the US) cumulative coal production up to 2015 was 285 billion tons. According to BP (2016), at the end of 2015, the world's total coal reserves were 891.5 billion tons and the world (excluding the US) coal reserves were 654.2 billion tons.

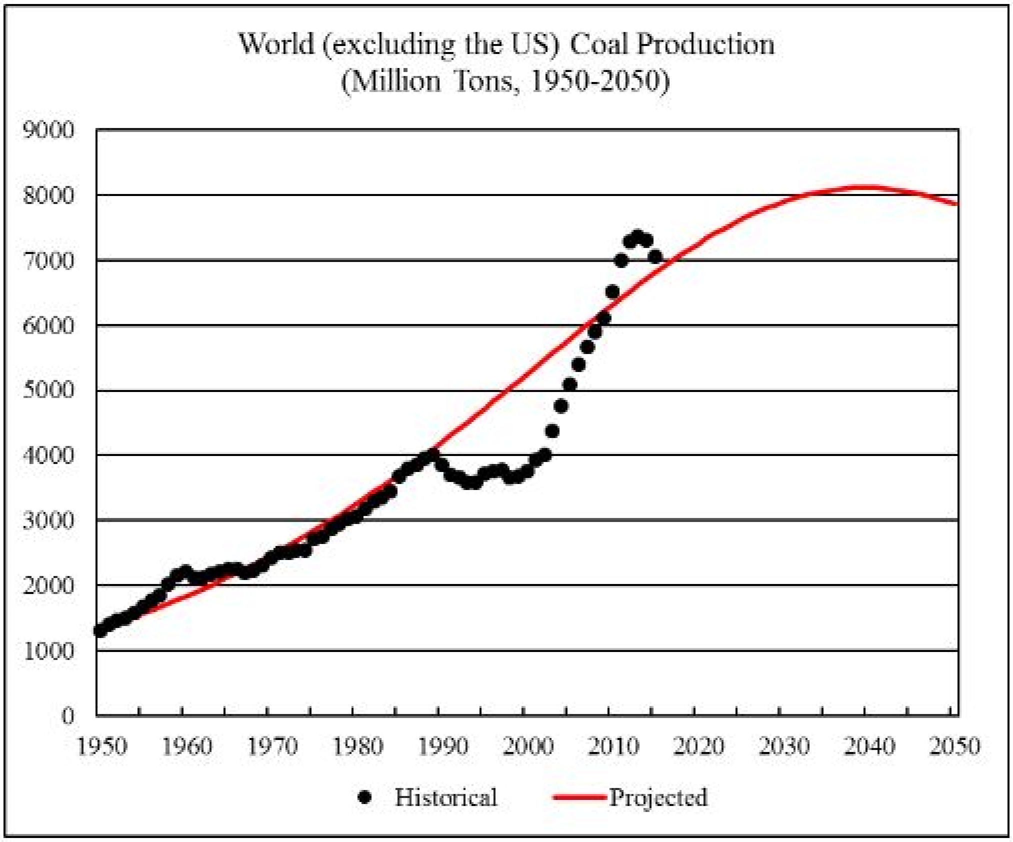

Figure 11
Sources: World historical coal production from 1950 to 1980 is from Rutledge (2011); world coal production from 1981 to 2015 is from BP (2016).

Figure 11 shows the historical and projected world (excluding the US) coal production from 1950 to 2050. The projection is based on the assumption that the world (excluding the US) ultimately recoverable coal resources will be 939 billion tons. The projected coal production curve is calibrated so that the world (excluding the US) coal production falls by about 140 million tons from 2015 to 2016. The world (excluding the US) coal production is projected to peak in 2040, with a production level of 8,115 million tons.

