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Energy and Investing:

Financing the Transition to Renewable Energy

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1. Introduction

In 1750, when the industrial revolution was just getting started in England, the world population was 700 million. At that time, global energy use per day per capita was on the order of 5 kilowatt hours (more about this measure later). By 2018, after more than 250 years of massive innovation and economic growth, the world population and energy use per day per capita had both increased by a factor of 10 resulting in world energy usage more than 100 times greater in 2017 than in 1750. As described by Smil (2017), the use of energy and the development of the modern economy are deeply interwoven.

Despite this remarkable development there are two flies in the ointment that have immense implications for future energy provision and, for that reason, future energy related investment. First, the source of energy on which much of the economic explosion was based was a large stock of carbon-based fuels built up over more than a billion years of history from the death and decay of living things that had produced complex carbon molecules via photosynthesis. That stock, though large, is not unlimited and, as discussed in detail in this report, the effective end is in sight. Second, the reliance on burning of carbon fuels has been found to have negative environmental impacts including both pollution and climate change. As a result, it may be wise to limit the burning of carbon-based fuels as an energy source even before their scarcity becomes a binding constraint. The importance of these two issues is no mystery. Thousands of articles related to energy provision and use have been written in fields ranging from climate science, to economics, to political science, to agriculture and even to medicine. Furthermore, the public debate regarding climate changes rages daily in the popular press and in the halls of Washington. This report takes a different tack and focuses on the investment implications of what I call the *great transformation* away from reliance on carbon-based fuels. However, the investment implications cannot be analyzed in a vacuum without reference to careful examination of the data on energy provision and usage. In fact, the sheer scope of the investment required for the *great transformation* means that innovative approaches to investing in energy and energy infrastructure will be required.

Despite the availability of detailed data from private sources such as British Petroleum and Exxon, and public sources including U.S. Energy Information Administration and OECD, there is surprisingly little reference to the details of the data in the public debate. Perhaps this is because the amount of data is so overwhelming, and the numbers are so large. Nonetheless, effective investment analysis requires sufficient understanding of the underlying data, so the initial part of this report is dedicated to summarizing the key data. Before doing that, there are two issues that need to be clarified: the distinction between energy and entropy and the way energy is measured.

Energy and Entropy

When driving a car most people think they are "using" energy by burning the gasoline in their car's tank. Formally, this is not true. Energy can never be "used" because one of the most basic laws of physics is that total energy is conserved. Energy cannot be created or destroyed – only transformed from one form to another. Nonetheless, there is a practical sense in which energy is "used up." This occurs because the energy is transformed from low entropy states, where it can be used to perform useful work, to high entropy states where it cannot. Driving provides an example. Before the car is driven, the energy is contained in the chemical bonds of the gasoline. This is a relatively low entropy form of energy. As the car is driven down the highway, the motor converts the energy in the gas into the kinetic energy of the moving car and into heat which dissipates into the surrounding air. As the car moves down the road the kinetic energy of the car is constantly being transferred to heat in the road and the surrounding air. Consequently, the motor must keep running to prevent this transfer from slowing the car. Finally, when the car is braked to a stop the kinetic energy is transferred to heat in the brakes. Looking at the process as a whole, the energy started as chemical bonds in the gasoline, was transferred in part to the kinetic of the car, and finally ended up as high entropy heat in the road and the surrounding air.

Though the mathematics of entropy can be intimidating, a practical understanding is all that is necessary for current purposes. The key practical point is that the lower the entropy, the greater the opportunity to perform useful work by transforming the energy into a higher entropy state. The "energy" problem that confronts humanity is how to procure the massive amount of low entropy energy necessary to power our civilization in the face of declining stocks of carbon-based fuels and without doing undue harm to the environment. To be accurate, therefore, this report should always refer to the transformation of low entropy forms of energy into higher entropy forms of energy. However, that language is both uncommon and cumbersome, so this report uses the common phrase "energy usage" with the understanding that means the transformation from low to high entropy forms of energy.

Measuring Energy "Usage"

Richard Feynman once quipped, "If energy is conserved, if it is all one thing, how come there are so many names for it?" There actually are so many names along two dimensions. First, there are the names of energy itself – kinetic energy, potential energy, chemical energy, electrical energy and so forth. Second, there are a host of different names for measures of energy – joules, calories, BTU, tons of oil equivalent, kilowatt hours and so on. Starting with the second point first, this report focuses on one measure of energy, the kilowatt hour. For instance, there are 1,700 kilowatt hours of useable energy in a barrel of oil. But this does not mean that if the oil is burned to generate electrical energy it would produce 1,700 kilowatt hours of electricity. The energy in oil can be converted to electricity with only about 40% efficiency, so that 1 kWh of chemical energy in oil produces only 0.4 kWh of electricity. This raises the question of how to compare amounts of energy across different sources. One choice is to simply transform the units on a one-to-one basis. Using this approach, one barrel of oil translates into 1,700 kilowatt hours of electricity. The other is to use conversion ratios and in using this approach, one barrel of oil translates into 680 kilowatt hours of electricity because of the energy lost in conversion. In this report, I use the one-to-one conversion rate when comparing different forms of energy. The point is to have a common unit of account so that it is easy to keep track of things and make direct comparisons. If conversions are used this may become confusing because, for example, most oil is not used to generate electricity.

At first blush, it may seem that using a one-to-one conversion rate leads to undercounting energy usage. For instance, one of the main sources of electricity is the combustion of natural gas. During the process of generation, only about 40% of the energy in the natural gas is converted to electricity and the rest is lost to heat. However, this loss is unrelated to the units used to measure the energy in the gas, whether it be in terms of cubic feet of gas or kilowatt hours. In fact, the complication introduced by conversion of one form of energy to another is more likely to result in *undercounting* energy usage, not overcounting. To continue the example, only the natural gas used to generate electricity should be counted as energy usage, not the subsequent use of the electricity. The gas is what is referred as a ***primary*** source of energy because it is the original source. The electricity is a secondary output. Total energy usage, or more precisely total energy transformation, is calculated by adding up all the primary sources. This procedure automatically accounts for any energy lost in conversion from a primary source to a secondary source by keeping track of how much primary energy was used. In this respect, the primary energy contained in the natural gas can be measured in any units. The unit used here is the kilowatt hour. But it is not the kilowatt hours of electricity produced by burning the gas, it is the chemical energy in the bonds of the gas measured in kilowatt hours. In this report, most all the measures of energy usage will be stated in terms of kilowatt hours. In the rare cases where I diverge from this convention, the use of the other measure will be explicitly noted.

Investing in the Great Energy Transformation

The thesis of this report, developed in detail below, is that in the 21st century there will be, by necessity, a great energy transformation. By the end of the century, new energy sources will have to replace, almost completely, the burning of carbon fuels due to a combination of their environmental impact and their increasing scarcity. The scope of this transformation cannot be understated. Currently, carbon-based fuels account for about 85% of global energy usage. What's more, global energy usage is predicted to continue rising throughout the century as world population grows and as development in poorer parts of the world accelerates. As a result, new primary energy sources must not only replace fossil fuels but also need to meet the growing demand.

At first blush, it may seem that this immense transformation should be a bonanza for private investors. But there are two hurdles. First, as Warren Buffett has stressed on numerous occasions, investors need to distinguish between the success of an industry and the success of specific companies within that industry. His poster child in this regard is the commercial airline industry. Despite all the benefits airlines has provided for travelers, airline companies have not been kind to investors. In his 2007 letter to Berkshire Hathaway shareholders, Buffett stated: *The worst sort of business is one that grows rapidly, requires significant capital to engender the growth, and then earns little or no money. Think airlines. Here a durable competitive advantage has proven elusive ever since the days of the Wright Brothers. Indeed, if a farsighted capitalist had been present at Kitty Hawk, he would have done his successors a huge favor by shooting Orville down.*[1]

Buffett's warning rings true for what can be called the "energy transformation industry." That is, the business of moving to long-run sustainable production of energy at a scale that can provide for the needs of a growing world economy without doing unacceptable environment damage. By necessity, this new industry must grow rapidly, and the capital requirements are astronomical, but it is unclear how any individual companies will be able to achieve durable competitive advantage.

Buffett's concerns aside, there is a second, far more significant, impediment for potential investors in the great energy transformation. The bigger problem is that the scale of the needed energy transformation business is so large and will cost so much that consumers of energy (and their governments) may balk at the prices that would be necessary to charge to pay back the needed investment. By the end of the 21st century, due to some combination of increasing scarcity and growing environmental impact, somewhere on the order of 80% of humanity's energy needs must come from renewable sources.[2] Access to sufficient energy

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[1] Warren Buffett, 2017, Berkshire Shareholder Letter, http://www.berkshirehathaway.com/letters/2007ltr.pdf.

[2] This report does not consider the possible impact of the widespread and economically viable application fusion technology. Although fusion is not a renewable source of energy, the amount of

will be a critical issue for virtually all the people who will inhabit the planet by 2100 (predicted to be more than 10 billion). This will make the provision and pricing of electricity a paramount, if not the supreme, political issue worldwide. Already the violent reactions in France in response to a small increase in energy taxes and prices provide a hint of how important the politics of energy transformation is likely to become. The issues related to the great transformation will be an order of magnitude larger than what we have experienced thus far. It seems inconceivable, therefore, that governments will not play a major, and more likely a predominant role in assuring energy provision and greatly influencing, if not setting, energy prices.

This has direct implications for investors. Remember that the value of an investment is the present value of the future cash flows the investment is expected to produce. The primary determinant of those cash flows is the revenue produced from sale of the product. In the case of energy, the key determinant of future cash flows, and therefore the value of energy investments, is the price that can be charged for the ultimate product. That means that returns on investments in energy assets such as solar generation plants, storage facilities, grid upgrades and so forth will depend on the price of energy which, in turn, will be determined by a complicated political process.

This raises unique problems, particularly in light of the fact that the required investments for the great transformation will run into the tens of trillions of dollars worldwide. An illustration of what can happen is provided by the experience of California's largest utilities, Edison International and Pacific Gas & Electric (PG&E). In 2001, PG&E

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fuel provided by the planet's oceans is so large that it might as well be. Currently, however, there is no clear path toward practical use of fusion for commercial energy generation.

was forced to file for bankruptcy because of issues related to deregulation of the electricity market in California. Edison International narrowly avoided bankruptcy. Equity investors in both companies sustained large losses. In January 2019, following two years of wildfires in Northern California, PG&E was again forced to file for bankruptcy. In both instances, the financial problems the utilities faced were related to disputes regarding which costs the utilities could recover from rate payers in the form of higher energy prices. The key risk to investors was political rather than economic. As one further example, NV Energy in Nevada, which is owned by Warren Buffet's company Berkshire Hathaway, has been involved in disputes regarding solar power and utility rights. Once again, the issue is a political determination of investor rights.

Put simply, governmental bodies are not going to allow energy prices to rise to the point where investors in the major infrastructure improvements and extensions necessary for the great transformation earn more than a "fair" rate of return. This is akin to the way utility regulation works in the United States. Energy prices are set so that utility shareholders earn a fair return, fair as determined by the regulators, on the capital invested in the utility known as the rate base, also determined by regulators. In other countries, there are different mechanisms including outright state ownership. Whatever the mechanism, however, future energy prices are not going to be allowed to be high enough that the capital investments necessary for the transformation will not earn anything like venture capital returns. This does not mean that venture level returns cannot be earned on small startups, if those startups develop new technologies that emerge as the winners. But once the new technologies grow to scale, the returns will be constrained to "fair" levels.

But I am getting ahead of myself. Before exploring these investment issues further, the stage must be set by looking at the data on energy provision and usage – past, present and future projections.

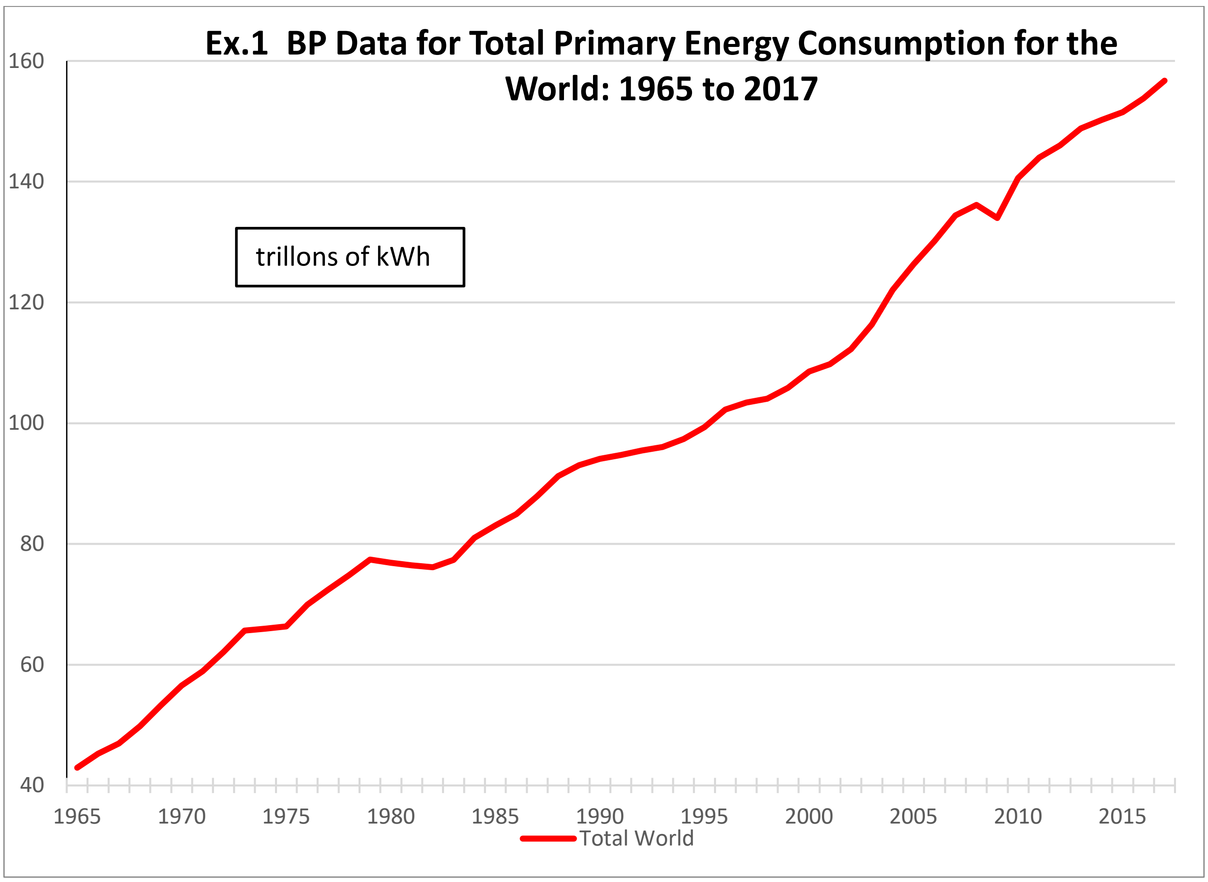
2. Energy Provision and Usage: Past, Present and Future

The difficulty in gaining an understanding of the data on energy provision and usage is not the paucity of information, but its abundance. Private organizations like British Petroleum and Exxon, public organizations such as the U.S. Energy Information Administration and the OECD, and specialized organizations like the International Energy Agency all produce massive reports crammed with tables and charts. To organize all this data and to draw out its investment implications, this report analyzes the information along four key dimensions: size (the amount of energy consumed), distribution (the variation in energy usage across countries), inertia (the rate of change in the makeup of primary energy), and energy related emissions of greenhouse gases. I consider each in turn, starting with size.

Size

The size of global energy usage is difficult to appreciate because the numbers are so large relative to common experience. To get started, Exhibit 1 plots the total global consumption of primary energy from 1965 to 2017, using data from British Petroleum's *Statistical Review of World Energy for 2018*. Before going further, a word on the choice of the data sources. In addition to the BP Statistical Review, I use two other primary sources of information, Exxon's *2018 Outlook for Energy*, and the U.S. Energy Information Administration's *Annual Energy Outlook 2018*. There are also references to data from other sources which are noted as used. Although the data produced by the three primary sources are not identical, in large part because categories like "renewables" are defined differently, careful checking reveals that any discrepancies are minor and have no material impact on the analysis presented in this report.

The data in Exhibit 1 are presented in terms of trillions of kilowatt hours per year. There are three main takeaways. First, the total usage is huge – amounting to 156.7 trillion kilowatt hours in 2017. Second, except for a few short dips associated with economic downturns, global consumption of primary energy has been rising steadily for the last 52 years. Third, the total growth in energy usage has been dramatic, rising more than 3.5 times over the 52-year period from 1965 to 2017.



A hypothetical calculation provides one perspective on the size of these numbers. How much would it cost to purchase solar photovoltaic panels to provide all the primary energy used in 2017? Utility scale solar farms cost about $1 per watt of power produced. To produce 156.7 trillion kilowatt hours of energy over the course of a year, power must be generated at the rate of 17.89 billion kilowatts or 17.89 trillion watts.[3] Therefore, the required cost of the panels alone (excluding cost of the land, and the need for storage and transmission) is nearly $18 trillion dollars. By comparison, the GDP for the United States was $19.39 trillion in 2017 and the total value of the U.S. stock market was just less $30 trillion at the end of 2017.

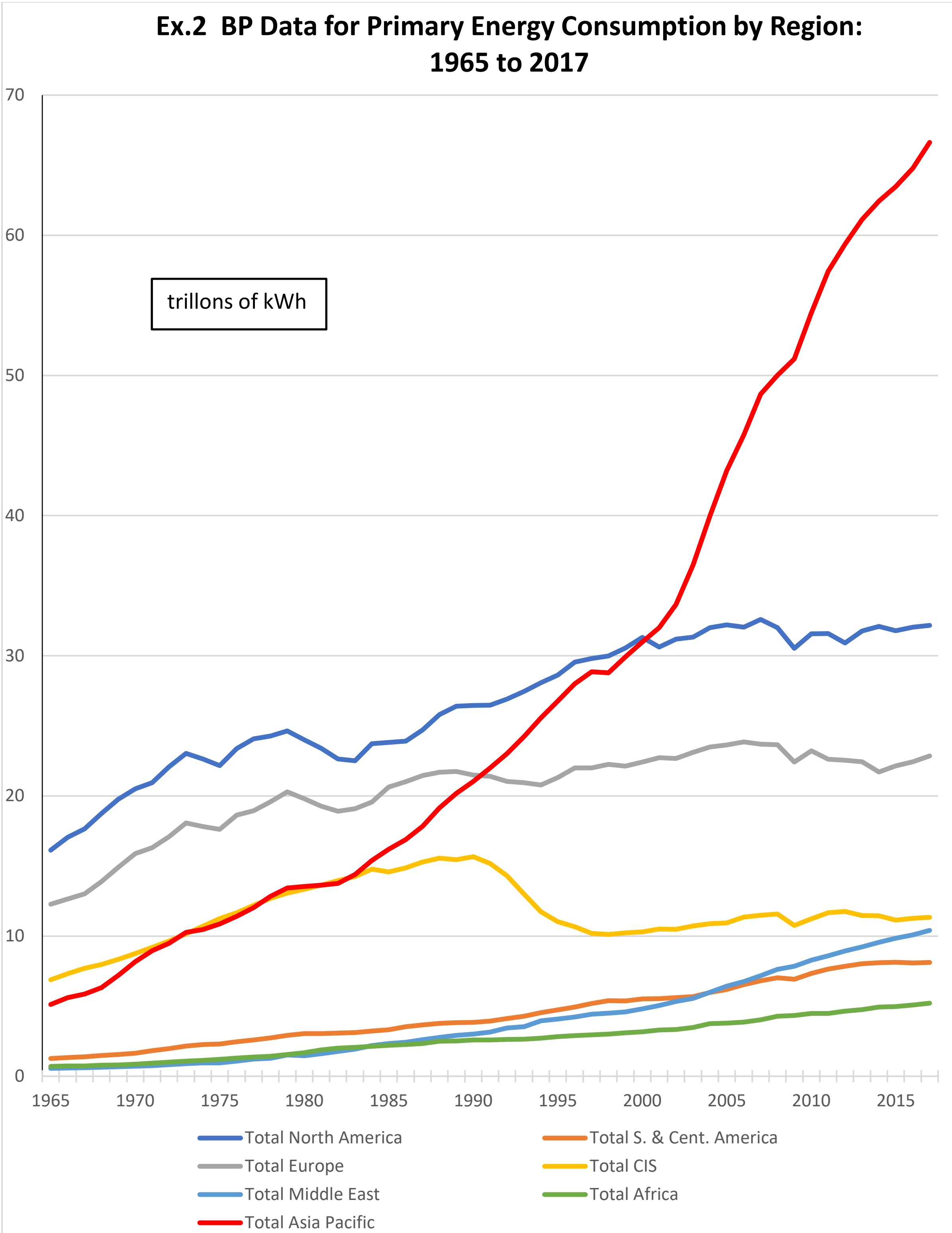
As another example, Japanese entrepreneur and chairman of SoftBank Masa Son and Liu Zhenya, the former chairman of China's State Grid Corporation, envision a global supergrid linked by transoceanic undersea cables and electrical superstations that could move renewable power around the world. They note that such a supergrid could solve many of the storage and intermittency problems associated with renewable energy because somewhere in the world the sun is shining, and the wind is blowing. More formally, the low correlation between renewable energy sources scattered around the globe render the aggregate output far more stable than output from any individual source. Unfortunately, Son and Zhenya estimate the price tag for their envisioned supergrid at $50 trillion. Furthermore, such a supergrid would require a heretofore unheard-of degree of international cooperation, not only to build it, but to share the power produced.