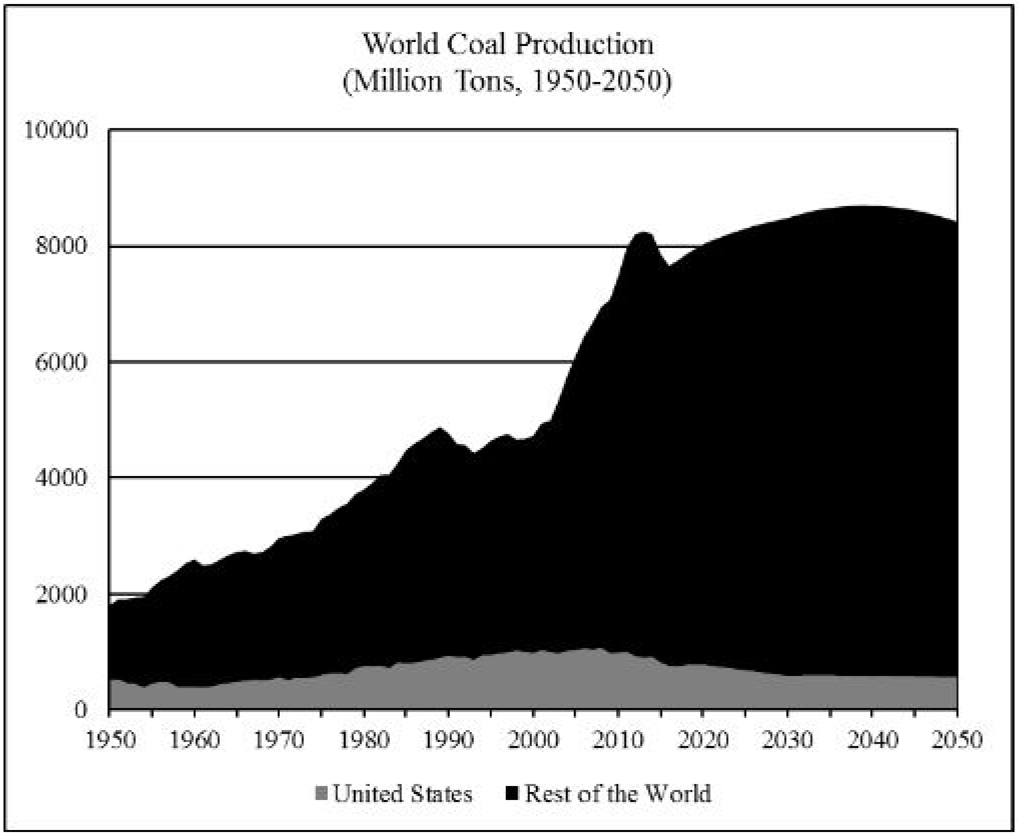

Figure 12
Sources: See Figure 10 and 11 for the US and the world (excluding the US) coal production.

Figure 12 shows the historical and projected world coal production. World coal production is projected to peak in 2039, with a production level of 8,695 million tons.

Nuclear Electricity

World consumption of nuclear electricity was 2,577 terawatt-hours in 2015, 1.3 percent higher than world nuclear electricity consumption in 2014.

I use the US Energy Information Administration's projection of nuclear generating capacity. According to EIA's projection, world nuclear generating capacity will grow from 355 gigawatts in 2015 to 602 gigawatts in 2040 (EIA 2016b).

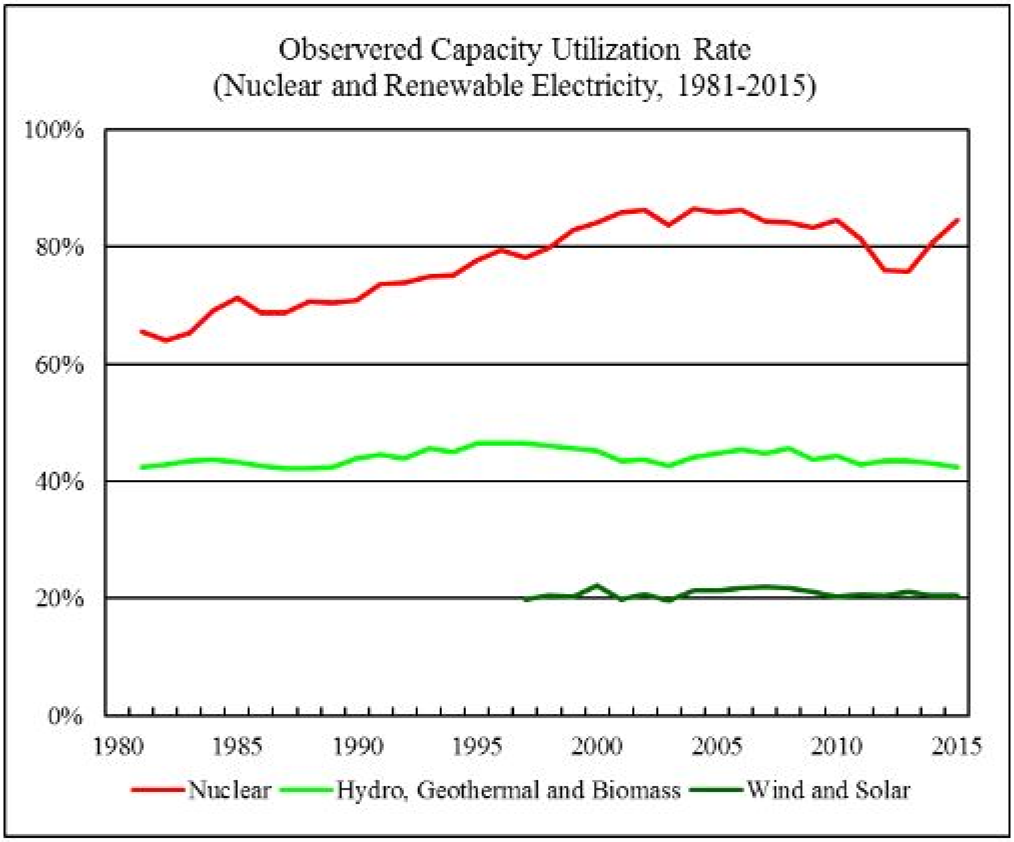

Figure 13
Sources: BP (2016) and EIA (2016b).

Figure 13 compares the observed capacity utilization rates for nuclear and renewable electricity.

The observed capacity utilization rate for electricity generation is calculated as follows:

Capacity Utilization Rate = (Annual Electricity Consumption * 2) / 8760 / (Beginning-of-Year Installed Capacity + End-of- Year Installed Capacity)

Electricity consumption data are from BP (2016). Electricity generating capacity data for years before 2010 are from the US Energy Information Administration, "International Energy Statistics." Electricity generating capacity data for years after 2010 are from EIA (2016b).

From 2000-2010, the world average capacity utilization rate for nuclear generating capacity fluctuated around 85 percent. The average capacity utilization rate for nuclear generating capacity fell sharply during 2011-2014, due to the impact of the Fukushima accident. But it recovered to about 85 percent in 2015.

I assume that the average capacity utilization rate for nuclear generating capacity will be 85 percent for the period 2016-2040. From 2040 to 2050, nuclear electricity consumption is assumed to grow following the linear trend from 2030 to 2040.

Nuclear electricity is converted into its thermal equivalent using the formula: 4.4194 terawatt-hours = 1 million tons of oil equivalent (assuming 38 percent conversion efficiency in a modern thermal power plant).

Hydro, Geothermal and Biomass Electricity

World consumption of hydro electricity was 3,946 terawatt-hours in 2015, 1.0 percent higher than world hydro electricity consumption in 2014. World consumption of geothermal and biomass electricity was 518 terawatt-hours in 2015, 5.3 percent higher than world geothermal and biomass electricity consumption in 2014.

I use the US Energy Information Administration's projection of hydro, geothermal and biomass generating capacity. According to EIA's projection, world hydro generating capacity will grow from 1,079 gigawatts in 2015 to 1,473 gigawatts in 2040; world geothermal generating capacity will grow from 14 gigawatts in 2015 to 52 gigawatts in 2040; world biomass generating capacity (including other minor sources of renewable electricity) will grow from 132 gigawatts in 2015 to 275 gigawatts in 2040 (EIA 2016b).

In recent years, the world average capacity utilization rate for hydro, geothermal and biomass generating capacity has fluctuated around 42-43 percent (see Figure 13). I assume that the average capacity utilization rate for hydro, geothermal and biomass generating capacity will be 43 percent for the period 2016-2040. From 2040 to 2050, hydro, geothermal and biomass electricity consumption is assumed to grow following the linear trend from 2030 to 2040.

Hydro, geothermal and biomass electricity is converted into its thermal equivalent using the formula: 4.4194 terawatt-hours = 1 million tons of oil equivalent (assuming 38 percent conversion efficiency in a modern thermal power plant).

Wind and Solar Electricity

World consumption of wind electricity was 841 terawatt-hours in 2015, 17.4 percent higher than world wind electricity consumption in 2014. World consumption of solar electricity was 253 terawatt-hours, 32.6 percent higher than world solar electricity consumption in 2014.

In 2015, the world installed 63 gigawatts of wind generating capacity and 51 gigawatts of solar generating capacity.

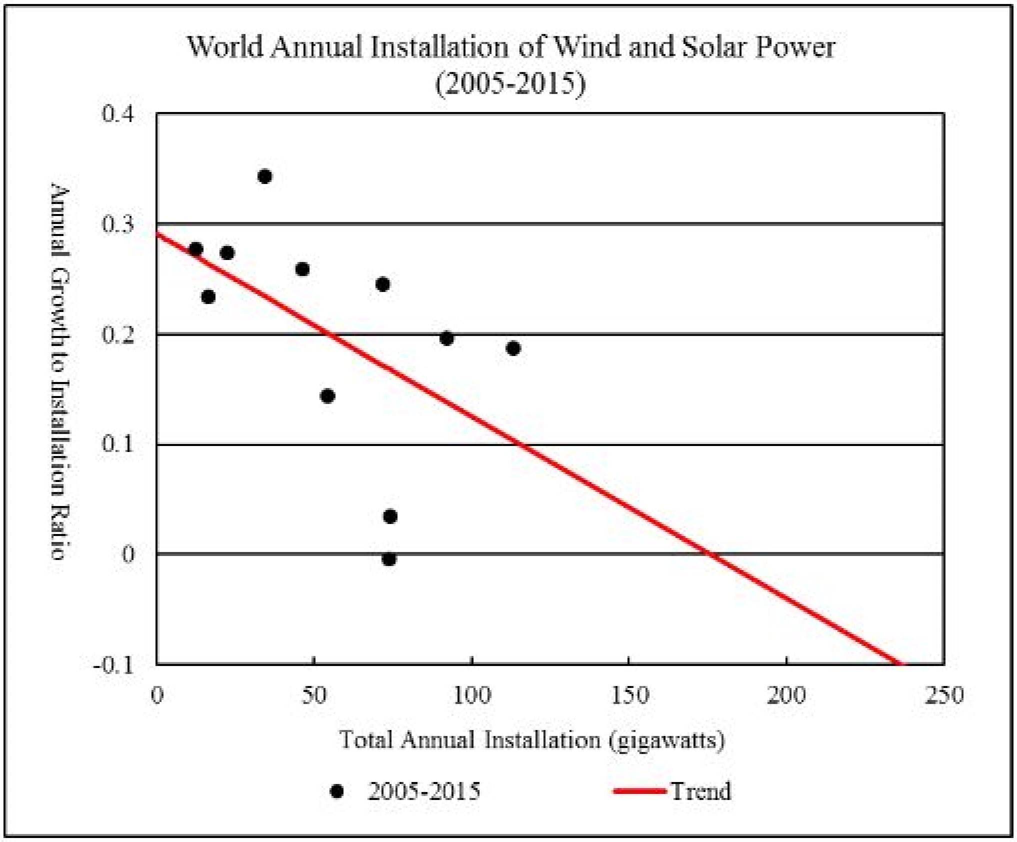

Figure 14
Sources: Annual installation of wind and solar generating capacity is from BP (2016).

Figure 14 compares the historical relationship between total annual installation of wind and solar power and the annual growth to the annual installation ratio (that is, the ratio of the growth of the annual installation to the annual installation). The downward inear trend (R-square 0.262) indicates that the total annual installation of wind and solar power should eventually approach the maximum of 176 gigawatts (where the linear trend meets the zero horizontal line).

The parameters of the linear trend can be used to project the future installation of wind and solar power. While the linear trend is preliminary, the implied future installation compares favorably against several mainstream forecasts.