Although a detailed analysis of the investment implications of the data is postponed until the final section of the report, it is worth noting that the size of the required investment in energy infrastructure has critical implications for the potential returns, even putting aside governmental price setting. When the scale of investment is in the trillions of dollars, the returns cannot be expected to much exceed market averages. As noted previously, the

[3] The required power equals 156.7 kilowatt hours divided by the number of hours in a year which gives 17.89 billion kilowatts.

outsize returns – for which investors such as hedge funds and private equity firms strive – require getting in sufficiently early so that massive growth is possible. For example, during the first five years of its life as a public company the market capitalization of Google increased by a factor of 5.2. Investors who bought Google early on were rewarded with outsized returns. For Google to increase by an equivalent factor in the next five years, it would have to grow to a market capitalization of $3.9 trillion by the end of 2023 – a preposterous number. And even Google is small compared to the tens of trillions required to invest in energy infrastructure. There is no escaping the fact that growth eventually slows as size increases. The limited potential for high returns and the needs for massive capital present obvious challenges for raising the funds necessary for the great energy transformation.

To provide further detail on energy usage, Exhibit 2 breaks down the global data by region and Exhibit 3 presents data for a sample of individual countries. Exhibit 2 shows that beginning in 1965 and up through 1990 North America and Europe were the largest energy consumers. However, due to a combination of population growth and economic development, Asia Pacific first passed Europe in 1990 and then passed North America by 2000. At the end of the sample period in 2017, Asia Pacific's total consumption of 66.6 trillion kilowatt hours was more than twice that of North America and three times that of Europe. The only region to show a meaningful decline in usage during the sample period was Commonwealth of Independent States (CIS) also called the Russian Commonwealth. The drop was associated with the collapse of the Soviet Union.


Ex.2 BP Data for Primary Energy Consumption by Region: 1965 to 2017
trillons of kWh
70
60
50
40
30
20
10
0
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Total North America
Total S. & Cent. America
Total Europe
Total CIS
Total Middle East
Total Africa
Total Asia Pacific

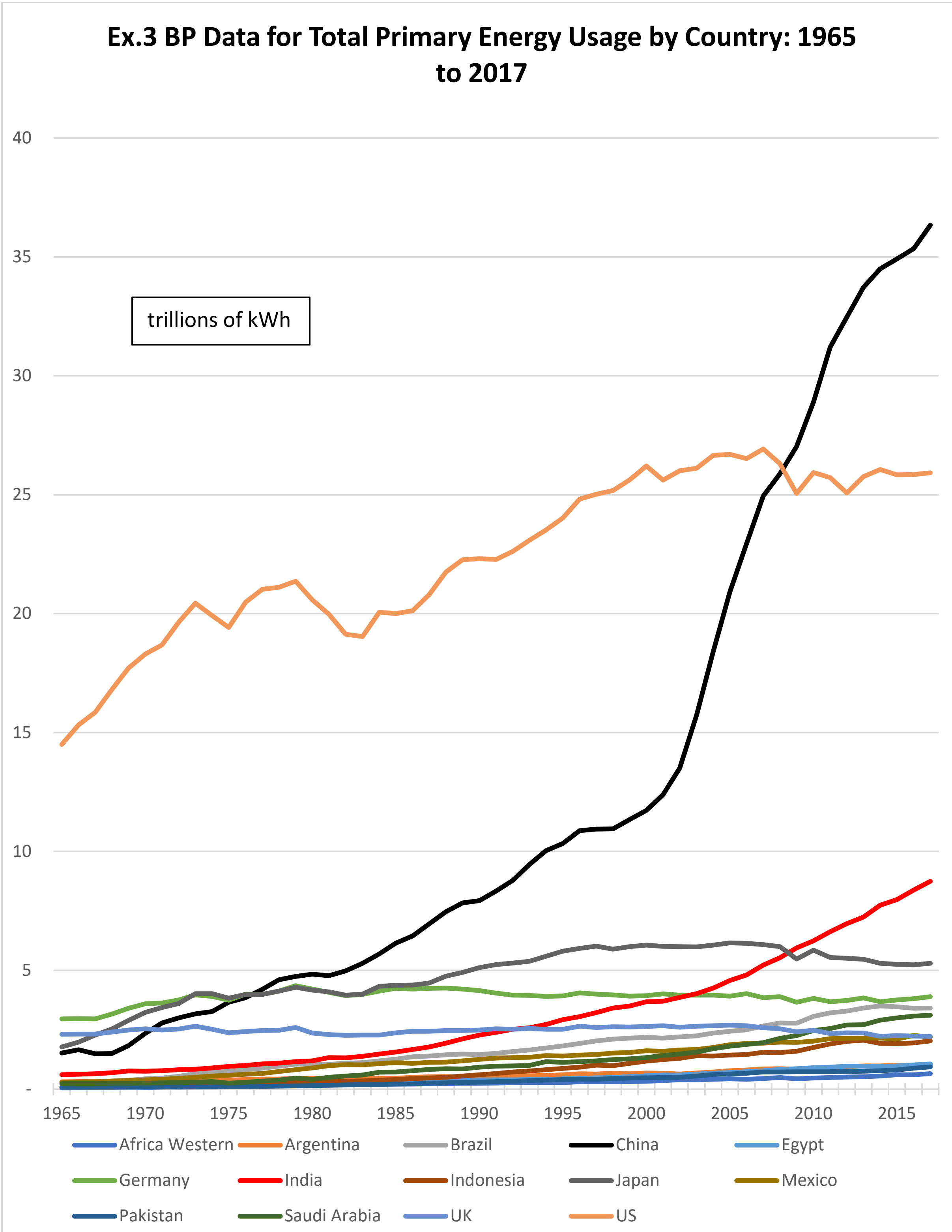
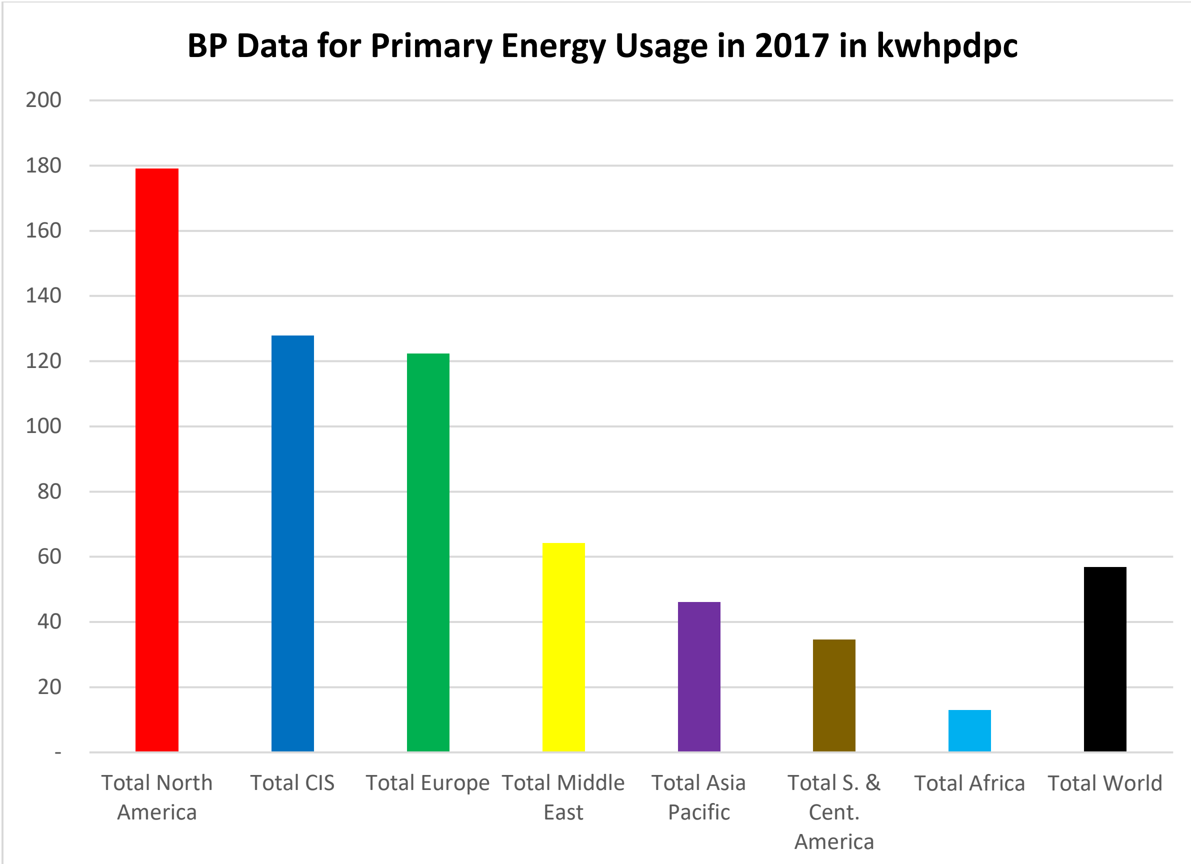

Ex.3 BP Data for Total Primary Energy Usage by Country: 1965 to 2017
trillions of kWh
40
35
30
25
20
15
10
5
-
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Africa Western
Argentina
Brazil
China
Egypt
Germany
India
Indonesia
Japan
Mexico
Pakistan
Saudi Arabia
UK
US

Exhibit 3 presents country level data. Three salient facts stand out. First and foremost is the dramatic rise in energy consumption by China which displaced the United States as the world's largest energy consumer. Second, is the continued high level of energy consumption by the United States. Third, is the low level of energy consumption in the developing countries. For instance, India with four times the population of the United States consumes only one-third as much energy. Discrepancies such as these, discussed further below, increase political tensions associated with energy provision and consumption. Those political pressures are another challenge for energy infrastructure investing.

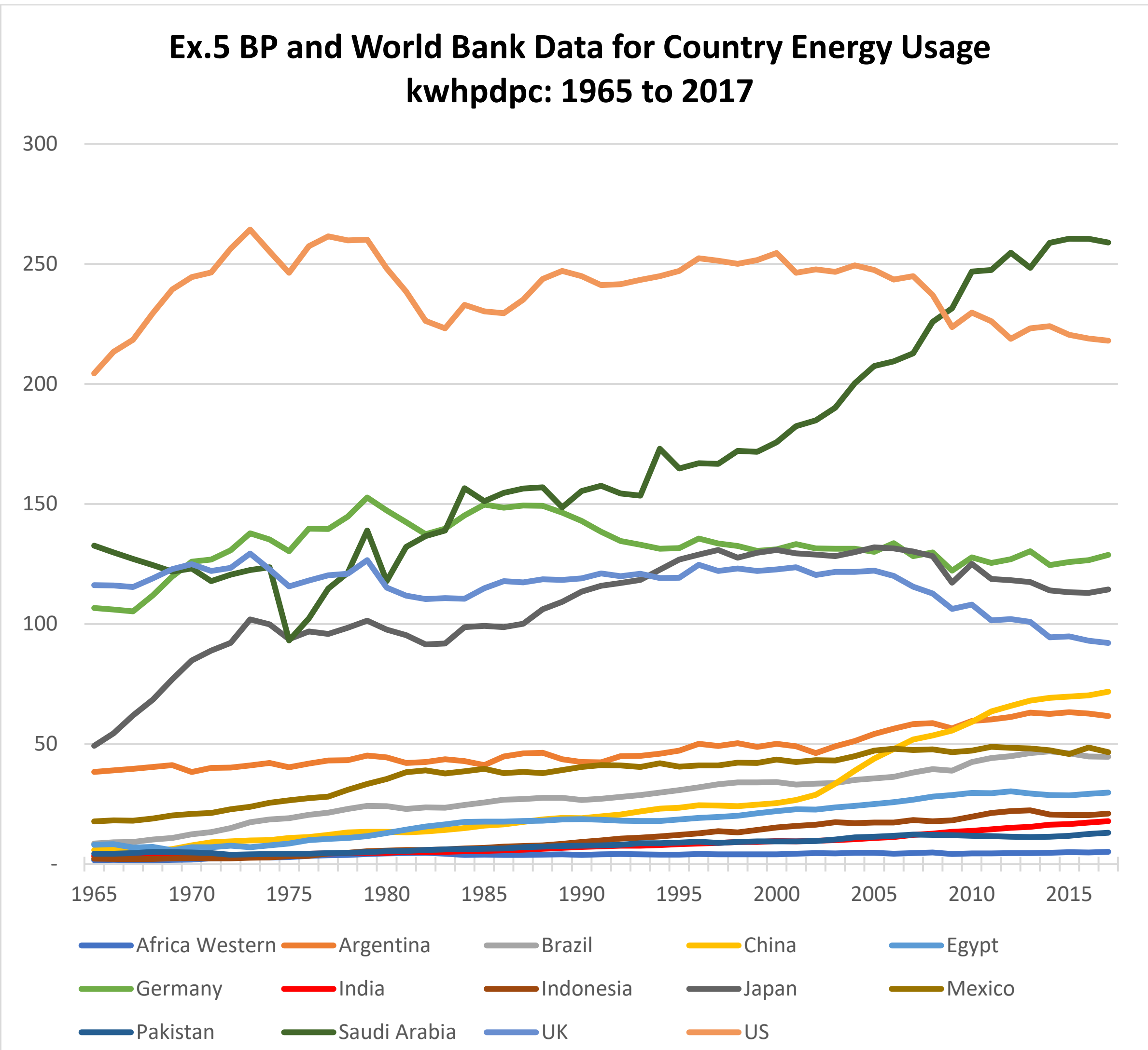
The Distribution of Energy Usage

A drawback of Exhibits 2 and 3 is their failure to take account of population. In addition, the raw size of the numbers makes comparisons difficult. Using MacKay's (2009) measure of kilowatt hours per day per capita (kwhpdpc) solves both problems. Exhibit 4 presents a snapshot of kwhpdpc usage by region. The exhibit shows that usage is much higher in North America than any other region coming in at 180 kwhpdpc. Europe and the CIS countries are at about 120 kwhpdpc which is often referred to as the European standard. Asia, despite its large gross energy consumption, comes in at about 50 kwhpdpc because of the area's huge population (Asia Pacific includes India). Finally, African kwhpdpc is barely greater than 10 due to lower levels of economic development. Energy consumption for the world is just below 60 kwhpdpc.

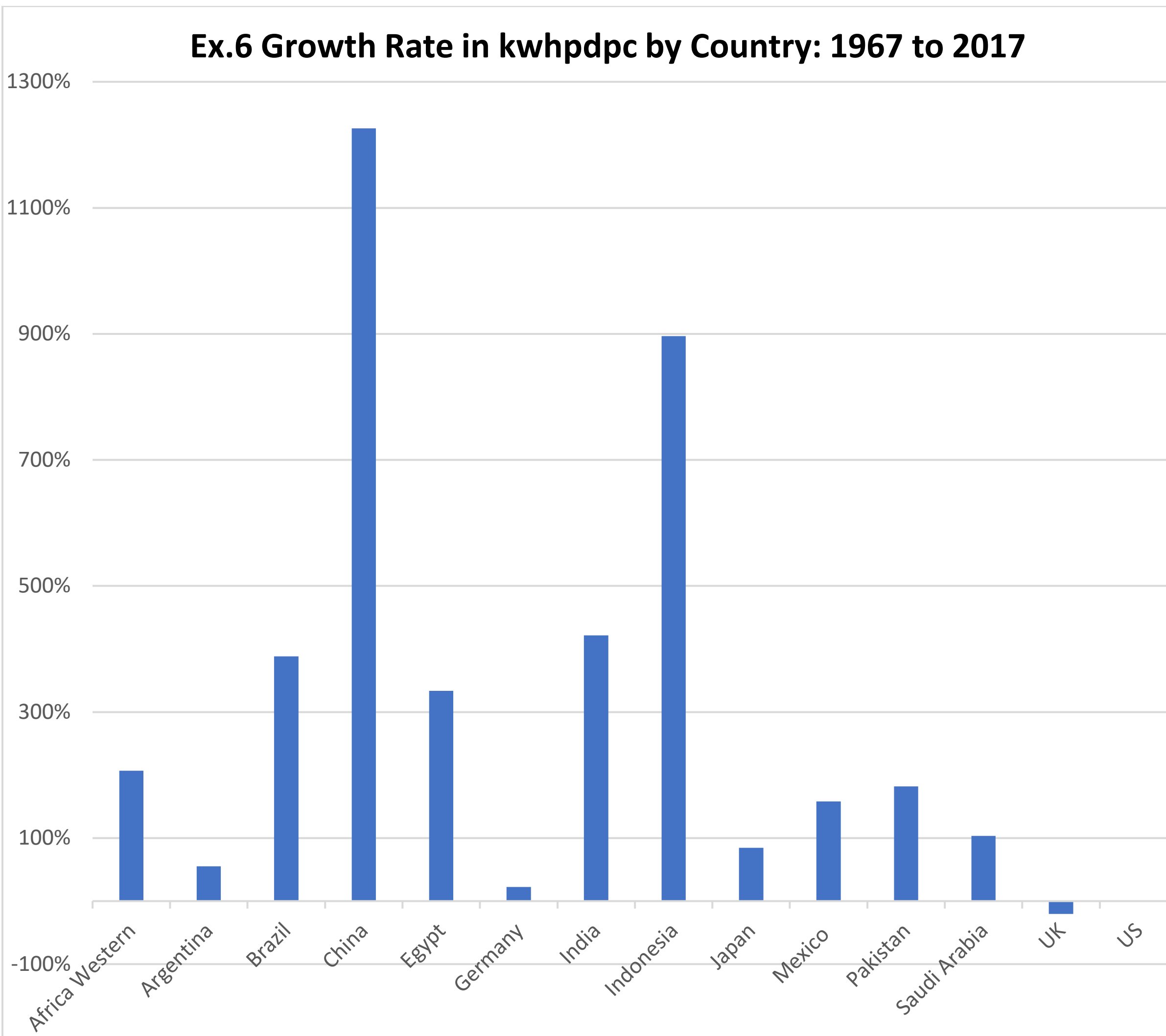


Further insight into the cross-sectional distribution of energy usage is provided by Exhibit 5 which provides historical data on kwhpdpc by country dating back to 1965. The exhibit shows that over the years from 1965 to 2017, U.S. consumption remained largely constant in a range between 200 and 250 kwhpdpc. This was far larger than any country except for Saudi Arabia whose energy usage grew rapidly during the period to top out at over 250 kwhpdpc in 2017. The UK, Germany and Japan all look like typical "European countries" with usage stable at around 120 kwhpdpc. Other than Saudi Arabia, China shows the fastest growth in kwhpdpc, rising from only about 10 to approximately 75. It is worth noting that despite China's dramatic economic development, and its current role as the world's leading industrial nation, its energy usage in terms of kwhpdpc is still well below the European average. That is likely to change as the country continues to develop. Given