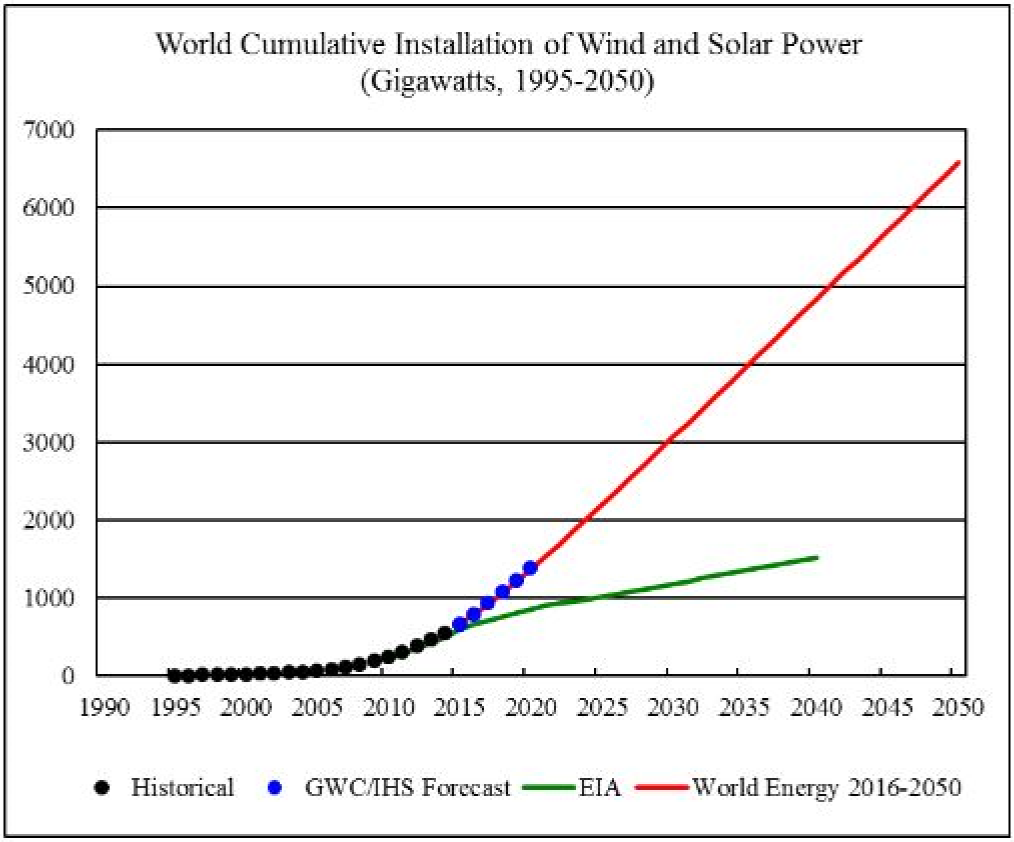

Figure 15
Sources: The US Energy Information Administration's forecast and historical data of cumulative installation of wind and solar generating capacity from 2010 to 2040 are from EIA (2016b). For Global Wind Energy Council's forecast of wind generating capacity from 2016 to 2019, see GWEC (2016). For IHS forecast of solar generating capacity from 2016 to 2019 (extended to 2020 by this author), see Beetz (2015).

Figure 15 compares this author's forecast of future installation of wind and solar generating capacity with the "GWC/IHS Forecast" and the US Energy Information Administration's official forecast published in EIA's International Energy Outlook (EIA 2016b).

According to Global Wind Energy Council's current forecast, the world will install 64 gigawatts of wind generating capacity in 2016, 68 gigawatts in 2017, 72 gigawatts in 2018, 75.5 gigawatts in 2019, and 79.5 gigawatts in 2020 (GWEC 2016). According to energy consultancy IHS's forecast, the world will install 65 gigawatts of solar generating capacity in 2016, 65.5gigawatts in 2017, 68.4 gigawatts in 2018, and 73.5 gigawatts in 2019 (Beetz 2015). I extend IHS's forecast to 2020 by assuming that the world will install 78.5 gigawatts of solar generating capacity in 2020. If one adds up GWEC's forecasts of wind installations and IHS's forecasts of solar installations (extended to 2020), then the world's cumulative installation of wind and solar generating capacity should rise to 1,375 gigawatts by 2020. By comparison, this report ("World Energy 2016-2050") projects that the cumulative installation of wind and solar generating capacity will be 1,373 gigawatts by 2020.

This report's forecast of future wind and solar installation is far more optimistic than the US Energy Information Administration's official forecast. According to EIA's forecast, the world's cumulative installation of wind and solar generating capacity will be 865 gigawatts by 2020 and 1,512 gigawatts by 2040. By comparison, this report projects that the world's cumulative installation of wind and solar generating capacity will rise to 4,826 gigawatts by 2040 and 6,585 gigawatts by 2050.

In recent years, the world average capacity utilization rate for wind and solar generating capacity has fluctuated around 20-22 percent (see Figure 13).

I assume that the average capacity utilization rate for wind and solar generating capacity will be 22 percent for the period 2016-2040. Wind and solar electricity is converted into its thermal equivalent using the formula: 4.4194 terawatt-hours = 1 million tons of oil equivalent (assuming 38 percent conversion efficiency in a modern thermal power plant).

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Wind and Solar Electricity Generation Cost

As the wind and solar electricity cost falls, it has become increasingly controversial regarding whether wind and solar electricity has become "cost competitive" against fossil fuels power plants.

This section uses a simple and transparent framework that compares the wind and solar electricity generation costs with the gas-fired electricity generation cost.

The average electricity generation cost is defined as the annual total generation cost divided by the annual electricity generation.

The annual electricity generation from one gigawatt of generating capacity is calculated as follows:

Annual Electricity Generation = 1 Gigawatt * Capacity Utilization Rate

In the US, gas-fired electricity serves as both base-load and load-balancing power. I assume that the gas-fired power plant has a capacity utilization rate of 50 percent.

In 2015, the world average observed capacity utilization rate for wind electricity was 24 percent and for solar electricity was 14 percent. The US had higher observed capacity utilization rates. The US observed capacity utilization rate for wind electricity was 31 percent and for solar electricity was 20 percent (calculated using data from BP 2016).