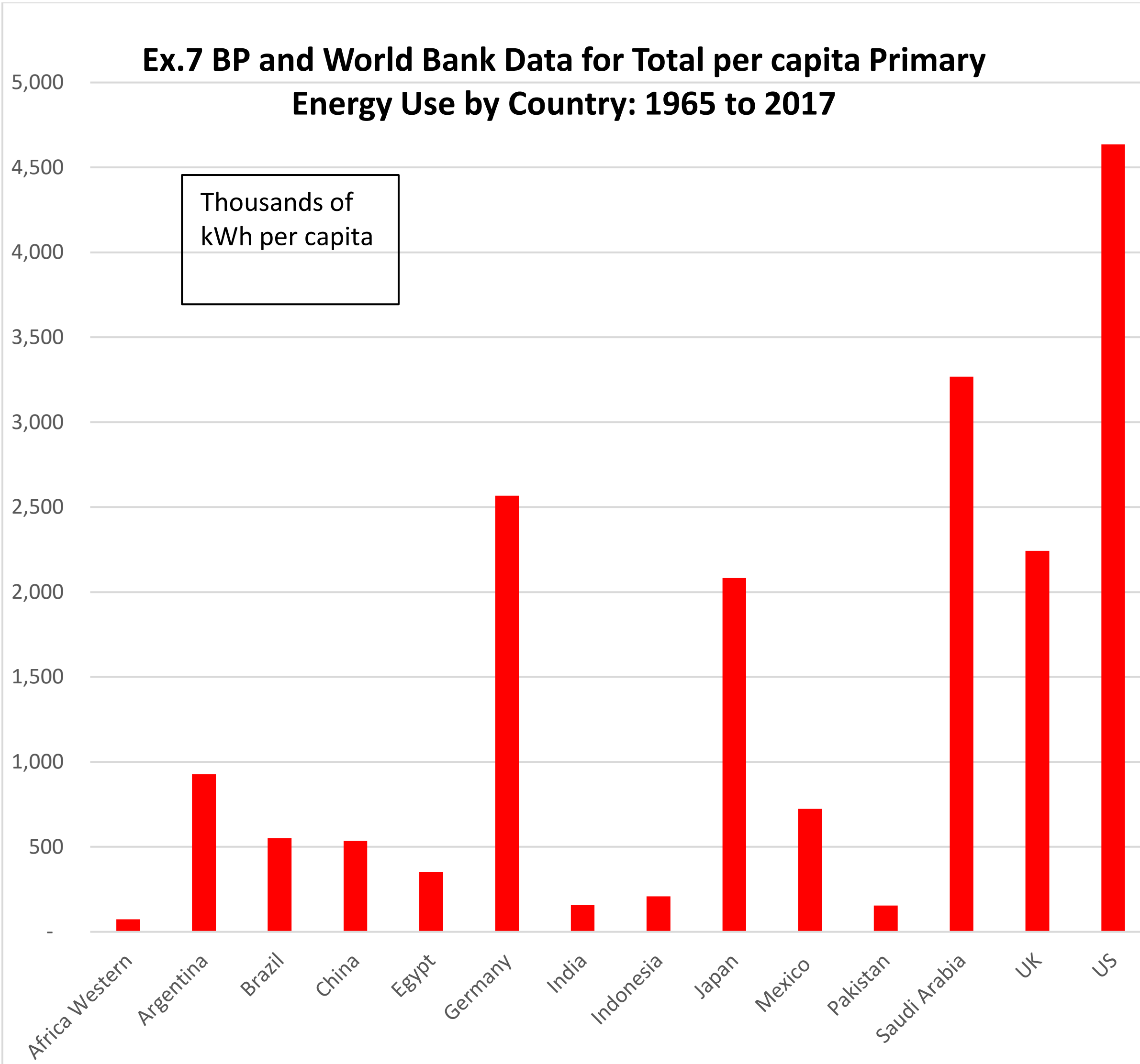
China’s population of 1.4 billion, an increase in Chinese kwhpdpc consumption to the European standard would have a pronounced effect on global energy consumption. Finally, in much of the developing world kwhpdpc is on the order of 20 or less. This includes India where the fact that over 300 million people lack access to electricity depresses energy usage. Given India’s population of over 1.3 billion, a huge increase in energy provision would be required for India to approach the European average. In Western Africa, the figures are even lower with energy usage less than 10 kwhpdpc.



As countries develop, growth in kwhpdpc tends to take off. Exhibit 6 presents the total percentage growth in kwhpdpc over the years from 1967 to 2017 for the same countries in Exhibit 5. The exhibit demonstrates that those countries which were developing the fastest such as China and Indonesia had huge growth rates in kwhpdpc, while the growth in developed countries such as Germany, the UK, and the US was virtually zero. Countries that were in the process of active development, including Brazil, India and Pakistan, had growth rates in the middle. At the bottom are those countries that are just starting to develop such as the nations of Western Africa.



Despite the large differences, the year-by-year data actually understate the diversity of historical energy usage because the annual differentials occur year after year. Exhibit 7 shows the total energy usage, per capita, summed over the entire period from 1965 to 2017. The results are dramatic. The total for the United States is more than fifty times greater than for India, Pakistan and Western Africa. More surprisingly, it is almost ten times that for China.



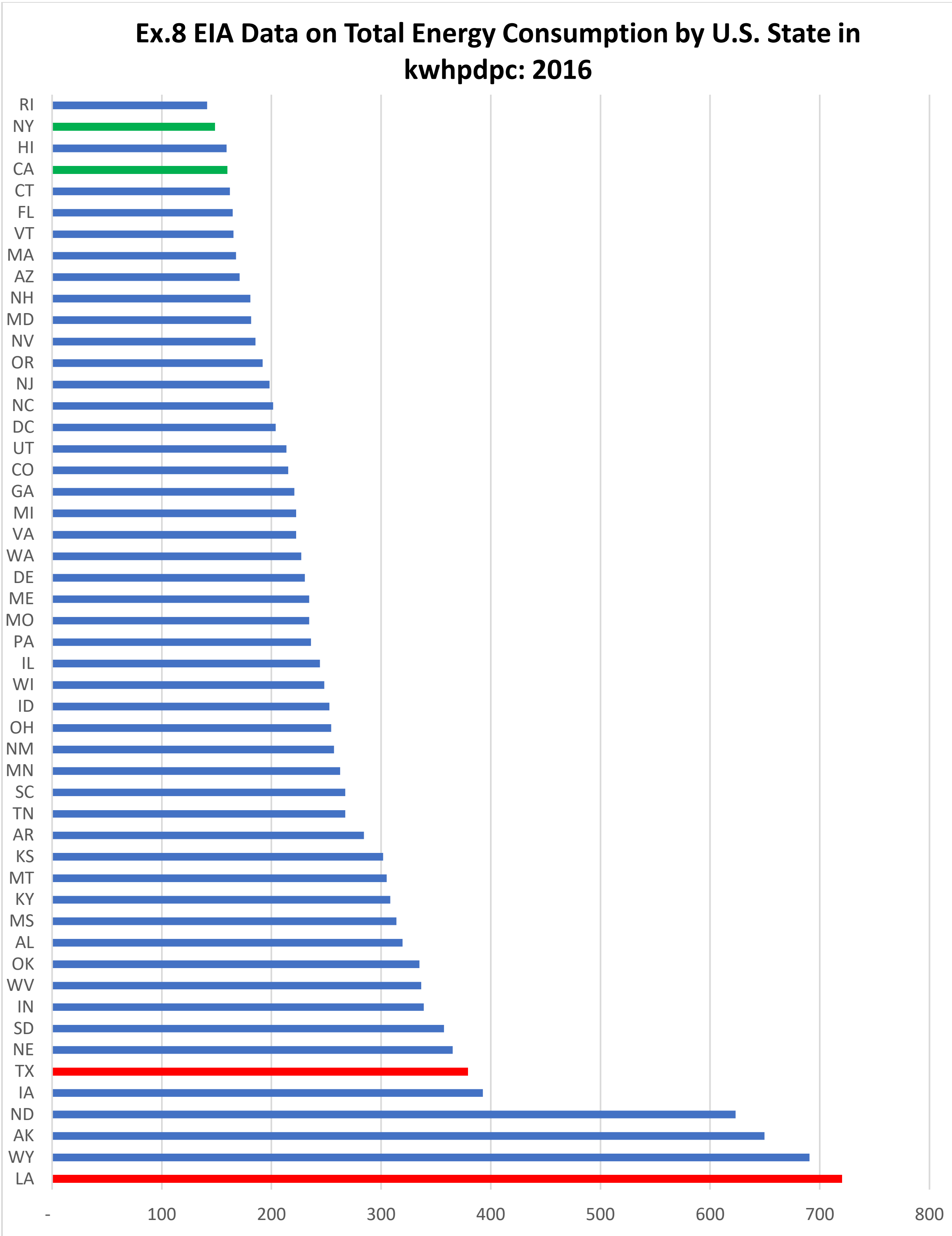
The data presented in Exhibit 7 raise obvious political issues for energy usage going forward. The developing countries have a clear basis for claiming that the developed countries in general, and particularly the United States, built their economies by relying on the exploitation of low-cost fossil fuels. Why should the developing countries be asked to conserve on their use of fossil fuels as they strive to grow? Should not the developed countries, who contributed most of the greenhouse gases, bear the great majority of the costs of the great transformation?

The extreme variation in energy usage is not just a global phenomenon, it also holds true for states within the United States. Exhibit 8 shows that some states, including New York and California, have energy usage rates of approximately 150 kwhpdpc, well below the country average of over 200. On the other hand, North Dakota, Arkansas, Wyoming and Louisiana have usage rates exceeding 600 kwhpdpc. Understanding the reason for such huge disparity is an important step in planning for the great transformation.

Inertia

Inertia refers to the continuance of "business as usual." Here that means continued reliance on carbon-based fuels. To provide initial perspective on the distribution of fuel use by fuel type the top half of Exhibit 9, reproduced from *Statistical Review of World Energy*, plots the consumption of primary energy by fuel type over the last quarter century from 1992 to 2017. The major impression the exhibit conveys is one of inertia. Despite global conferences in Copenhagen in December 2009 and in Paris in December 2015, the exhibit reveals that global use of fossil fuels, including coal, rose consistently throughout the quarter century to record highs in 2017. The only noticeable dip in fossil fuel usage occurred during the global recession of 2008/2009 and that short-term drop was quickly overcome by continued growth. It is true that renewables, excluding hydro, grew rapidly, but that is largely because they started from such a low base. Even by 2017, renewables remained a small sliver of global primary energy consumption. The bottom half of the exhibit breaks down the data by region in 2017. The exhibit shows that in both the CIS countries and the Middle East there is no measurable use of renewable energy. Africa shows some usage, but that is misleading because the "renewable" energy there is largely wood and biomass.

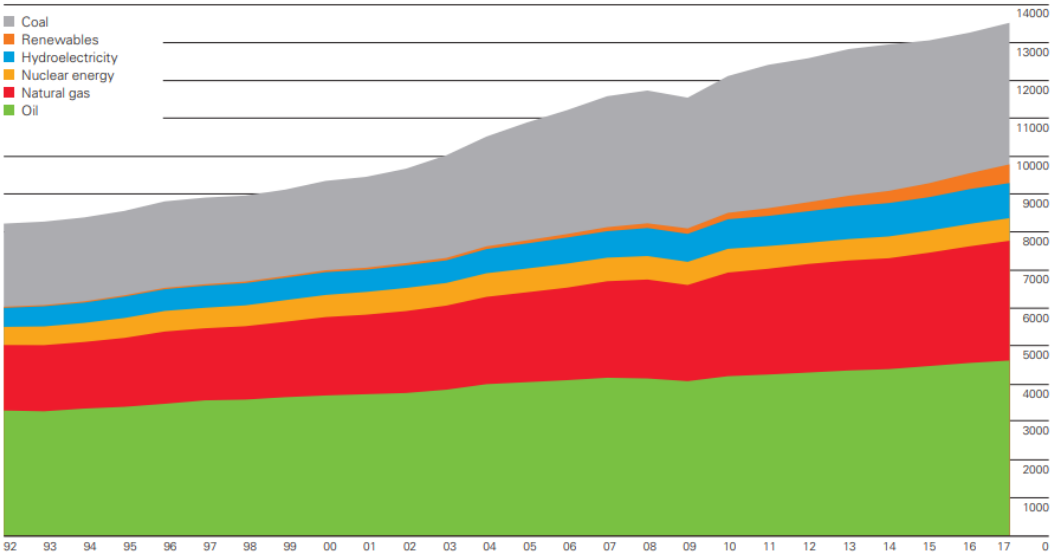
Furthermore, African renewables are a visible sliver only because total energy consumption in Africa is so low.



Ex.8 EIA Data on Total Energy Consumption by U.S. State in kwhpdpc: 2016
RI
NY
HI
CA
CT
FL
VT
MA
AZ
NH
MD
NV
OR
NJ
NC
DC
UT
CO
GA
MI
VA
WA
DE
ME
MO
PA
IL
WI
ID
OH
NM
MN
SC
TN
AR
KS
MT
KY
MS
AL
OK
WV
IN
SD
NE
TX
IA
ND
AK
WY
LA
-
100
200
300
400
500
600
700
800

World consumption

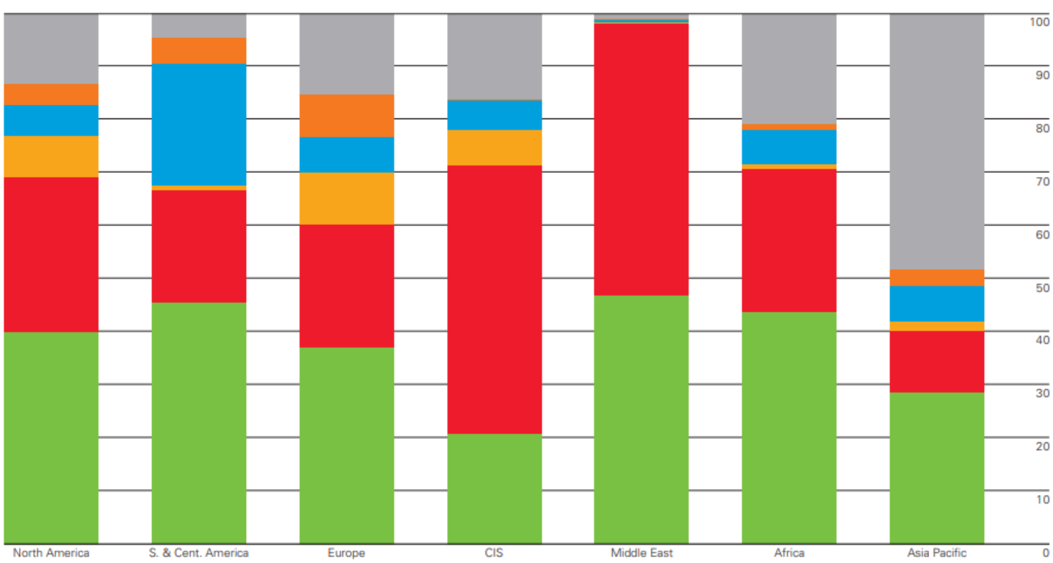
Million tonnes oil equivalent



World primary energy consumption grew by 2.2% in 2017, up from 1.2% in 2016 and the highest since 2013. Growth was below average in Asia Pacific, the Middle East and S. & Cent. America but above average in other regions. All fuels except coal and hydroelectricity grew at above-average rates. Natural gas provided the largest increment to energy consumption at 83 million tonnes of oil equivalent (mtoe), followed by renewable power (69 mtoe) and oil (65 mtoe).

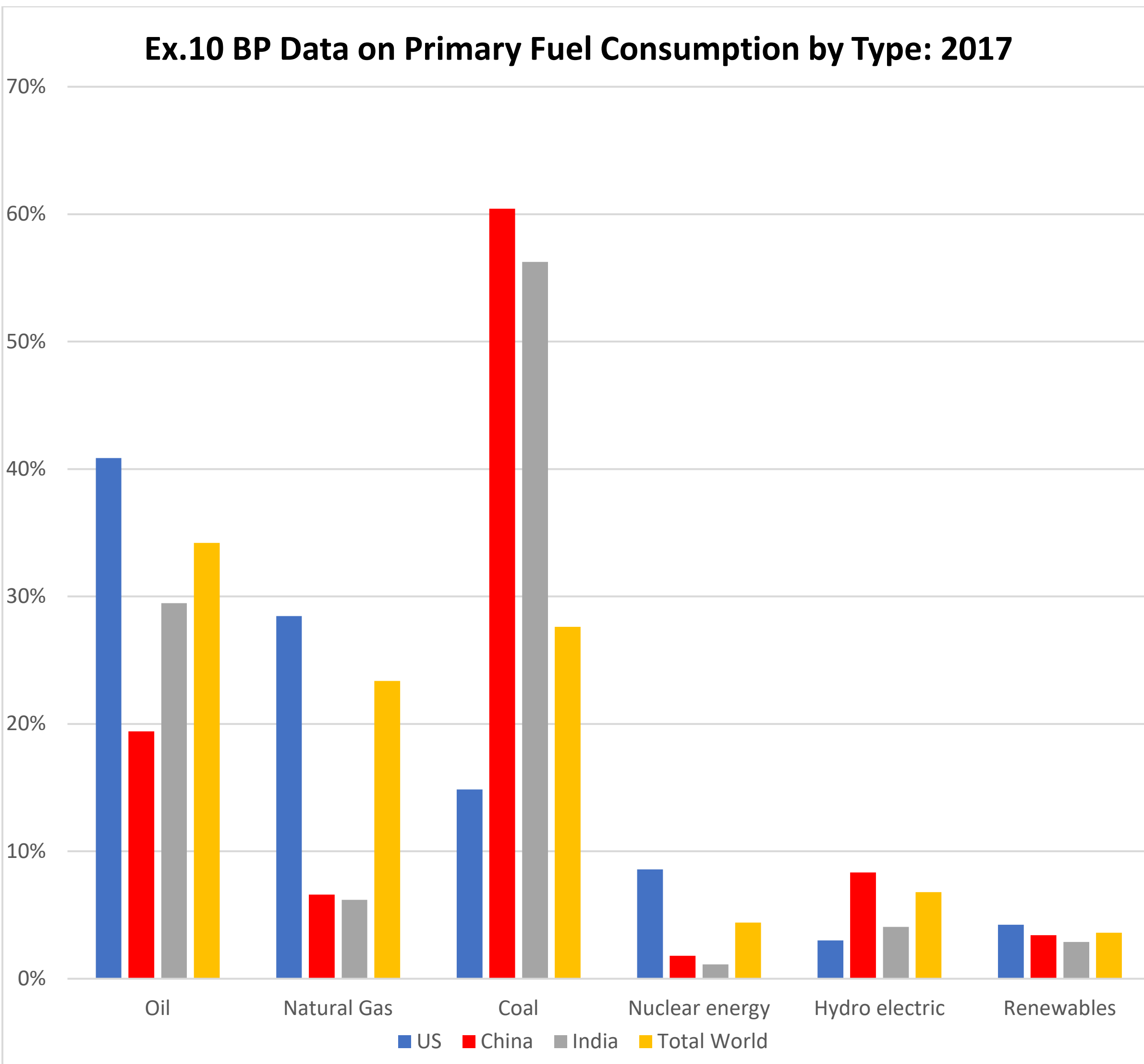
Regional consumption by fuel 2017

Percentage



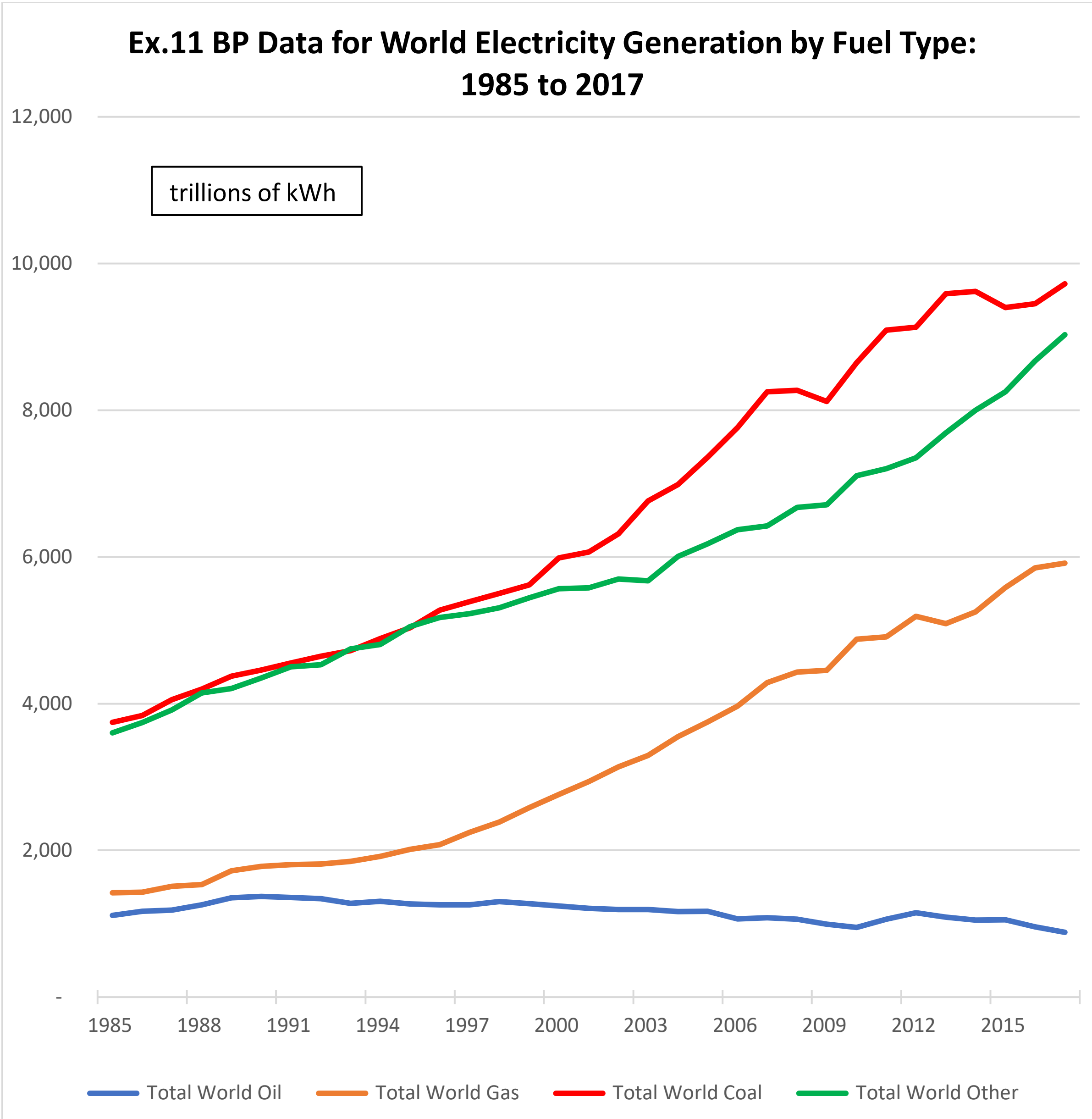
Oil remains the dominant fuel in Africa, Europe and the Americas, while natural gas dominates in CIS and the Middle East, accounting for more than half of the energy mix in both regions. Coal is the dominant fuel in the Asia Pacific region. In 2017 coal's share of primary energy fell to its lowest level in our data series in North America, Europe, CIS and Africa.

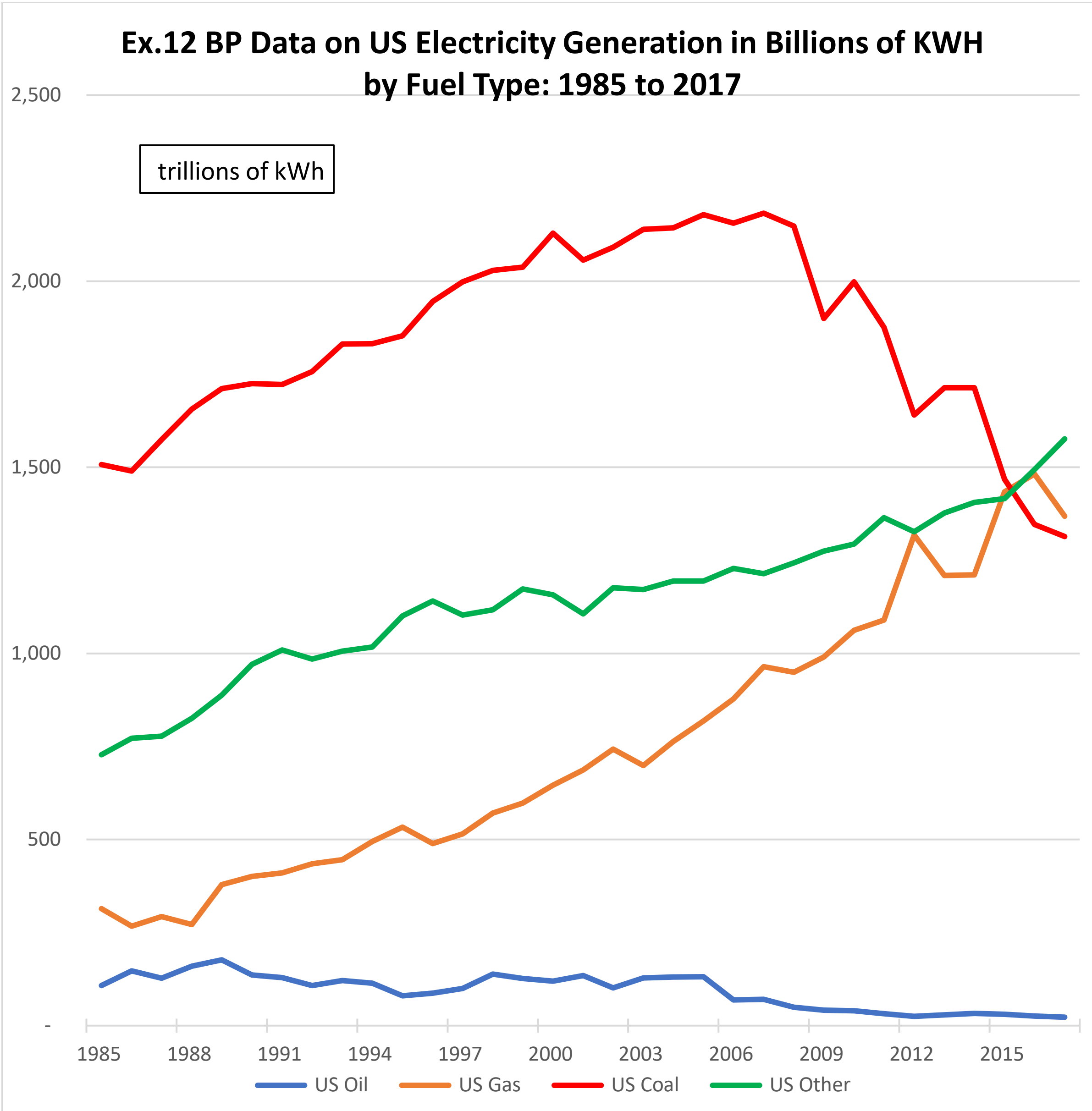
To provide further insight, Exhibit 10 plots primary energy consumption by fuel type in the world's three most populous countries, China, India, and the United States, along with the global data for 2017. The picture for renewables is much the same for all three countries and basically mirrors the global average. Fossil fuels account for over 80% of the primary energy in all three countries. The main difference between the three countries is the heavy reliance on coal in India and China compared to the US which relies more on natural gas.

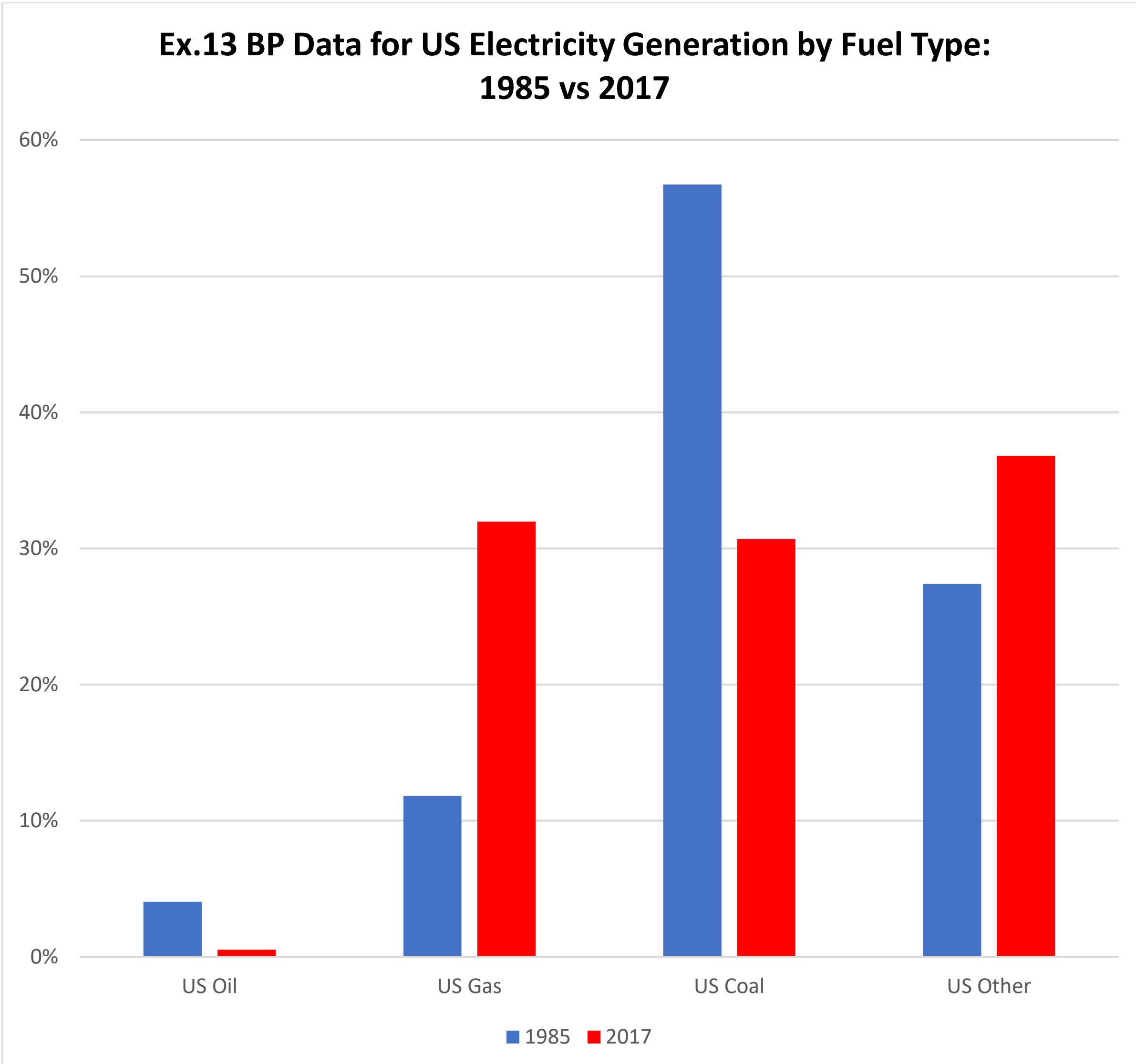


Unlike fossil fuels, renewable forms of energy are difficult to use directly. You cannot put wind in your car. Instead, renewables such as hydro, wind and solar are primarily used to generate electricity that can then be used to perform useful functions. Therefore, the first critical step in replacing fossil fuels with renewables is using them to generate the great majority of electricity. The second step is using electricity, wherever possible, to replace fossil fuels in transportation, industrial and residential use. Starting with the first step, the historical record shows progress. Exhibit 11 presents data on the fuels used globally to generate electricity over the years, ranging from 1985 to 2017. The data are broken down into four informational categories: coal, natural gas, oil and other. “Other” includes hydro and nuclear as well as renewables. The problem is that although the use of “other” non-carbon fuels rises steadily throughout the period, so does the consumption of coal and natural gas. From an environmental standpoint, the continued rise of coal use is the most troubling because coal-fired plants produce about twice the CO2 of natural gas processing plants. The continued rise in coal consumption has been driven primarily by Asia (including India).

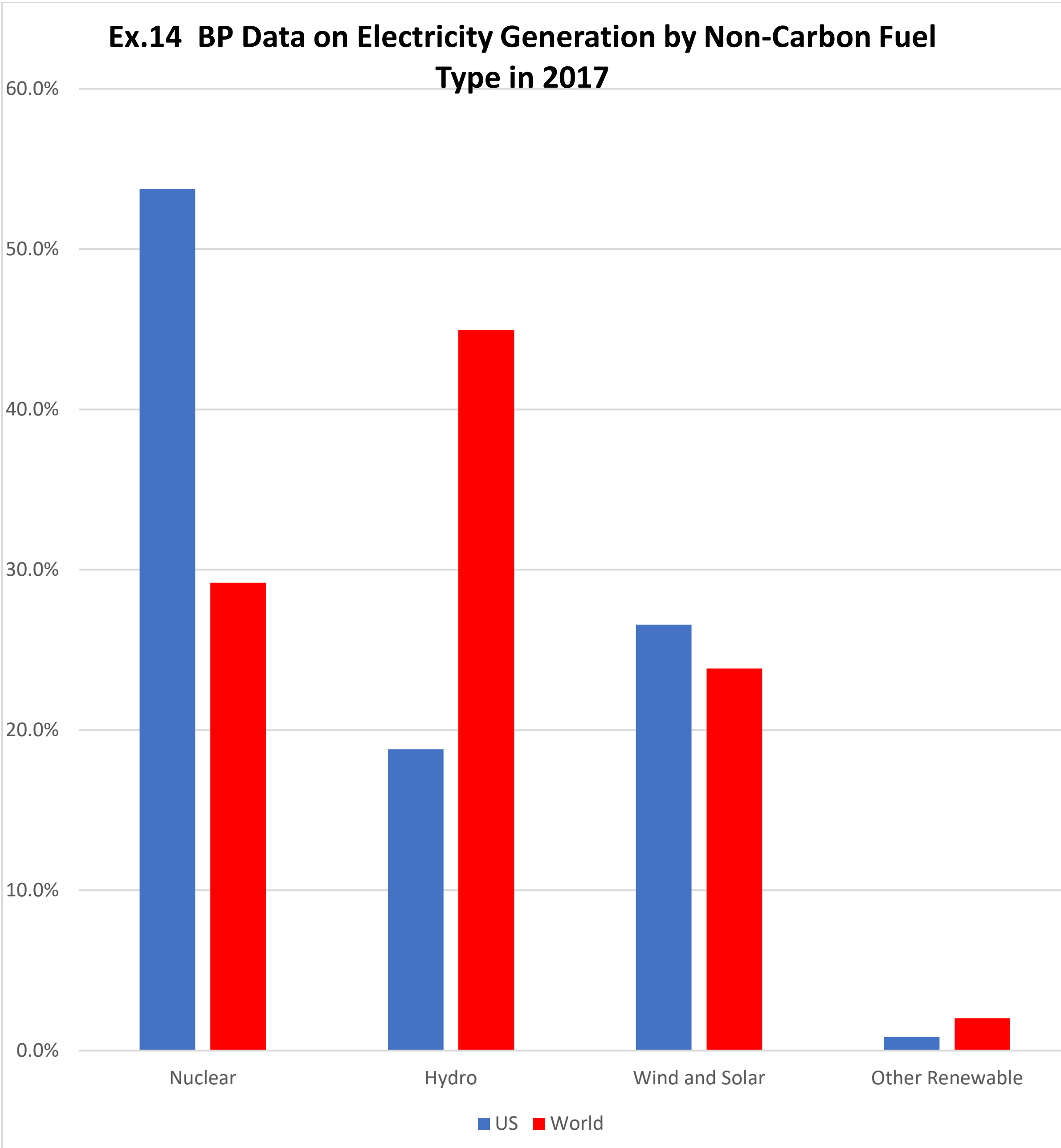
In Europe and the United States, efforts have been made to curb the use of coal. In addition, it would be expected that the rich, developed nations would lead the drive to employ renewable in electricity generation. Data on this conjecture are provided by Exhibit 12 which presents the same historical data as Exhibit 11 but limited to the United States. There are two pieces of welcome environmental news. First, the usage of coal began to decline sharply in 2005, dropping more than 30% by 2017. Second, the use of “other” fuels almost triples to become the largest source of electricity generation. On the other hand, the biggest increase for any fuel is the rise of natural gas. To get a direct comparative view, Exhibit 13 presents a breakdown of the USA’s electricity generation by fuel type in 1985 versus 2017. The rise of natural gas and the fall of coal are evident, as is the increase in "other." In addition, the exhibit highlights the fact that in the United States oil is no longer used to generate a meaningful amount of electricity. Despite the movement toward the use of renewables, the pace of change is limited. If that pace were to continue, there is no way the United States could meet ambitious goals such as 80% electricity generation from renewable sources by 2050. In addition, that goal depends on what is meant by "renewable." In the previous two exhibits, the "other" category included nuclear energy, which while non-carbon is not renewable. For this reason, Exhibit 14 subdivides the "other" category for the United States and the world in 2017. The exhibit shows that the combination of nuclear and hydro make up the largest share of non-carbon electricity generation for both the United States and the World. This is a problem because neither is expected to grow significantly. Furthermore, as noted above, nuclear is typically not counted as a "renewable." That being the case, a goal of 80% of electricity generation from renewable sources is not a reasonable target unless there is immense investment in renewable infrastructure.


Ex.11 BP Data for World Electricity Generation by Fuel Type: 1985 to 2017
trillions of kWh
12,000
10,000
8,000
6,000
4,000
2,000
-
1985
1988
1991
1994
1997
2000
2003
2006
2009
2012
2015
Total World Oil
Total World Gas
Total World Coal
Total World Other


Ex.12 BP Data on US Electricity Generation in Billions of KWH
by Fuel Type: 1985 to 2017
trillions of kWh
2,500
2,000
1,500
1,000
500
-
1985
1988
1991
1994
1997
2000
2003
2006
2009
2012
2015
US Oil
US Gas
US Coal
US Other



Ex.13 BP Data for US Electricity Generation by Fuel Type:
1985 vs 2017
60%
50%
40%
30%
20%
10%
0%
US Oil
US Gas
US Coal
US Other
1985
2017


Ex.14 BP Data on Electricity Generation by Non-Carbon Fuel Type in 2017
60.0%
50.0%
40.0%
30.0%
20.0%
10.0%
0.0%
Nuclear
Hydro
Wind and Solar
Other Renewable
US
World

The extent of the historical inertia in the use of fossil fuels is not surprising given the extensive infrastructure investment related to their provision, transportation and exploitation made over the past century. This includes, but is not limited to: 1) a massive stock of industrial, commercial and private land, water, air and space vehicles propelled by petroleum products; 2) power plants with their respective stations and distribution assets including 2.4 million miles of pipelines in the USA; 3)heating for industrial, commercial, public and residential customers; industries using petroleum products (such as hydrocarbon gas liquids) as feedstocks for manufacturing many products and product parts; 4) oil tankers, and a wide variety of industrial and agricultural equipment designed to use fossil fuels. Many of these infrastructure assets have long lives. For example, gas and coal fired power plants have lives of approximately forty years. In addition, they are serviced by specialized assets such as rail and pipe lines that bring fuel to the plants and employees trained to operate and repair the plants.

Characteristics of both electricity and its generation from renewables also add to the inertia of using fossil fuels. Electricity is difficult to store. Currently, the United States has storage capacity that amounts to 43 minutes of usage. Most of that capacity is in the form of pumped storage, where water is pumped up to a reservoir when demand for power is low and then allowed to flow back down through turbines when demand is high. This form of storage is difficult to expand as it requires access to areas where hydropower is generated. Sivaram (2017) discusses a host of storage alternatives that have been proposed, including battery power, but they are all expensive and difficult to scale.