I assume that the wind power plant has a capacity utilization rate of 30 percent and the solar photovoltaic power plant has a capacity utilization rate of 20 percent.

The annual total generation cost is the sum of annual fixed cost and annual fuel cost.

Annual fixed cost is assumed to be 10 percent of the capital cost. Annual fixed cost includes interest rate (assumed to be 5 percent) and depreciation and maintenance cost (assumed to be 5 percent of the capital cost).

Wind and solar electricity has no fuel cost. For gas-fired electricity, the technology is assumed to be advanced combined cycle. Natural gas consumption for gas-fired electricity is calculated assuming 55 percent thermal conversion efficiency (or a heat rate of 6,200 British thermal units per kilowatt-hour) and natural gas price is assumed to be 5 dollars per million British thermal

unit (in 2015, the US Henry Hub natural gas price was 2.6 dollars per million Btu).
Table 2 reports the estimated generating cost for gas-fired, wind, and solar photovoltaic electricity. Given the current technologies, gas-fired electricity costs 5.6 cents per kilowatt-hour, wind electricity costs 6 cents per kilowatt-hour, and solar photovoltaic electricity costs 14 cents per kilowatt-hour. Wind electricity costs about the same as the gas-fired electricity and solar photovoltaic electricity is about two-and-a-half times as expensive.

Table 2 Electricity Generation Cost: Natural Gas, Wind, and Solar (2016 Scenario)

	Natural Gas	Wind	Solar PV
Generating Capacity (gigawatts)	1	1	1
Capacity Utilization Rate	50%	30%	20%
Annual Generation (gigawatt-hours)	4380	2738	1777
Capital Cost (million dollars)	1080	1644	2480
Annual Fixed Cost (million dollars)	108	164.4	248
Annual Fuel Cost (million dollars)	135.8	0	0
Annual Total Cost (million dollars)	243.8	164.4	248
Average Generation Cost (dollar per kwh)	0.056	0.060	0.140

Sources: Capital cost for new generating technologies is from EIA (2016a), "Cost and Performance Characteristics of New Generating Technologies, Annual Energy Outlook 2016."

Limits to Wind and Solar Electricity

In the medium- and long run, wind and solar electricity will be constrained by their intermittency and the growing difficulties to incorporate them into the electric grid.

An article published in China Electric Power studied the problem of incorporating wind and solar electricity into the electric grid of China’s Gansu province (a Chinese province is about the size of an European country). As of 2013, Gansu province had 12 gigawatts of wind generating capacity and 5.3 gigawatts of solar photovoltaic generating capacity (Yao, Zheng, and Li 2014). By comparison, Spain had a total installation of wind and solar generating capacity of 16 gigawatts in 2007.

The conventional generating capacity that is available for load balancing can be calculated from the following formula:

P L = (P total – Grid Reserve – Plant Self-Consumption and Transmission Losses) * "Balancing Depth" Factor

In the above formula, P total is the total nameplate conventional generating capacity. P L is the conventional generating capacity available for load balancing. The authors of the study subtracted 13 percent of the total capacity as the "reserve capacity." Power plant self-consumption and transmission losses are assumed to be 10 percent of the electricity generated.

"Balancing Depth" refers to the degree to which the conventional generating capacity can increase or decrease generation on short notice. This is assumed to be 30 percent of the effective generating capacity. Thus, overall, only about 23 percent of the nameplate conventional generating capacity is actually available for load balancing.

Out of the conventional generating capacity that is available for load balancing, some has to be used to meet peak load demand that is not offset by wind or solar generation. This is estimated to be about 20 percent of the average load or 10 percent of the total nameplate capacity. Thus, only 13 percent of the nameplate conventional generating capacity is available to balance the intermittency of wind and solar electricity.

In the case of Gansu province, it was estimated by the authors that for 17 gigawatts of wind and solar power, load balancing need would be 7-9 gigawatts or between 40 and 55 percent of the wind and solar generating capacity. Take the lower limit of 40 percent. As the balancing need of wind and solar generating capacity is 40 percent and only 13 percent of the conventional generating capacity is available for balancing the intermittency of wind and solar electricity, it follows that the total conventional generating capacity needs to be about three times as large for the electric grid to be balanced (40 / 13 = 3.08).

Let us make some optimistic assumptions. Suppose the grid reserve can be reduced to 10 percent of the total nameplate conventional generating capacity and the balancing depth can be increased to 50 percent. Thus, 40 percent of the nameplate capacity can be made available for

load balancing. Subtracting 10 percent of the capacity required to meet peak load demand, 30 percent of the nameplate conventional generating capacity can be made available to balance wind and solar intermittency.

On the other hand, suppose through better coordination and building of long-distance transmission lines, the balancing need for wind and solar electricity can be reduced to 30 percent of the generating capacity. After these adjustments, it would still take at least one gigawatt of conventional generating capacity to match one gigawatt of wind or solar generating capacity.

According to EIA's International Energy Outlook, the world will have 1,970 gigawatts of coal-fired generating capacity, 2,252 gigawatts of gas-fired generating capacity, 320 gigawatts of liquids-fired generating capacity, and 1,473 hydroelectric generating capacity by 2040. Thus, by 2040, the total conventional generating capacity adds up to 6,015 gigawatts.

According to this report's projection, the world will have 4,826 gigawatts of wind and solar generating capacity by 2040 and 6,586 gigawatts by 2050. Thus, the technical limits of the world's electric grids to accommodate wind and solar electricity will be tested by the 2040s.

In the very long run, the expansion of wind and solar electricity will be constrained by the availability of land and material resources.

According to Castro et al. (2011), global technical potential for wind electricity generation is about one terawatt. The materialization of this potential would require the building of wind electric power over a land area as large as 10 million square kilometers. Assuming a capacity utilization rate of 25 percent for wind power, it takes 4,000 gigawatts of wind generating capacity to generate one terawatt of wind electricity.

The current global land occupation by human settlement and infrastructure is estimated to be 2-4 million square kilometers or 1.3-2.7 percent of the world's total land surface area. In the next few decades, 1 million square kilometers of additional land will be occupied for human settlement and infrastructure because of population growth and urbanization. By the end of the century, there will be about 4-6 million square kilometers occupied by human settlement and infrastructure. If 10 percent of the total settlement and infrastructure land area can be made available for solar electric power, the total land area where the solar electric power can be built will amount to about 500,000 square kilometers by the end of the 21st century.

Assuming a power density of 4 watt per square meter, a land area of 500,000 square kilometers can generate solar electricity of two terawatts or 2,000 gigawatts (Castro et al. 2013).

Assuming a capacity utilization rate of 15 percent for solar power, 2,000 gigawatts of solar electricity generation requires about 13,000 solar generating capacity.

Thus, by the end of the 21st century, the world has a total technical potential of wind and solar generating capacity of about 17,000 gigawatts. According to this report's projection, the world will have built about 6,600 gigawatts of wind and solar generating capacity by 2050.

Beyond 2050, if the world keeps building 175 gigawatts of wind and solar generating capacity each year, the world will have more than 15,000 gigawatts of wind and solar generating capacity by 2200. This is consistent with the technical potential estimated above.

World Energy 2016-2050

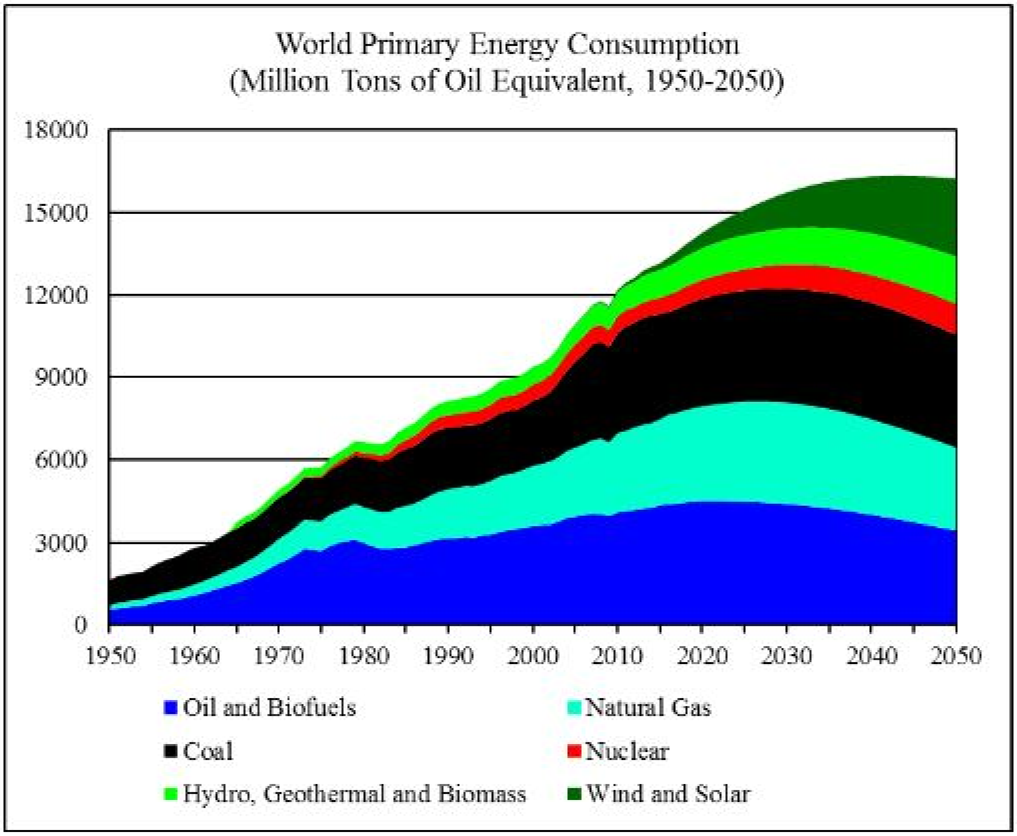

Figure 16
Sources: World historical oil, natural gas, and coal consumption from 1950 to 1964 is assumed to be the same as production; world primary energy consumption and its composition from 1965 to 2015 is from BP (2016); world primary energy consumption and its composition from 2016 to 2050 is based on this report's projections.

Figure 16 shows the historical and projected world primary energy consumption from 1950 to 2050.

World historical consumption of oil, natural gas, and coal from 1950 to 1964 is assumed to be the same as production.

World primary energy consumption and its composition from 1965 to 2015 is from BP (2016).

World consumption of oil, natural gas, and coal from 2016 to 2050 is assumed to be the same as production. Oil consumption includes biofuels. Coal production in tons is converted to coal consumption in tons of oil equivalent using the formula: 2.05 tons of coal production = 1 ton of oil equivalent of coal consumption (based on the observed relationship in 2015).

World consumption of nuclear, hydro, geothermal, biomass, wind, and solar electricity from 2016 to 2050 is based on projections explained in the above sections.

World primary energy consumption is projected to peak in 2043 at 16,333 million tons of oil equivalent.