The importance of storage increases as the fraction of electricity generated from renewables rises because of the intermittency of the primary renewable sources, solar and wind. The electricity industry strives for "six nines" reliability in "uptime." That means that power is reliably available 99.9999% percent of the time with a maximum downtime of 31.5 seconds per year. Clearly renewables, without massive storage capabilities or extensive back-up systems, cannot provide that type of reliability. There must be a way to provide customers with electricity when the wind is not blowing, and the sun is not shining. Aside from storage, another solution is to improve the grid so that power can be shuttled between areas that are sunny and windy to other areas that are dark and still. But without a global grid of the type envisioned by Son and Zhenya, this approach cannot produce anything approaching 99.9999% reliability.

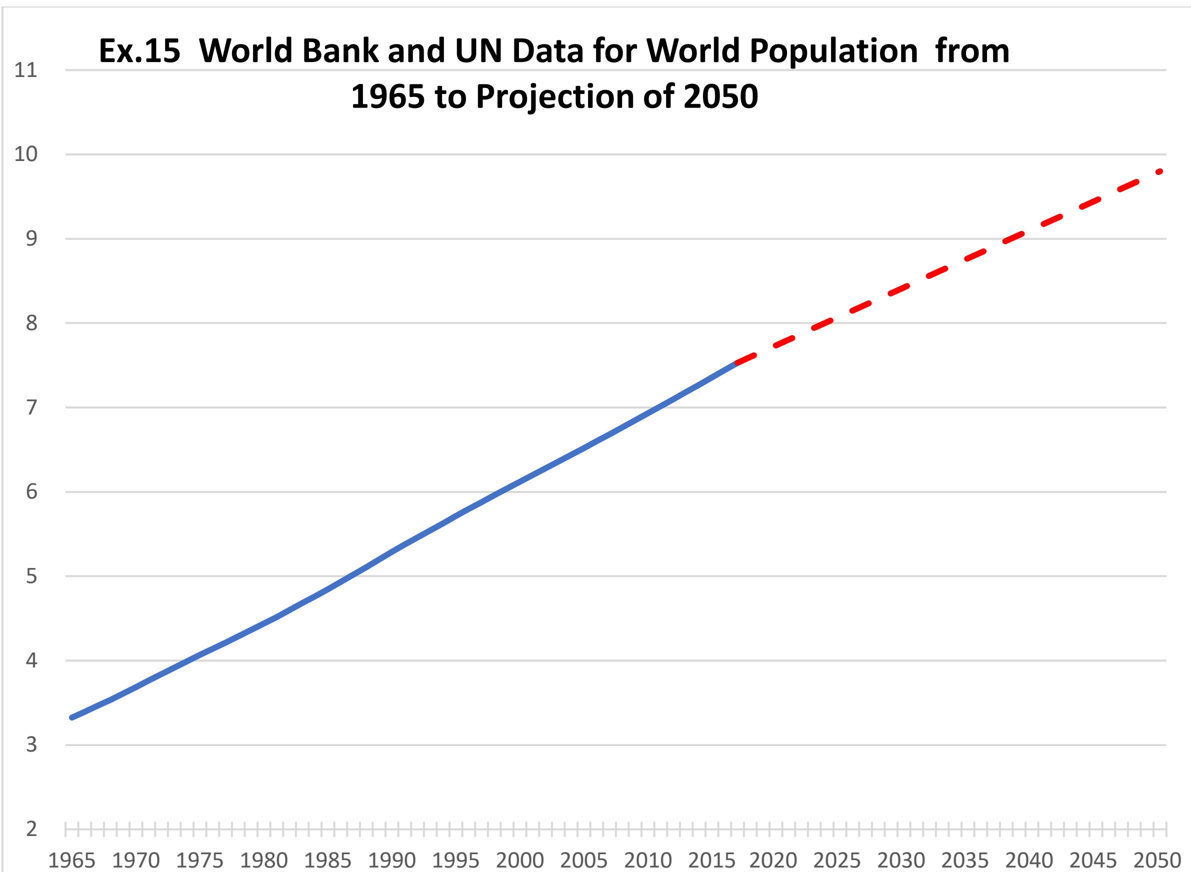
Keep in mind that these problems exist at the current level of electricity generation. But as population rises toward 10 billion people by 2050 and the global economy expands, so will the demand for electricity. More importantly, the great transformation will require the substitution of electricity in activities such as transportation, industry and residential usage that are currently are currently dominated by fossil fuels.

The real question, however, is not as much as historical inertia in the use of fossil fuels, but the extent to which that inertia can be expected to continue. That depends on the factors that will affect future demand and supply of fossil fuels. The key factors are the following:

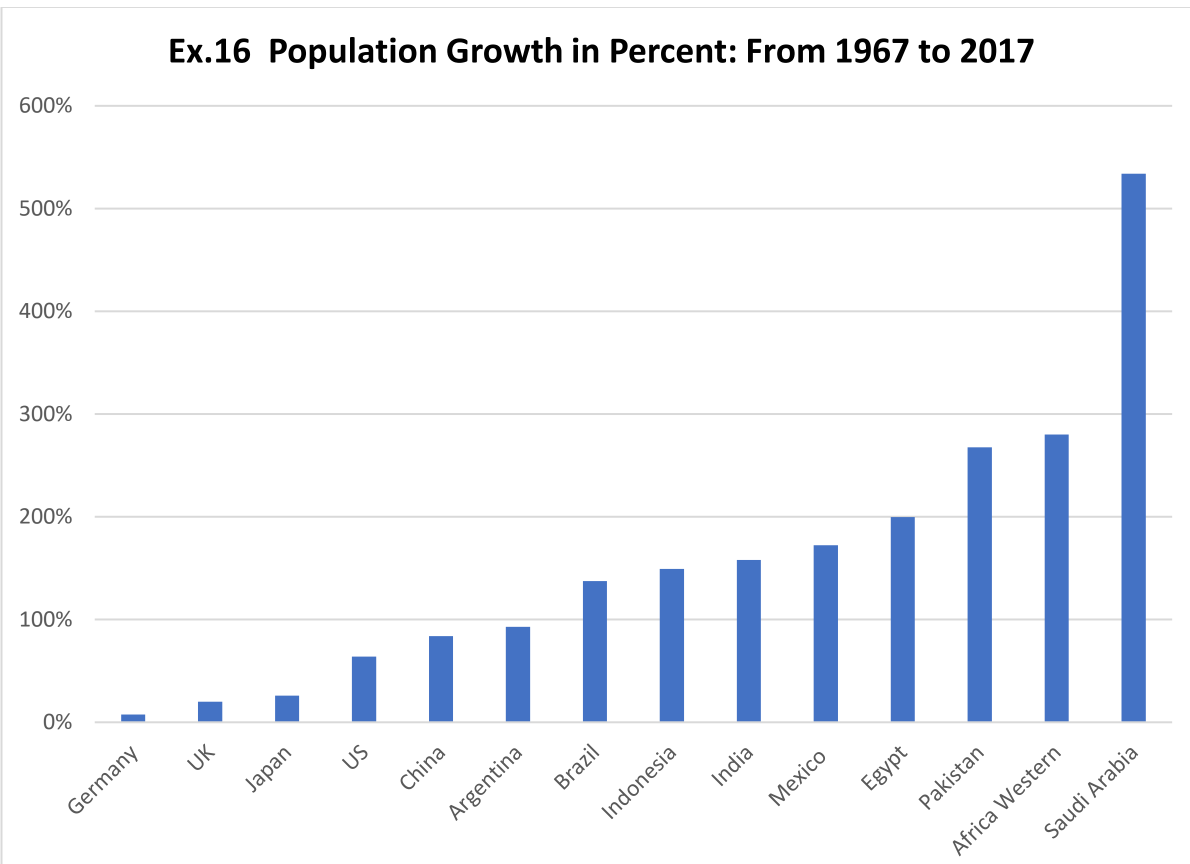
- Population growth as measured both by size and growth rate;
- Economic growth as measured by real GDP per capita;
- The economic efficiency of the economy as measured by the number of dollars of real GDP produced by a kilowatt of primary energy;
- The stock of fossil fuels; and

- The predicted substitution of renewables for fossil fuels.

Starting with population, Exhibit 15 plots the world population from 1965 to 2017 (shown as a solid line), along with United Nations' projections for population through 2050. Between 1965 and 2017, world population rose steadily, though at a declining growth rate, from 3.32 billion to 7.53 billion. The UN projects that although the growth rate will continue to slow, population size will keep rising. By 2050, the UN predicts that the world population will be 9.80 billion.



Global data obscures the fact that population growth varies significantly by country, education, level of development and other factors. Exhibit 16 provides background information on population growth over the historical period from 1965 to 2017 for the sample of countries used in previous energy related exhibits. The differences across countries are dramatic. For instance, Germany's population remained largely constant while Saudi Arabia's grew more than five-fold. The Saudi case, however, is a bit anomalous because the population of the kingdom was only 4 million in 1965. In terms of absolute numbers, the growth in India's population was astonishing. Between 1965 and 2017, India added almost 850 million people – more than the combined current populations of Europe and the United States. Pakistan's population nearly quadrupled from 50 million to 200 million. The fastest population growth was in Western Africa where the region, led by Nigeria, added 260 million people.



Looking forward, the UN predicts the historical patterns to continue. Population growth will be greatest in the developing areas of the world including Latin America, Africa, the Middle East and parts of Asia. In contrast, populations in Europe and Japan are expected to remain largely constant and to grow very slowly in the United States. From the perspective of energy usage, the world is "lucky" that people in these areas where population is expected to increase the most currently use relatively little energy. As shown in Exhibit 6, the kwhpdpc usage in India, Pakistan and West Africa is very low. But continued poverty and related low energy usage can hardly be counted on as means to constrain energy consumption in the years ahead. The basic message is that world population is going to continue to grow and the new world citizens will aspire to energy usage levels approaching the European standard.

As shown in Exhibit 17, the World Bank reports that global GDP in 2017 was $80.68 trillion and estimates that it will nearly triple to $207 trillion by 2050. That represents a compound real growth rate of 3%. Growth is projected to be higher than that in the developing countries and lower in the developed world. The faster growth in the developing world is due, in part, to movement of manufacturing to those regions. That manufacturing, however, is energy intensive. It should be noted that the World Bank figures are for real GDP, not real GDP per capita, therefore the 3% estimated growth rate includes the impact of estimated population growth.

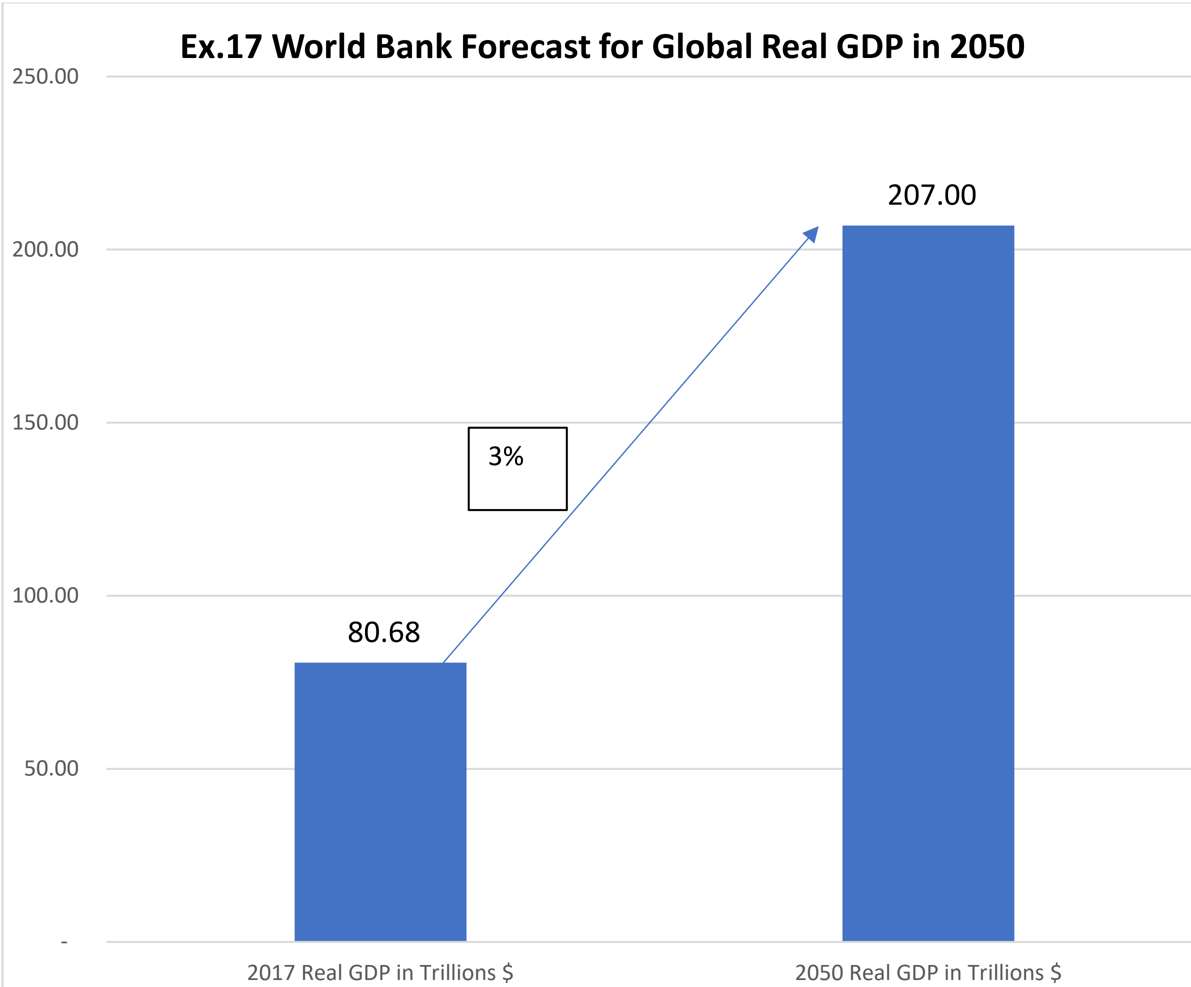
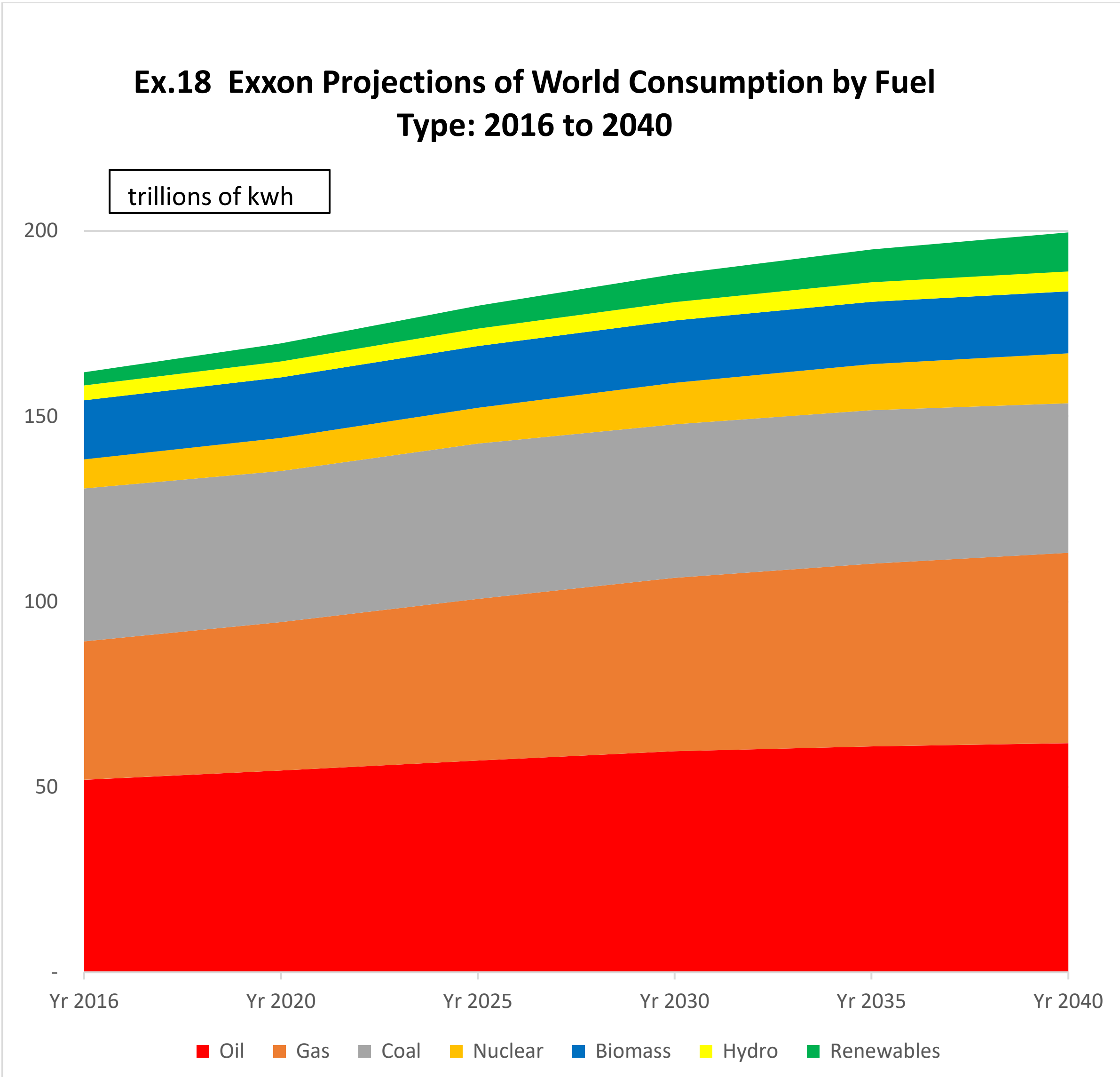


Exhibit 18 presents Exxon's forecast of global energy consumption starting from actual levels in 2016 and projected through 2040. Exxon forecasts an increase of 23.3% in total global consumption from 161.9 trillion kWh to 199.6 trillion kWh. That equates to an annual growth rate of 0.88%, well below the forecast real GDP growth of about 3.0%. The difference reflects the impact of increased efficiency and corresponding drop in the energy intensity of GDP. However, those predicted efficiencies are not enough to offset fully the combined impact of increase in real GDP per capita and growing population.

Regarding the distribution of energy provision by fuel type, the impact of inertia is obvious in Exhibit 18. Despite the fact that it started from a large base, the consumption of oil is predicted to rise by 19% and the consumption of gas is predicted to increase 37% over the forecast period from 2016 to 2040. The consumption of coal, also starting from a large base, remains largely constant. Exxon predicts that nuclear fuel will at least partially overcome its political problems and its use will rise 71% from its current low level. The good news for energy transformation is that the biggest predicted percentage increase is for renewables which jump 195%. The bad news is that the base in 2016 was so low that even a 195% increase leaves renewables with a small fraction of the total energy pie in 2040.



To gain further insight into the role of increasing efficiency, Exhibit 19 examines the relation between energy usage and real GDP growth for the United States. The exhibit shows that real GDP grew much faster than energy usage during the years from 1965 to 2017, so that energy efficiency doubled during the period. However, GDP, driven by a combination of improved labor productivity and growing population, grew even faster so the total primary energy consumption rose through 2000 before leveling off. The data suggest that with respect to the developed countries of North America, Europe and Japan future growth in consumption is likely to be limited as efficiency continues to improve, population stops growing, and growth in real GDP per capita slows. It is reasonable to predict little, if any, future increase in primary energy consumption for these countries. Unfortunately, the same is not true of the developing world.

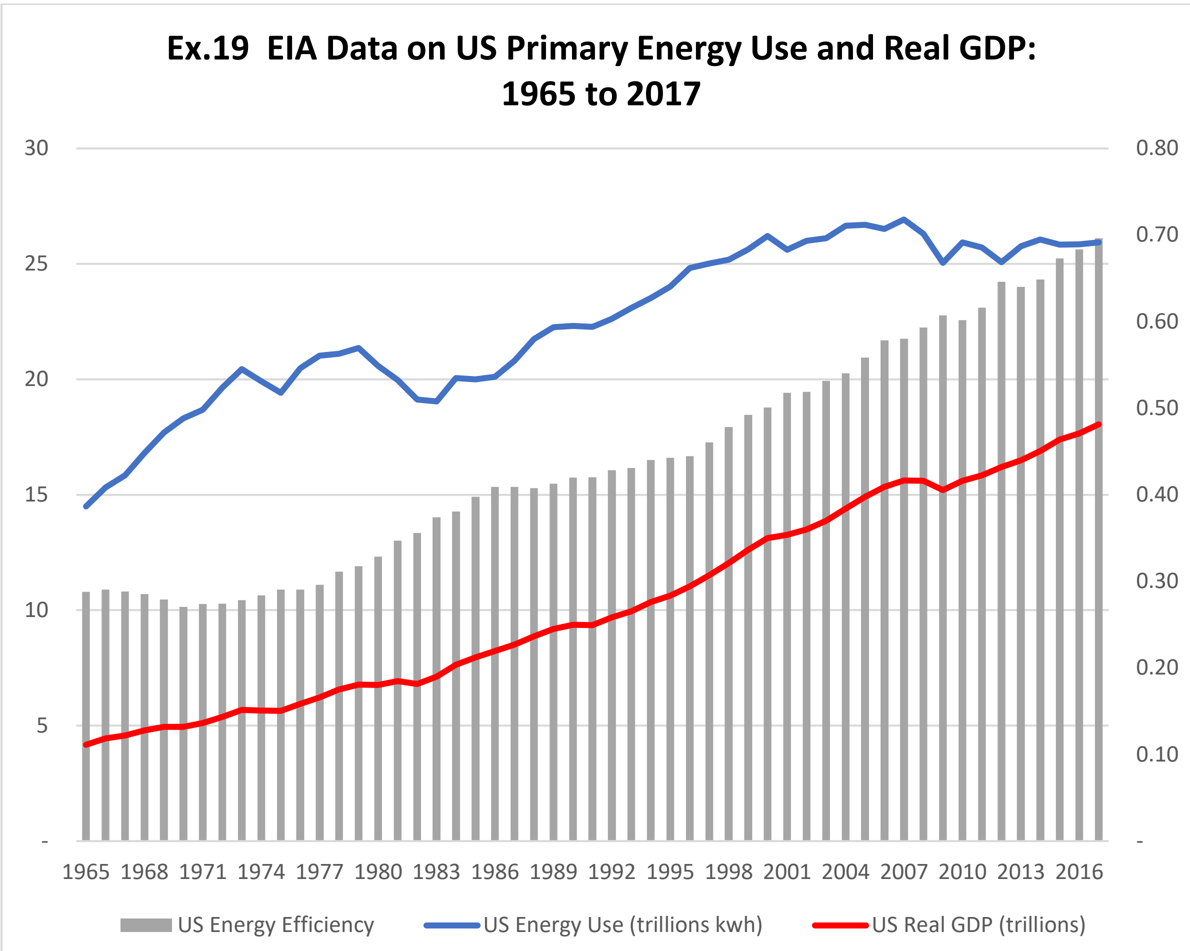
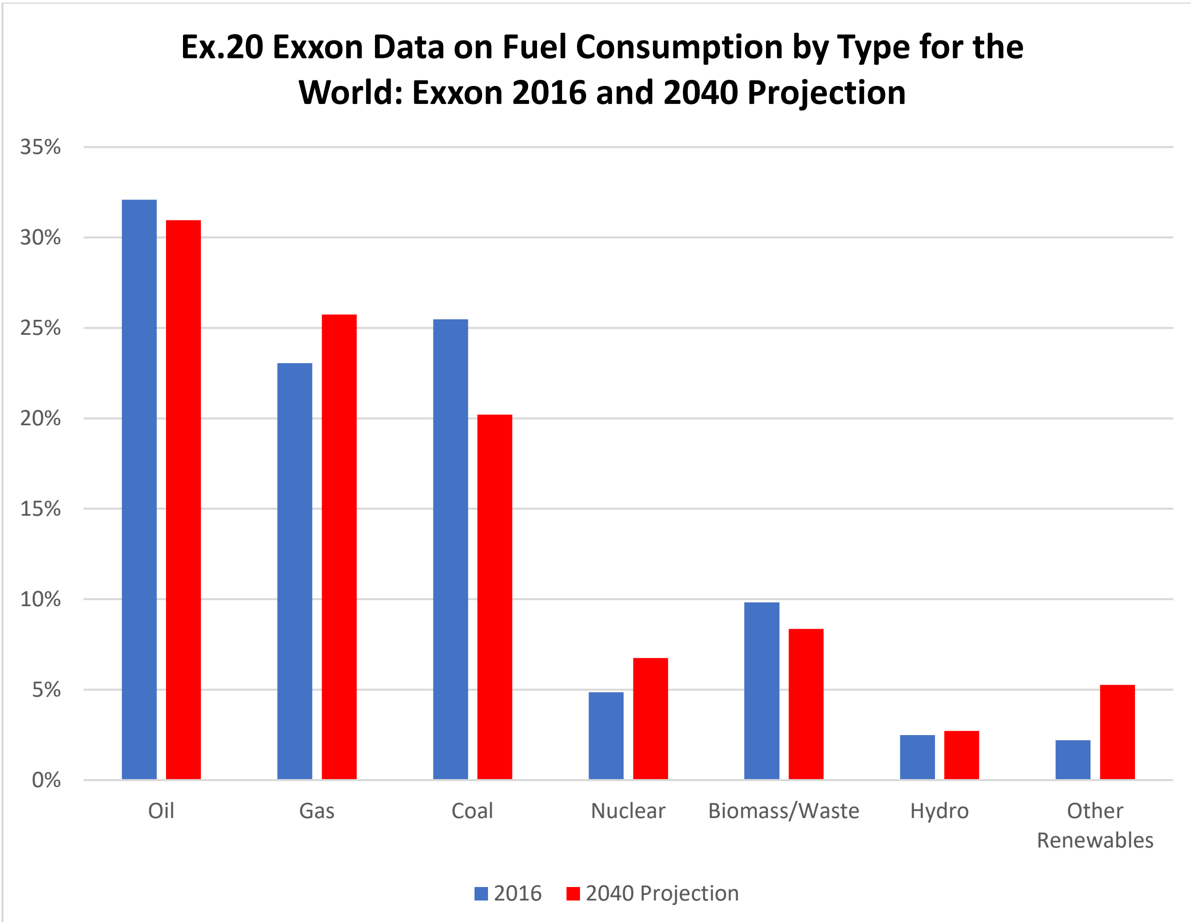
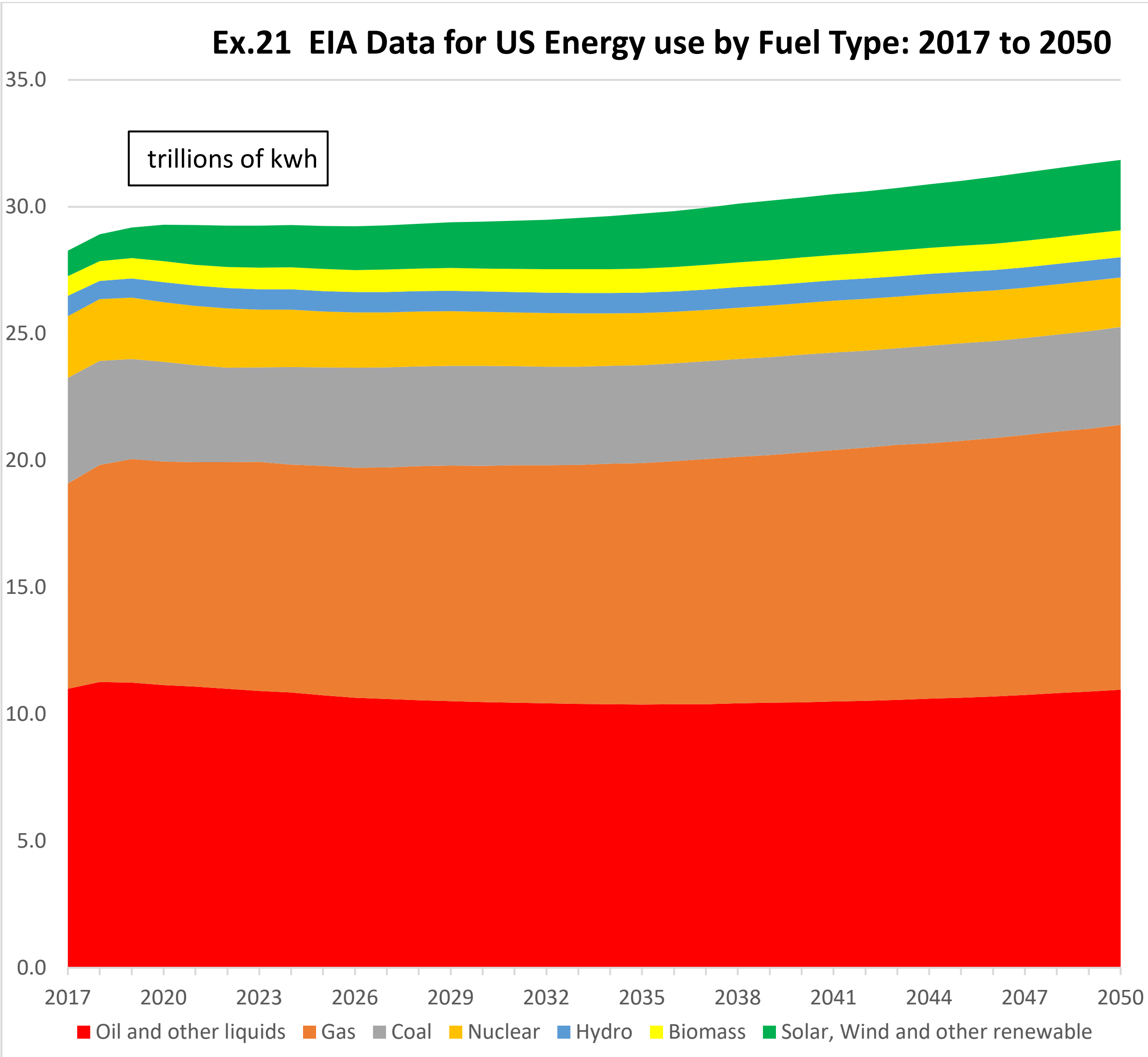


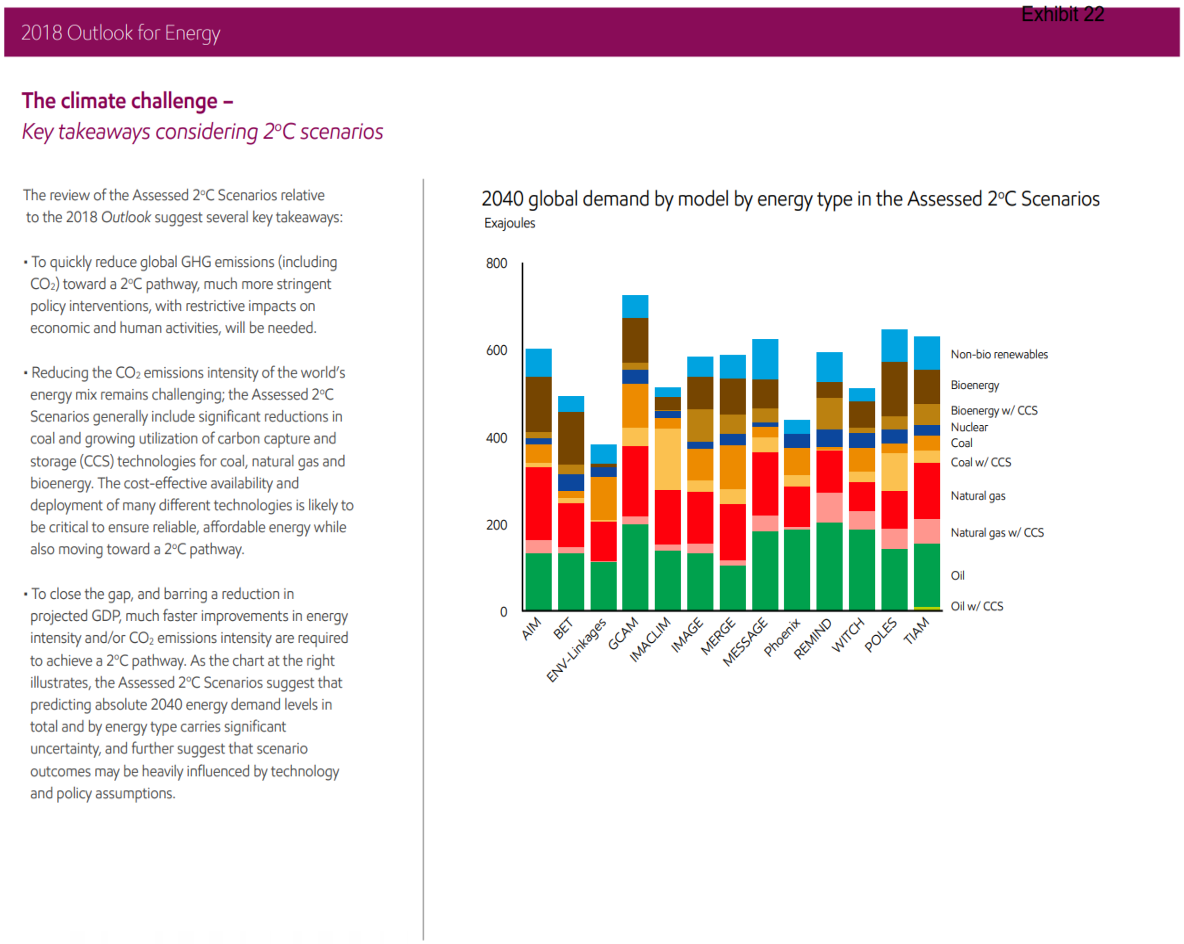
Exhibit 20 offers another view of the data that compares 2016 actual values and 2040 forecasts in terms of the percentage usage of each fuel type. The doubling of the role of renewables is clearly evident in the exhibit, but so is their continued low level. Fossil fuels remain the predominant source of primary energy in 2040. Overall, the projected breakdown of energy use by fuel type in 2040 looks much like it was in 2016.



With slower growth in energy demand, great wealth, and less reliance on manufacturing, one would hope that the developed countries would be leading the transition to renewables. Exhibit 21 investigates that possibility. The exhibit shows the US Energy Information Agency's (EIA) forecast energy usage by fuel type from 2017 through 2050 for the United States. As expected, the growth rate in total primary energy at only 0.36% is smaller than for the world as a whole. What is disappointing, at least from the standpoint of energy transformation, is that usage of all three major carbon fuels remains basically constant. Renewables do grow faster than any other category, but because they start at such a low base, they remain a sliver even in 2050.

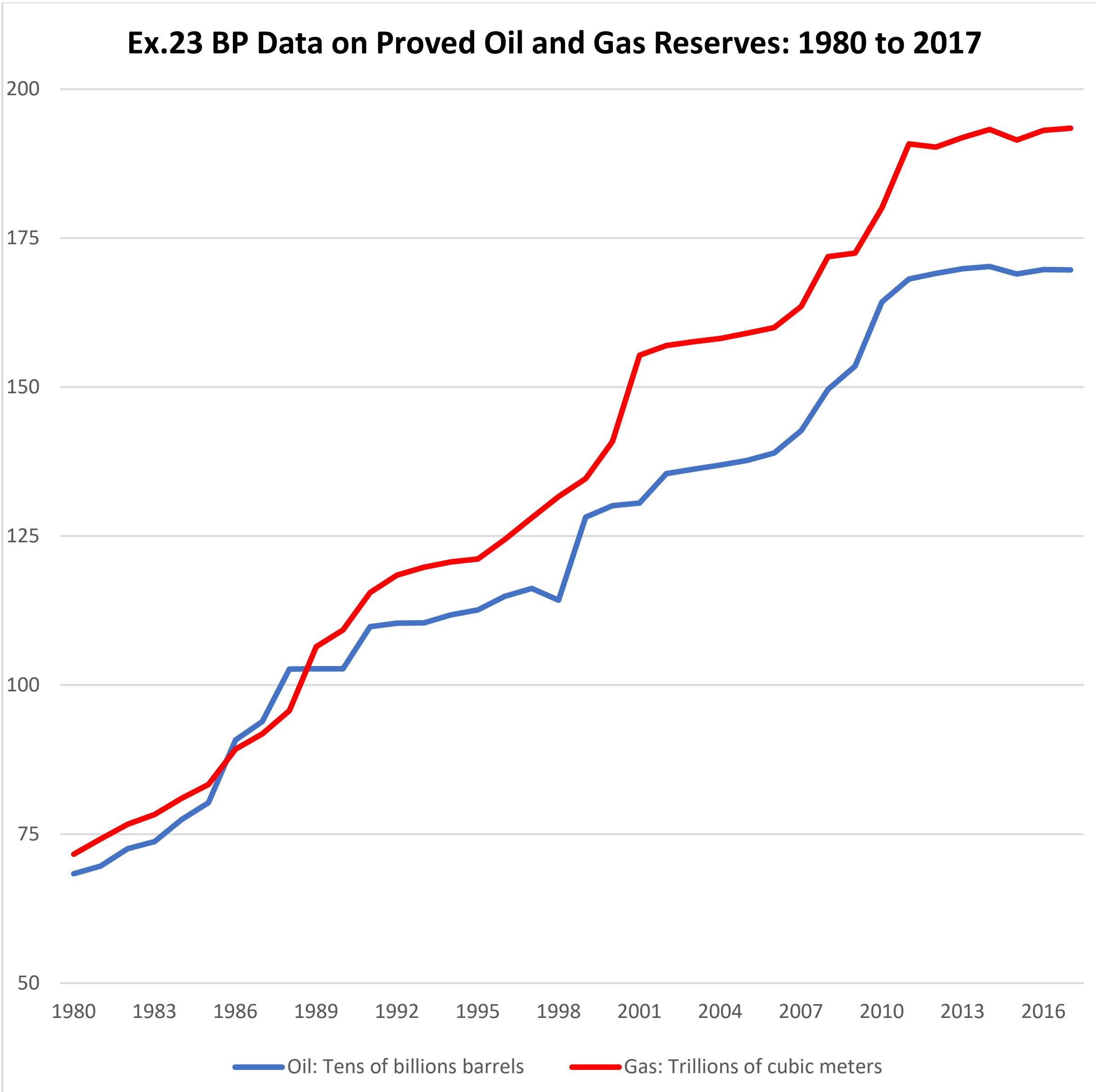


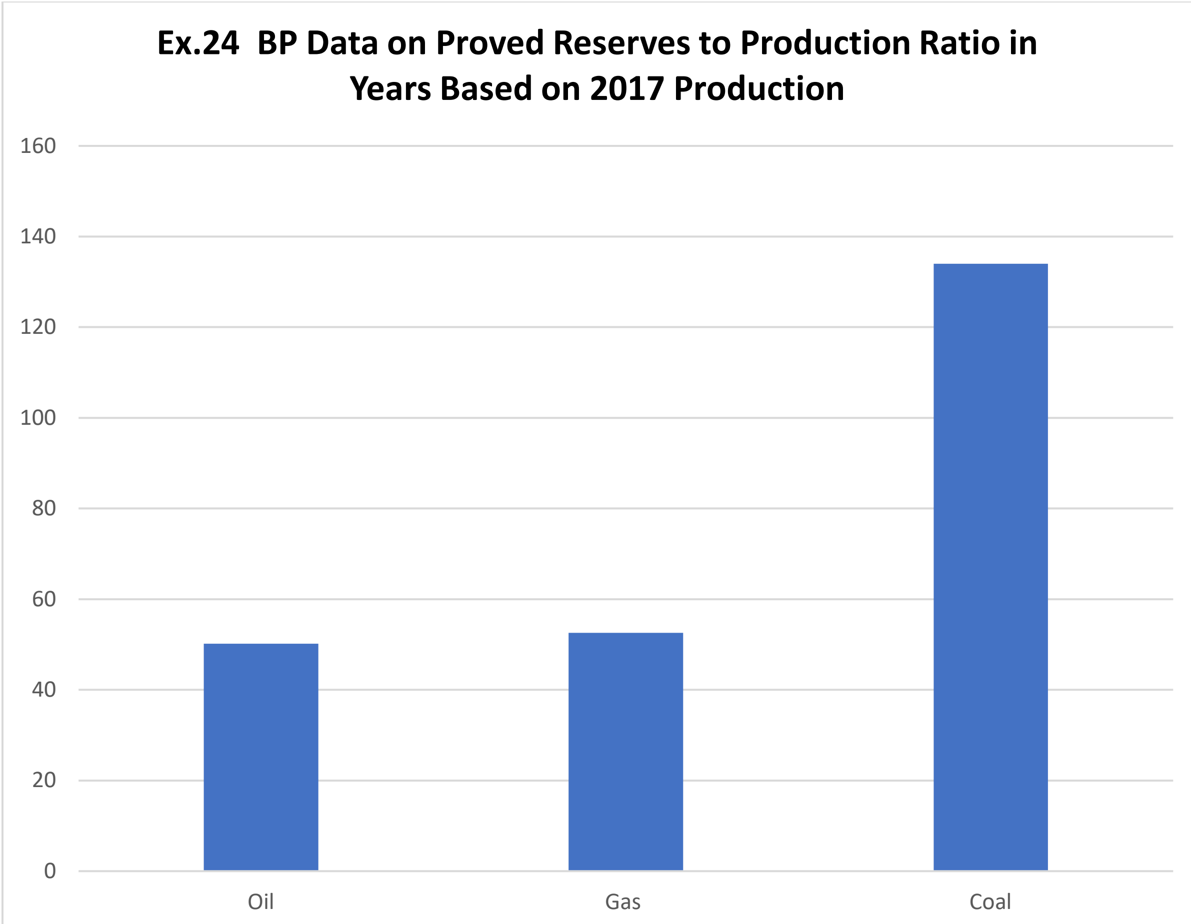
Because many of the previous exhibits were based on forecasts produced by oil companies, there may be a suspicion that they are based toward predicting the continued use of fossil fuels. To counter that suspicion, Exhibit 22 summarizes the forecasts of energy use by fuel type produced by thirteen different academic organizations and think tanks. The forecasts are not most likely outcomes, but outcomes that are designed to be consistent with an increase in global temperature of two degrees centigrade or less by 2040. Despite this restriction, all the forecasts show the active utilization of fossil fuels. The impact of inertia is clear.