For 2016-2050, the relationship between the primary energy consumption growth rate and the economic growth rate is defined as follows:

Economic Growth Rate = (Primary Energy Consumption Growth Rate + 0.0112) / 0.904

In other words, it is assumed that the trend relationship between the two variables observed for the period 1991-2015 will continue to hold for the period 2016-2050.

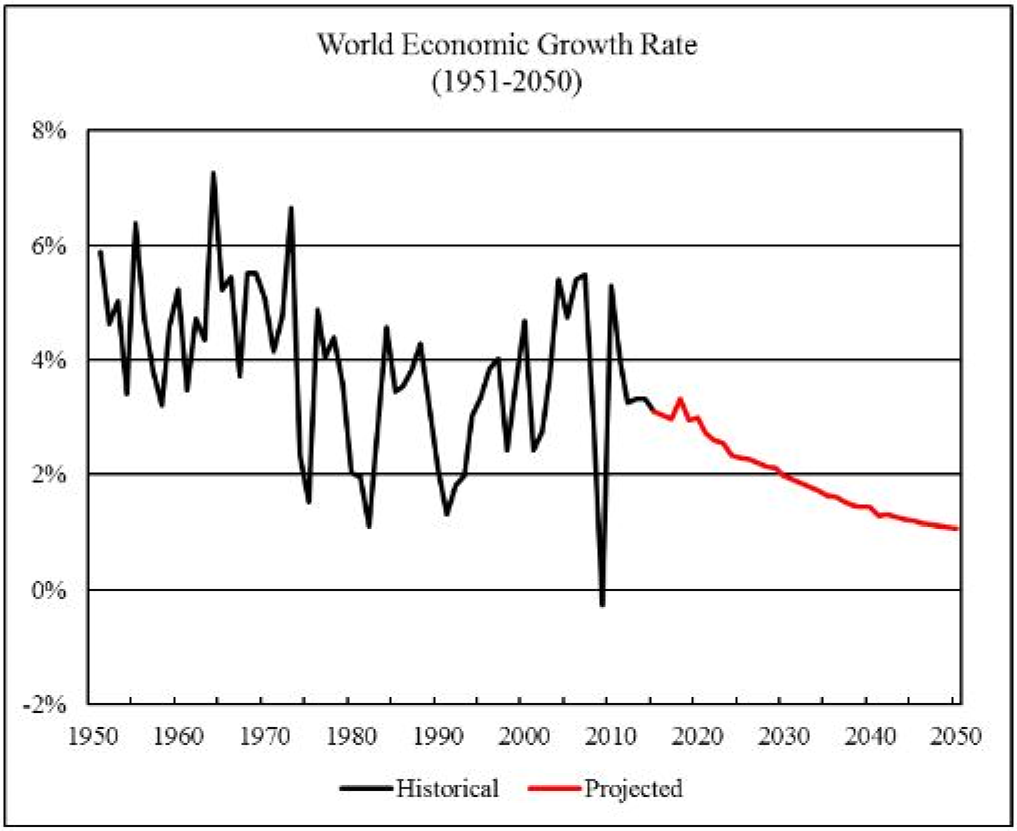

Figure 17
Sources: World economic growth rates from 1951 to 1990 are calculated from Maddison (2010); growth rates of gross world product in constant 2011 international dollars from 1991 to 2015 are from World Bank (2016); world economic growth rates from 2016 to 2050 are based on this report's projections.

Figure 17 shows the historical and projected world economic growth rates from 1951 to 2050. World (trend) economic growth rate is projected to fall below 3 percent by the 2020s, fall below 2 percent by the 2030s, and approach 1 percent by the 2040s.

After the Second World War, global economic growth rate fell below 2 percent only in several occasions: 1975, 1982, 1991, and 2009. These were all considered to be deep global economic recessions. During 1913-1950, when the global capitalist system suffered from major wars, revolutions, and the Great Depression, world economy actually grew at an average annual rate of 1.8 percent (Maddison 2010).

Thus, by the mid-21st century, although the global economy will continue to grow, world economic growth rate may become too close to zero so that the global capitalist system will suffer from persistent economic and political instability.