The continued inertia through 2050 raises the obvious question of how long this can go on. Ass Herbert Stein so sagely observed: "If something cannot go on forever, it will stop." As noted at the outset, there are two fundamental reasons why the use of fossil fuels will stop or, more accurately, slow significantly – increasing scarcity and unacceptable environmental impact. The scarcity issue is less controversial. However, it is complicated by the fact that proved reserves are a moving target. To highlight the potential impact of increasing scarcity, Exhibit 23 plots proved oil and gas reserves over the period from 1980 through 2017.[4] The tendency of proved reserves to rise over time is evident with proved reserves of both oil and gas doubling between 1980 and 2017 despite rising consumption. This reflects, in large part, the development of new technologies such as fracking. Notice, though, that starting about 2012 both curves stop rising. That suggests we are reaching the point where new discoveries are just offsetting current consumption. To be fair, though, it is difficult to predict how proved reserves will move in the short term. However, in the long term, the stock of carbon fuels is clearly finite, and scarcity will become binding at some point. One way to estimate that point is to calculate the ratio of proved reserves to current production. Data on that ratio are presented in Exhibit 24. The ratios for both oil and gas are about fifty years, implying that scarcity will become a binding issue during the second half of the 21st century. The ratio for coal is higher at about 130. But that brings us to the second reason for limiting the use of carbon fuels – the environmental impact. Coal is the biggest culprit in that regard.

[4] Historical data on proved coal reserves is not available from my sources.


Ex.23 BP Data on Proved Oil and Gas Reserves: 1980 to 2017
200
175
150
125
100
75
50
1980
1983
1986
1989
1992
1995
1998
2001
2004
2007
2010
2013
2016
Oil: Tens of billions barrels
Gas: Trillions of cubic meters

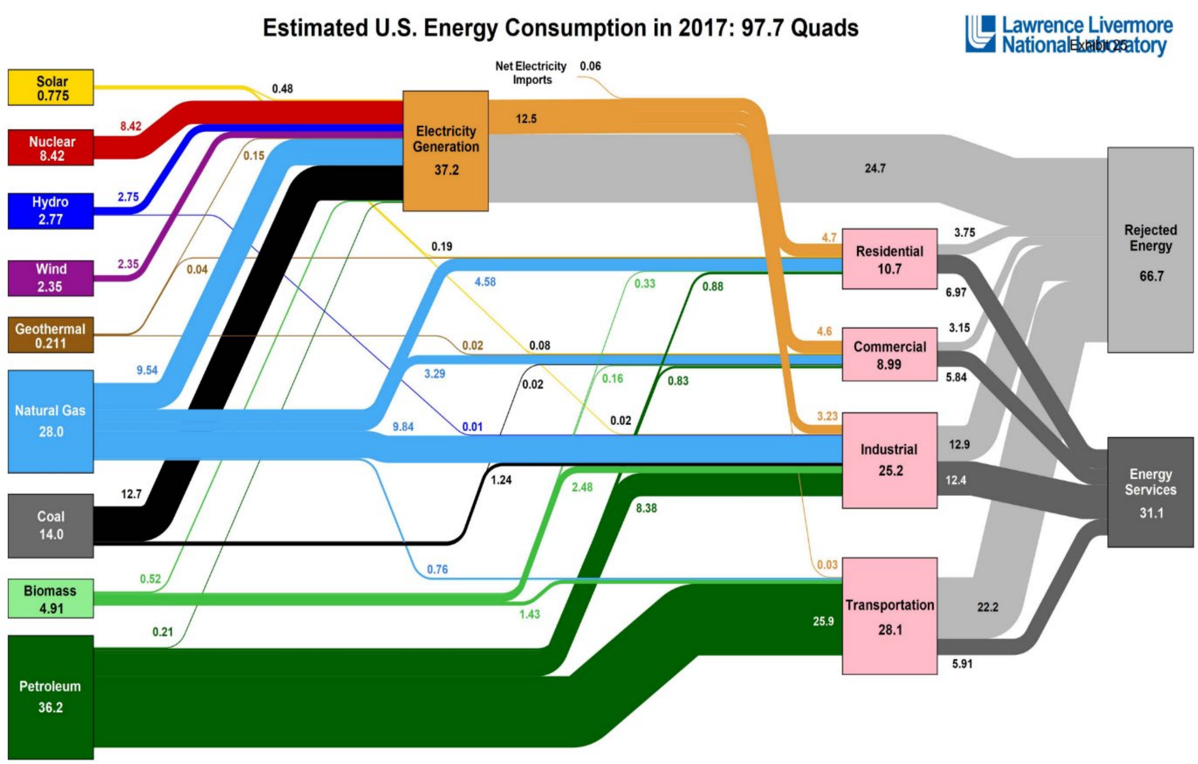


The debate regarding the environmental impact of burning fossil fuels has spawned tens of thousands of books and articles. For those interested in pursuing this subject, the work of 2018 Nobel Prize winner Willaim Nordhaus is an excellent starting point.[5] I take it is as given that the environmental impact of burning fossil fuels is both negative and significant and provides another motive for the great transformation to the use of renewable energy.

Returning to the inertia phenomenon, another reason for the inertia is that in many activities it is difficult, or close to impossible, to substitute other energy sources for carbon-based fuels. Examples include air travel, industrial production of products like cement and

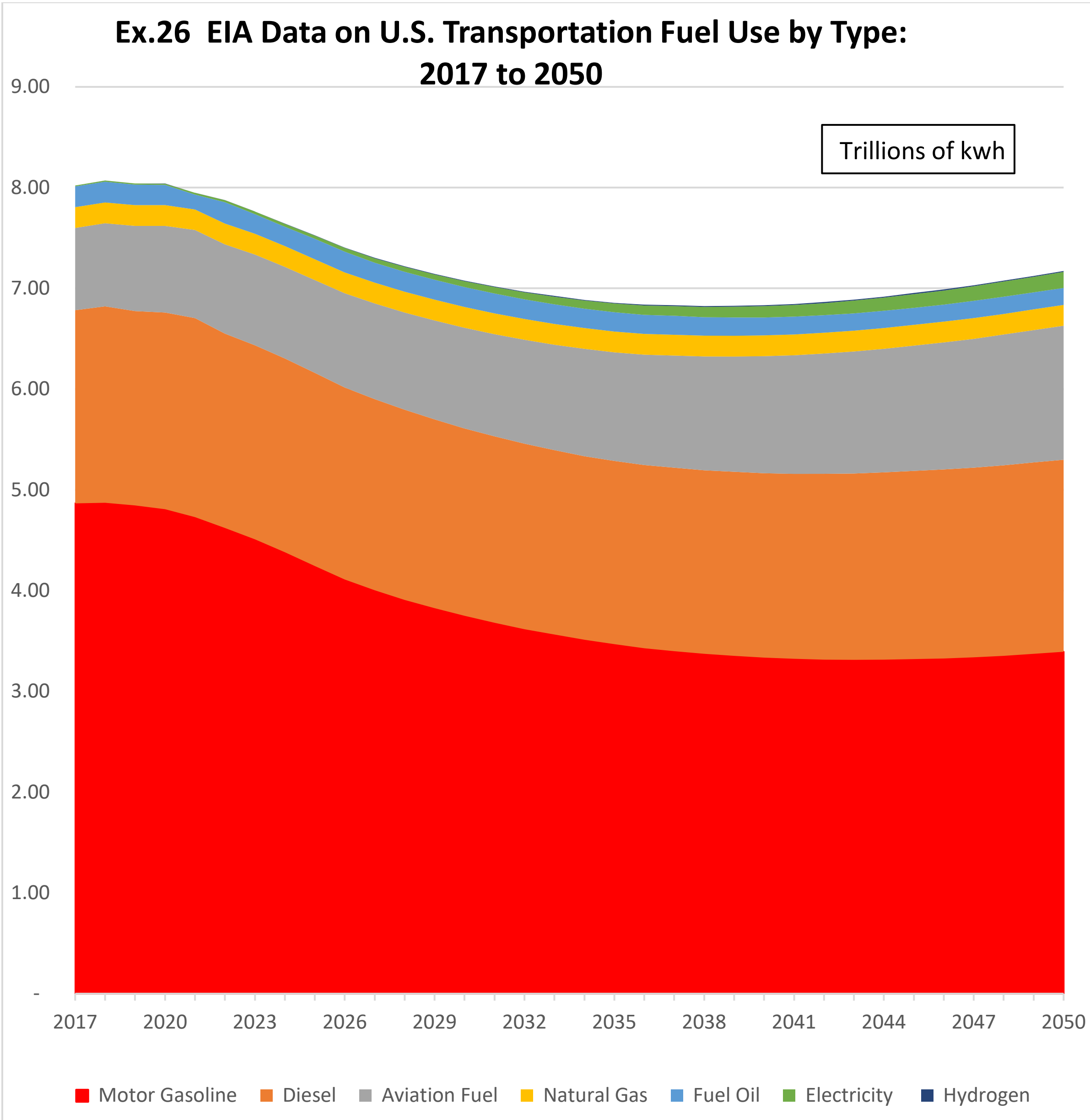
[5] See, for example, Nordhaus (2013).

steel, construction, agriculture, and railroading. Insight into how fuels are used is provided by energy flow diagrams. Exhibit 25, produced by the Lawrence Livermore National Laboratory, shows the flow of energy in the U.S. economy in 2017 and documents the extensive use of petroleum in transportation and industry. ("Industry" includes agriculture in Exhibit 25.) It also shows the widespread use of natural gas as a direct input into many industrial, commercial and residential uses. In addition, the exhibit highlights the difficulty of turning primary energy into useful energy services. Over 68% of the primary fuel is lost to heat (rejected energy), much of that in the generation of electricity.



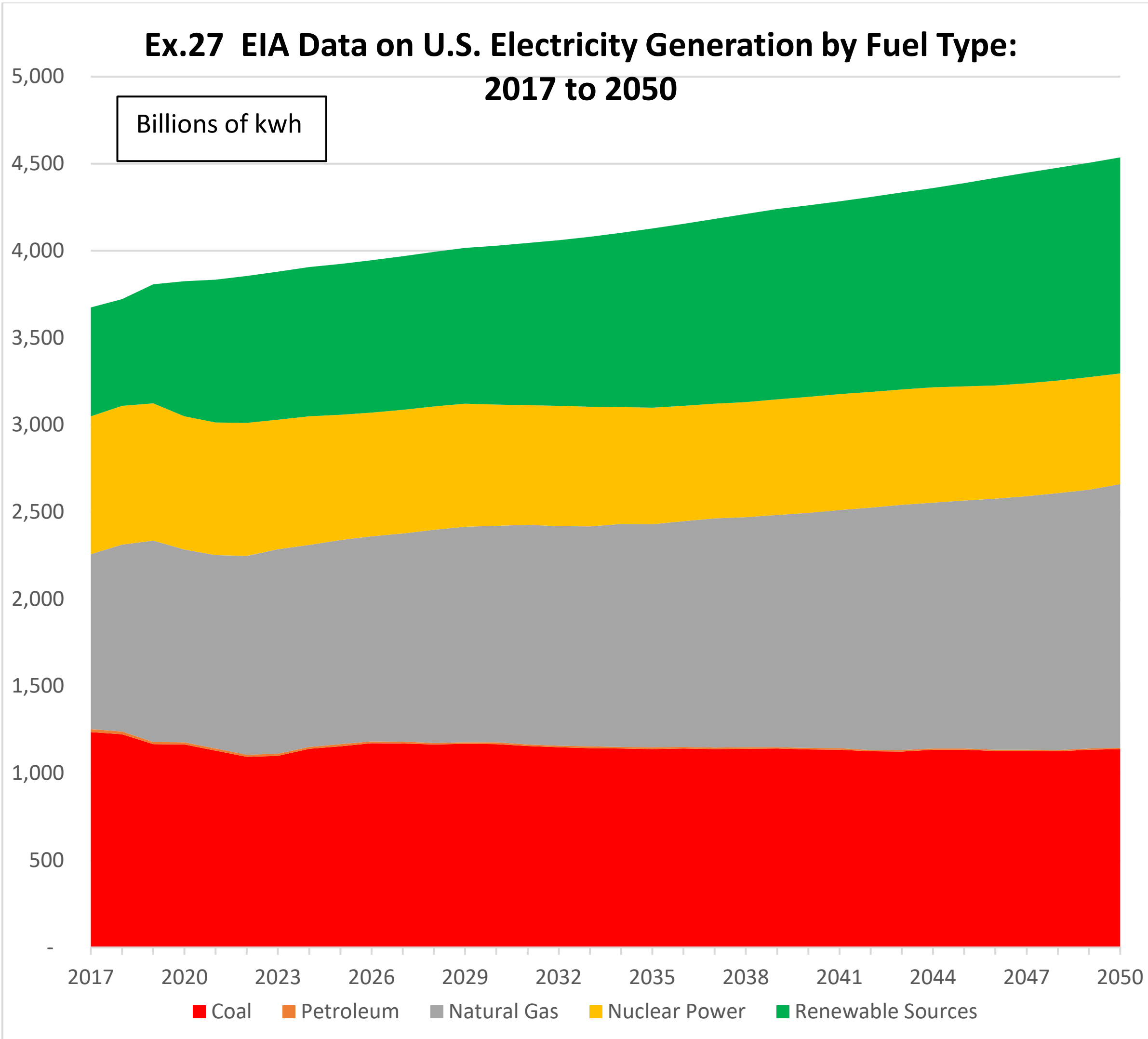
Although the government is often thought to be a force for overcoming inertia because of the widespread publicity given to plans and programs for transitioning to renewables, governments also play a role in perpetuating inertia. For instance, as noted earlier, a key step for expanding renewable electricity generation and consumption is improving the grid so that power can be shuttled around to overcome intermittency. Putting aside Son and Zhenya's futuristic vision of a global grid, even within the confines of the United States, Steven Chu (a former secretary of energy) has stressed that a long-distance interconnected transmission grid is a big piece of the climate puzzle. Nonetheless, in the U.S., it can take more than a decade to secure the necessary approvals for the towers, wires and underground tubes that cut across swaths of federal, national, state, county and private lands – on the rare occasion when they get approved at all. Without such approvals, there is a great incentive to rely on the current fossil fuel-based system.

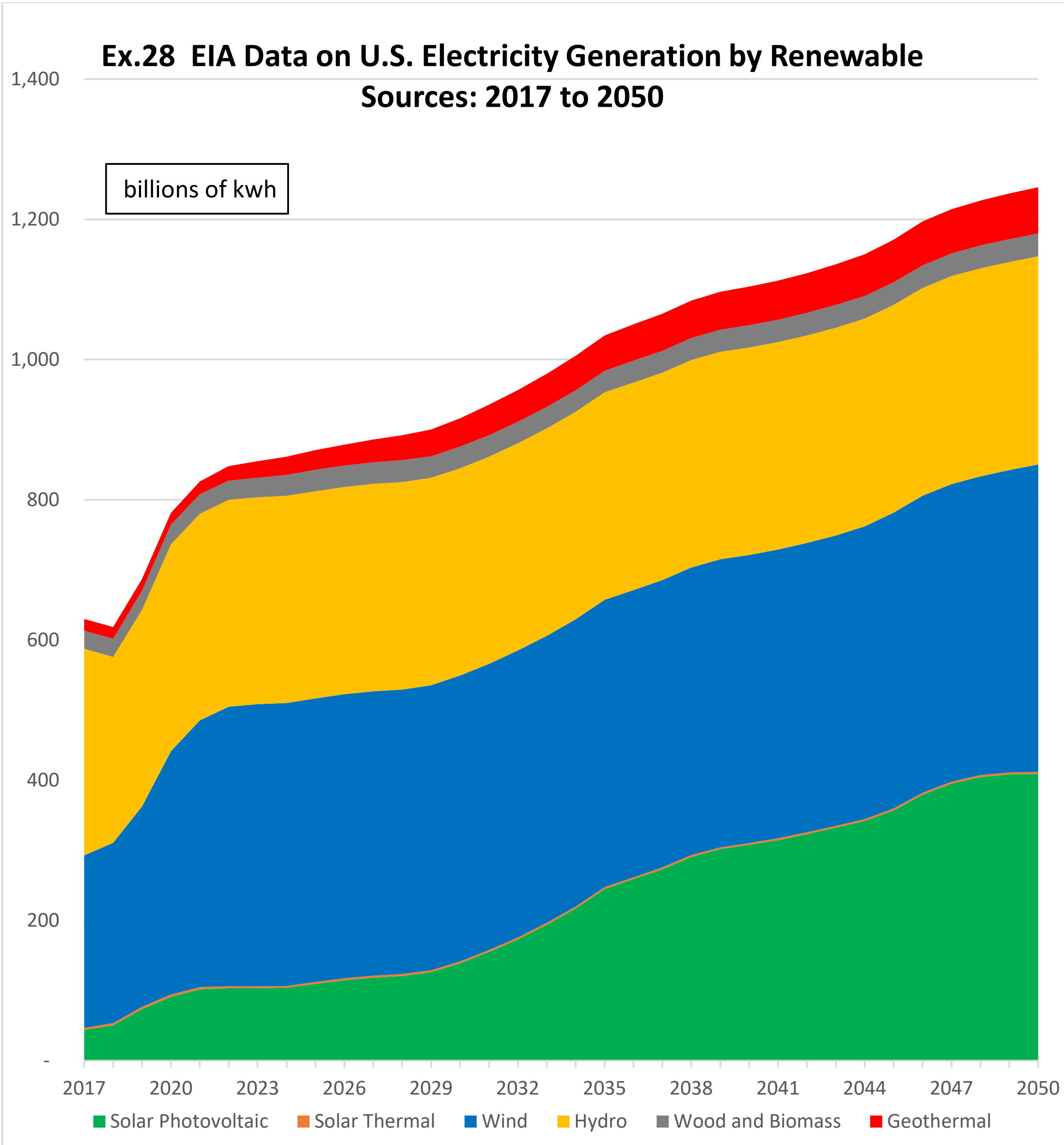
Because there has been so much attention paid to the electrification of vehicle transportation with the rise of firms like Tesla, Exhibit 26 takes a closer look at the EIA's projections for energy usage by fuel type in the transportation industry. Despite the publicity surrounding electric vehicles, the impact of inertia is evident once again. The EIA predicts that motor gasoline, diesel fuel, aviation fuel and fuel oil – all petroleum derivatives – will continue to account for about 90% of energy consumed in transportation each year up through 2050. Further, part of the remaining 10% is natural gas – another fossil fuel. Electricity remains a small slice throughout the forecast period. The good news, however, is that due to increases in efficiency, the EIA predicts that aggregate energy consumption will drop despite an increase in transportation miles traveled.