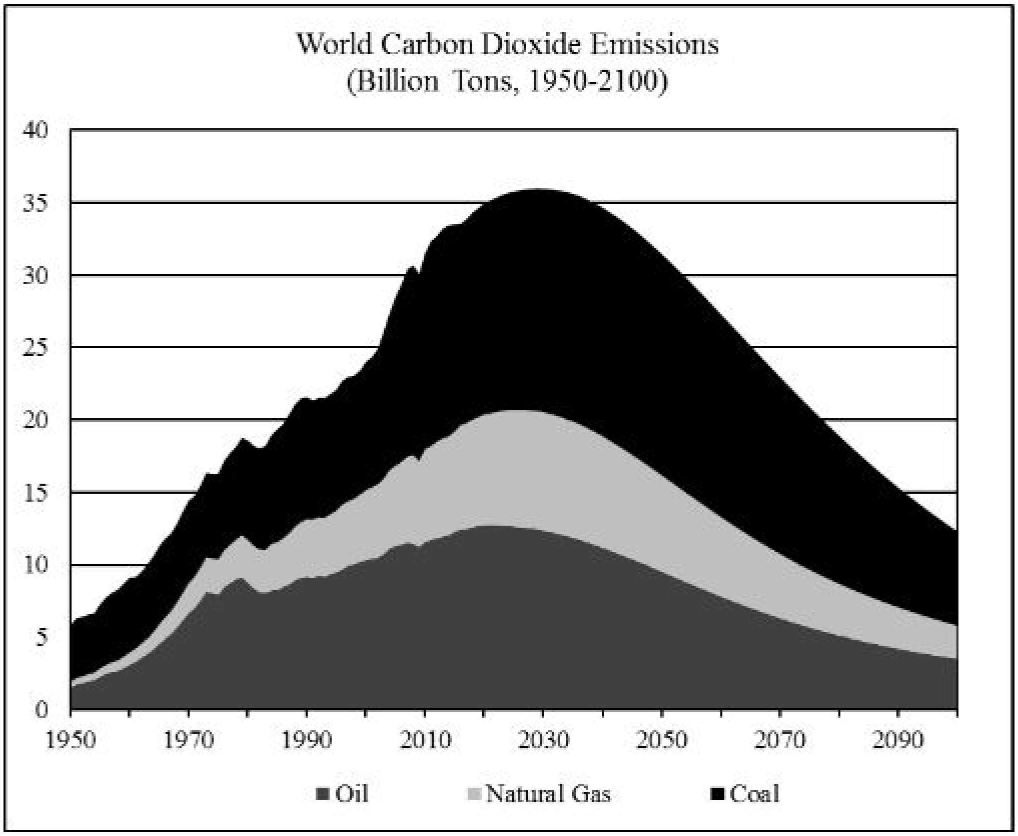

Figure 18
Sources: World carbon dioxide emissions from fossil fuels burning for 1950-1964 are from EPI (2015); world carbon dioxide emissions from 1965 to 2015 are estimated using data for oil, natural gas, and coal consumption from BP (2016); world carbon dioxide emissions from 2016 to 2100 are estimated using oil, natural gas, and coal consumption projected by this report.

Figure 18 shows the world carbon dioxide emissions from fossil fuels burning from 1950 to 2100.

Carbon dioxide emissions are estimated using oil, natural gas, and coal consumption data from BP's Statistical Review of World Energy. In previous editions of Statistical Review of World Energy, BP used the following conversion factors to calculate carbon dioxide emissions: 1 ton of oil emits 3.07 tons of carbon dioxide; 1 ton of oil equivalent of natural gas emits 2.35 tons of carbon dioxide; 1 ton of oil equivalent of coal emits 3.96 tons of carbon dioxide. In the 2016 edition of Statistical Review of World Energy, BP revised the estimates of carbon dioxide emissions without providing conversion factors for fuel types.

I estimate the carbon dioxide emissions from oil, natural gas, and coal consumption by using the conversion factors provided in previous editions of Statistical Review of World Energy and multiplying the conversion factors by an adjustment factor. The adjustment factor is 0.97 for 1965-1970, 0.96 for 1971-1980, 0.95 for 1981-1990, and 0.94 for 1991-2100. For example, carbon dioxide emissions from oil consumption in 1965 are estimated as: oil consumption in 1965 * 3.07 * 0.97. For years after 1990, biofuels production is subtracted from oil consumption in estimating carbon dioxide emissions from oil consumption. The total carbon dioxide emissions so calculated are very close to the carbon dioxide emissions reported by BP (2016) for the period 1965-2015.

World carbon dioxide emissions are projected to peak in 2029 at 35,953 million tons.

Cumulative world carbon dioxide emissions from fossil fuels burning from 2011 to 2100 will be 2,432 billion tons. These are emissions from direct fossil fuels combustion only and do not include emissions from cement production and gas flaring.

According to Intergovernmental Panel on Climate Change's Fifth Assessment Report, cumulative carbon dioxide emissions of 2.4 trillion tons from 2011 to 2100 are within the range of "representative concentrated pathways" RCP 4.5. It will lead to atmospheric concentration of carbon dioxide equivalent of 650 parts per million by 2100 and result in a median estimate of global warming of 2.6 degrees Celsius by 2100 (compared to 1850-1900), with about one-third chance that global warming by 2100 may actually exceed three degrees Celsius (IPCC 2014, Table SPM.1).

According to Hansen et al. (2015), global warming by more than two degrees may lead to the melting of West Antarctica ice sheets, causing sea level to rise by 5-9 meters over the next 50-200 years. Bangladesh, European lowlands, the US eastern coast, North China plains, and many coastal cities will be submerged. This will lead to the end of civilization as we know it.

If global warming rises above three degrees Celsius, slow climate feedbacks (through ice sheet melting and vegetation change) may eventually lead to a long-term global warming by up to six degrees Celsius (Hansen et al. 2008). In that event, much of the world will no longer be suitable for human inhabitation.

Table 3 World Energy and Economy: 2000-2050 (2016 Scenario)

	2000	2010	2020	2030	2040	2050
World Energy Consumption (Mtoe):						
Oil and Biofuels	3,588	4,080	4,485	4,387	3,999	3,440
Natural Gas	2,185	2,887	3,460	3,694	3,475	3,003
Coal	2,379	3,634	3,917	4,138	4,240	4,107
Nuclear	584	626	687	888	1,009	1,129
Hydro, Geothermal and Biomass	644	869	1,149	1,321	1,522	1,723
Wind and Solar	7	85	565	1,301	2,066	2,833
Total	9,388	12,181	14,264	15,729	16,311	16,234
Gross World Product (billion $)	62,548	90,494	124,340	156,483	184,150	207,212
GWP per Capita ($)	10,229	13,069	16,027	18,408	20,110	21,307
Energy Efficiency ($/toe)	6,662	7,429	8,717	9,949	11,290	12,764
Carbon Dioxide Emissions (Mt)	24,010	31,507	34,941	35,939	34,665	31,460

Mt: million metric tons.
Mtoe: million metric tons of oil-equivalent.
$: constant 2011 international dollars.
$/toe: constant 2011 international dollars per ton of oil-equivalent.

Table 3 reports the summary statistics of this Annual Report. To calculate the future gross world product per capita, United Nations' world population forecast (median variant) is used (UN 2015).

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