Because of the difficulty of substitution for fossil fuels in many activities, the great transformation should begin by replacing fossil fuels in the generation of electricity and expanding the use of electricity wherever possible. In that regard, Exhibit 27 presents the EIA's forecast for electricity generation by fuel type in the United States over the years from

2017 to 2050. The good news is that renewables are a large and growing share of the energy mix – reaching almost one-third of the total by 2050. There is a footnote, however. Renewables in Exhibit 27 are defined broadly and include hydro. Exhibit 28 breaks down the forecast by type of renewable. It shows that a large, and basically constant, portion of the renewables is hydro power. More positively, it also shows continued and relatively rapid growth in the use of solar and wind power to generate electricity which along with hydro are the three main sources of projected renewable electricity generation in 2050. The not so good news is that even by 2050, coal and natural gas still account for a majority of the energy used to generate electricity in the United States. Furthermore, the amount of coal and natural gas used in this capacity is larger in 2050 than it was in 2017 because of the increased consumption of electricity. If the EIA forecasts are close to the mark, even by 2050 the great transformation will just be getting underway. The largest changes, and the biggest investments, will be made in the second half of the century.


Ex.27 EIA Data on U.S. Electricity Generation by Fuel Type:
2017 to 2050
Billions of kwh
5,000
4,500
4,000
3,500
3,000
2,500
2,000
1,500
1,000
500
-
2017
2020
2023
2026
2029
2032
2035
2038
2041
2044
2047
2050
Coal
Petroleum
Natural Gas
Nuclear Power
Renewable Sources



Greenhouse Gas Emissions

This section can be short because the generation of greenhouse gases is so closely tied to the use of carbon fuels that has already been analyzed. To get started, Exhibit 29 plots the CO_2 emissions (in millions of tons) for each of the seven regions of the world and for the global total. It mirrors the previous exhibits on the projected consumption of primary fuels. In particular, global CO2 emissions rise throughout the period except for short-term drops associated with economic recessions. On a positive note, emissions in the developed world peaked with the global economic expansion in 2005 and have declined slightly since then. Furthermore, there was also a decline in the emissions from the CIS countries following the collapse of the Soviet Union. Conversely, the developing countries of Africa and South and Central America show rapid emission growth over the period, but the starting point is so low that even by 2017 emissions are small compared to the developed world. This is not true of Asia. Led by the development in China, and to an extent India, and catalyzed by the rapid population growth, energy usage, and thereby emissions, skyrocketed. Asia surpassed North America as the largest emitter in 2001, and by 2017 was emitting three times North America's CO2. The growth in Asia was sufficient to ensure that total emissions kept growing worldwide throughout the period to record highs in 2017. This is not surprising given the inertia in the use of fossil fuels documented in the previous subsection.

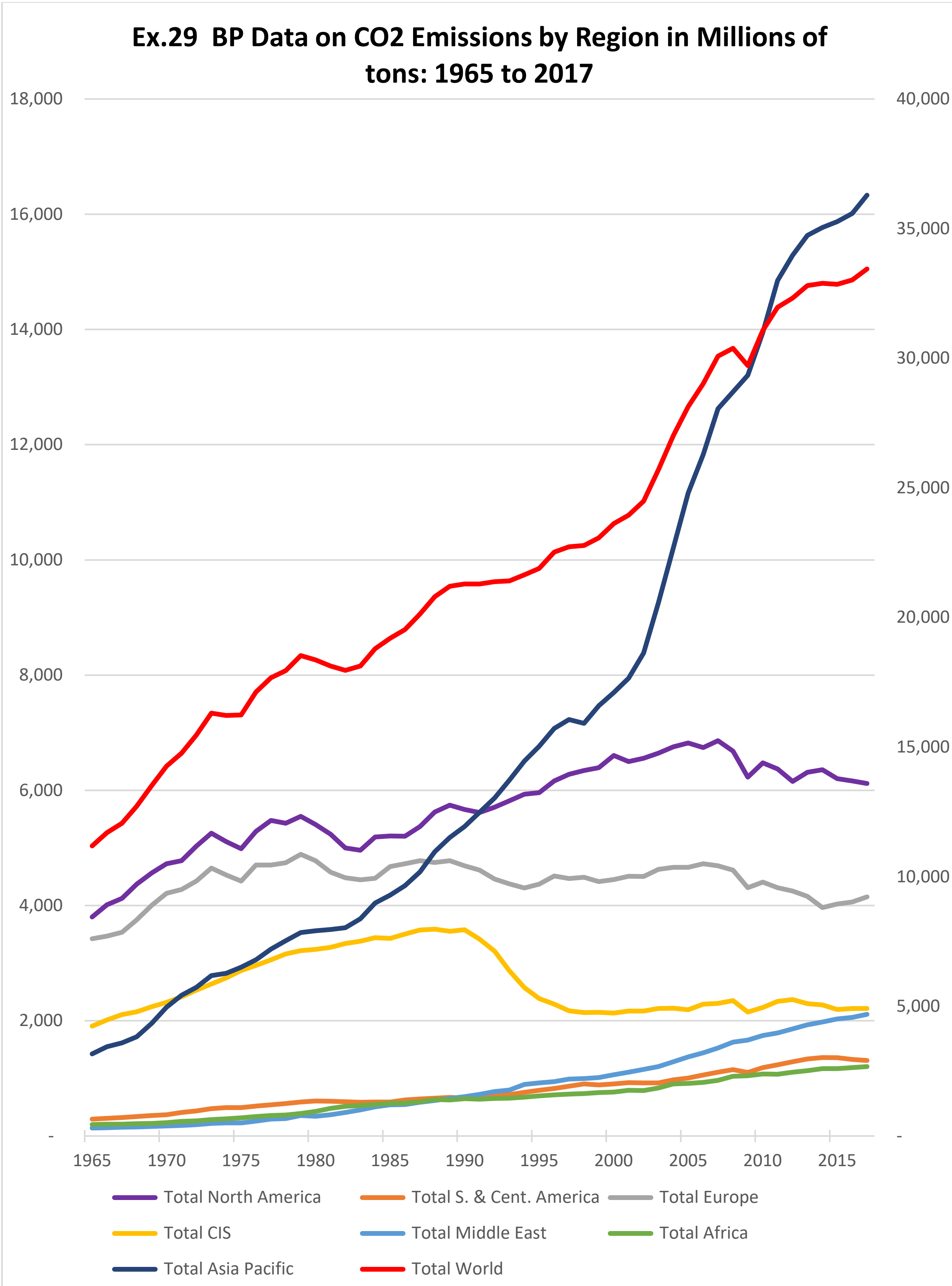
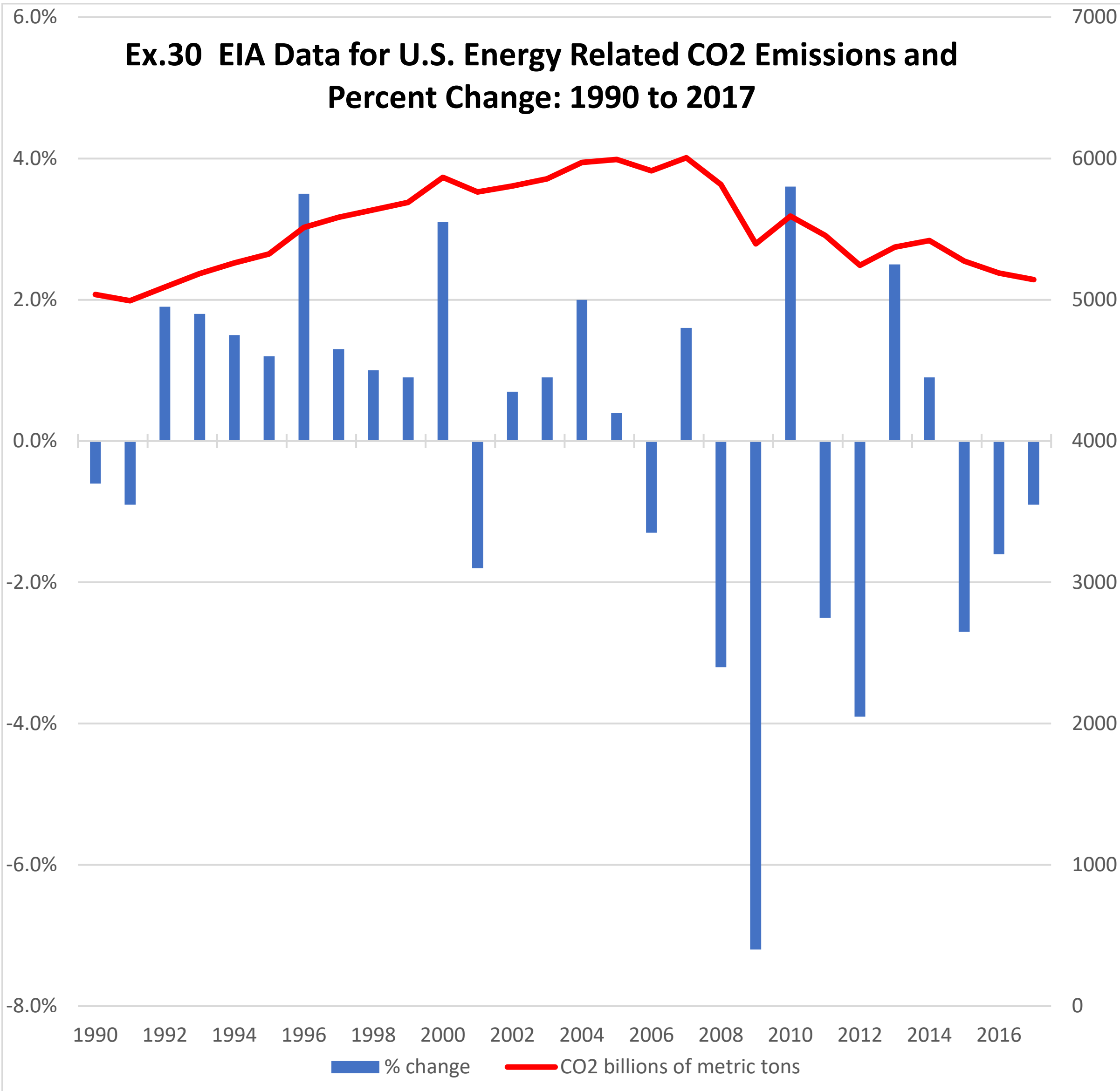

Ex.29 BP Data on CO2 Emissions by Region in Millions of tons: 1965 to 2017
18,000
16,000
14,000
12,000
10,000
8,000
6,000
4,000
2,000
-
40,000
35,000
30,000
25,000
20,000
15,000
10,000
5,000
-
1965
1970
1975
1980
1985
1990
1995
2000
2005
2010
2015
Total North America
Total S. & Cent. America
Total Europe
Total CIS
Total Middle East
Total Africa
Total Asia Pacific
Total World

Exhibit 30 provides a more comprehensive look at the United States data for CO2 emissions over the years from 1990 to 2017. It also shows the annual growth rates. The two most noticeable features are the sharp drop in emissions during the great recession and the overall decline in the years 2011 to 2017 that offsets the increase in earlier years. The final three years from 2015 to 2017 all show a decline in CO2 emissions. Unfortunately, the preliminary 2018 data, which became available in January 2019 as this report was in progress, reversed that trend.[6] In 2018, U.S. emissions rose by 3.4%, one of the largest jumps in the past three decades. Even in the electricity generation sector, which saw a record number of coal fired power plants retired, emissions increased by 1.9% as expanded use of natural gas, more than renewables, was used to replace most of the coal-based generation and to feed the growth in electricity demand associated with the strong economy. The building and industrial sectors also posted big year-on-year emissions gains. In the transportation sector, gasoline demand declined marginally by 0.1% as modest efficiency gains offset a minor increase in miles traveled. But robust growth in demand for both trucking and air travel increased demand for diesel and jet fuel by 3.1% and 3.0%, respectively leading to an overall rise in emissions for the sector. This highlights the challenges in decarbonizing the transportation sector beyond light-duty vehicles. Overall, the preliminary 2018 data underscore the continuing inertia in the use of fossil fuels and the associated emissions. It is worth noting that the step back in 2018 makes it highly unlikely that the United States will reach the Paris Agreement target of a 26-28% reduction in 2005 levels by 2025. To reach that target, the U.S. would need to reduce energy-related CO2 emissions by an average of

[6] See, the Rhodium Group (2019).

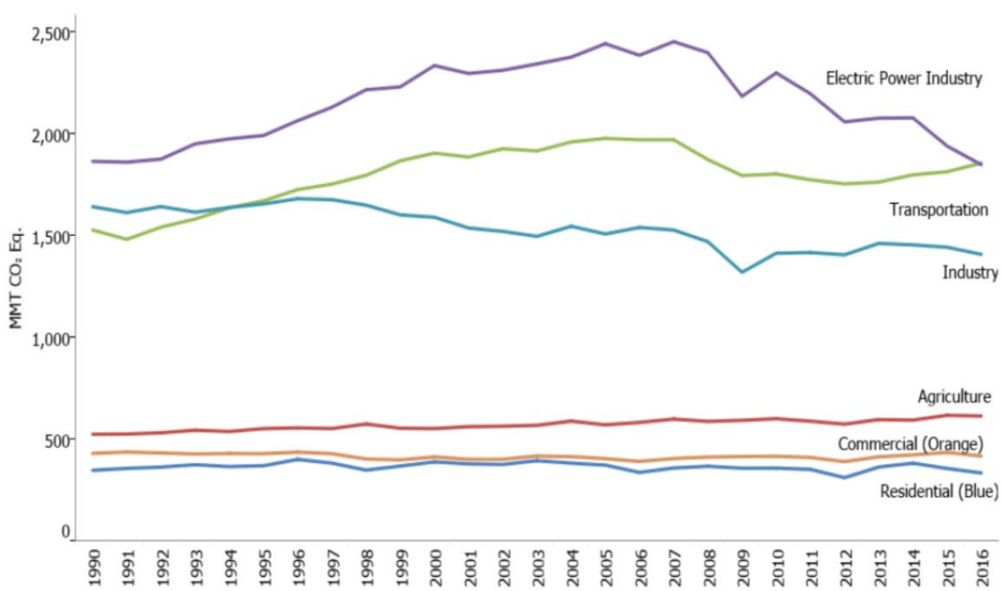
2.6% over the next seven years. That's more than twice the pace the U.S. achieved between 2005 and 2017 and significantly faster than any seven-year average in U.S. history.



Taking a step back, it is useful to see how U.S. emissions break down across the economy. Exhibit 31, copied from the EPA's 2018 report greenhouse gas emissions and sink, plots greenhouse gas emissions by type of economic activity over the years from 1990 to 2017. The exhibit shows that the three major emitting sectors are electric power generation, transportation and industry. The data show the aforementioned decline in emissions from electricity generation, at least prior to the disappointing jump in 2018. There is also a slight drop in emissions from industrial uses, but that is offset in part by the increase in 2018. The emissions in other areas remained largely constant or rose slightly throughout the period. Overall, the exhibit shows the strength of the inertial forces behind the use of fossil fuels and their associated emissions.

Exhibit 31

Figure ES-14: U.S. Greenhouse Gas Emissions Allocated to Economic Sectors (MMT CO_2 Eq.)



The foregoing analysis leads to three fundamental takeaways. The first is size. The world uses an immense amount of energy. As a result, the financing necessary to fund the great transformation will be enormous, easily reaching tens of trillions of current dollars worldwide. Second, the transformation will be intensely political, even in so called free market countries like the United States. As technology continues to advance, access to reliable power will become increasingly critical to citizens around the global. Governments will not be able to avoid becoming intimately involved with key issues such as the pricing of electricity. Third, although the transformation is coming, it is not coming quickly. There is enough inertia and sufficient stocks of fossil fuels to delay the most dramatic change until the second half of the 21st century.

3. Energy and Investing

There are a host of articles and books that examine energy finance. Examples include Bradford (2018), Donovan (2015), Donavan and Li, (2018), Gaddy, Sivaram, Jones and Wayman (2016), McKinsey (2016), and Sivaram (2018).

The argument here is that there has been a failure to explore fully three key aspects of the problem of financing the great transformation that are of central importance for finance. The first is related to the incentive to invest. The second is related to the sheer size of the investment required. The third is related to the role of politics and the importance of asymmetric information.

To see the role these factors play requires a brief review of the finance theory of investing. Finance theory teaches that a "good" investment is one for which the investor's analysis reveals that the value of the investment exceeds the amount invested. To see how it works, consider an example in which an investment company is considering investing $10 million to buy a small start-up in the business of developing perovskite solar cells to compete with silicon. If the investment firm is following finance theory, the firm should first project future cash flows the start-up is expected to produce.[7] Those expected cash flows are then discounted to present value at a discount rate that reflects the risk of the investment.[8] If the present value of the expected cash flows, the value of the investment, exceeds $10 million, the investment is a good one and the investor should proceed. A "home run" investment is one for which the cash flows observed after the fact greatly exceed the original expectations so that the value of the investment rises dramatically. For instance, assume that subsequent to the investment, the perovskite cells are found to perform better than expected and be less expensive to manufacture. The expected cash flows from the business would increase, most likely by a significant factor, and the value would jump accordingly. Note that for the value of the investment to increase by a factor of 10, so must the expected future cash flows. If those cash flows are initially small, such an increase is within the realm of possibility. However, if the initial expected cash flows are on the order of hundreds of billions of dollars, as would be the case for major investment in infrastructure as part of the transition to renewable sources of energy, such increases are not feasible. That is a major reason why the size of an investment limits the potential return. But in the case of investment in energy infrastructure, there is another major reason as well. To understand what it is requires a short detour into electric utility regulation.

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[7] The term expected means the probability weighted average of potential future cash flows.

[8] Risk is generally measured by applying an asset pricing model, such as the capital asset pricing model.

Because electric utilities are assumed to be monopolies due to their control over the grid that distributes electricity, the prices that they charge their customers are regulated. The first step in setting the price is to calculate the rate base, which is basically the amount of capital invested in the operating assets of the utility. In step two, the regulators set the return on the equity to what is determined to be fair compensation for the risk equity holders bear. This rate is typically less than the average return on the overall stock market because regulators generally conclude that equity investments in utility stocks are less risky than the market. In step three, the allowed costs are added up. The word “allowed” is important because regulators may not include all costs as we shall see in a minute. Finally, the price of electricity is set so the utility’s revenues exceed its costs by an amount equal to the allowed rate of return multiplied by the rate base. One downside of this procedure from the standpoint of investors is that utility investments can never be home runs. Future cash flows cannot jump by some large multiple because they are constrained by the regulatory process. This means that investor returns can never be much greater than the regulatory determined fair rate of return.

On the plus side for investors, the regulatory process should yield low risk, stable rate of return for investors. If costs such as fuel rise unexpectedly, for instance, those costs can be passed on to rate payers leaving the cash flow for investors largely unchanged.

The foregoing implies that even in the United States, a country that endorses allocation of resources via markets, the final price of electricity to consumers is determined through a regulatory process. In the years ahead, the move toward renewables will make electricity an even more important product. Unlike fossil fuels, few sources of renewable energy can be used directly. Therefore, the switch to renewables must, by necessity, involve a greatly expanded role for electricity as the premier source of final energy. That will make its price a central issue for people worldwide. As a result, the political importance of electricity will no doubt rise. Given that the price is already highly regulated, if not set outright, by governmental bodies today, it is only reasonable to expect more of the same in years ahead.

This means that the ultimate source of revenue backing investment in the renewable energy space is a product whose price will be set by a political process of undetermined nature. To illustrate the potential problems that might arise consider the recent experience of equity investors in Pacific Gas and Electric (PG&E). In 2017 and 2018, PG&E faced large costs associated with major wildfires in Northern California. Recall that in setting the price of electricity, regulators set a price sufficiently high that revenues exceed *allowed* costs by amount that provides equity investors with a fair return. In the case of the wildfires, it is uncertain whether and to what extent California regulators will permit those costs to be passed on to rate payers in the form of higher electricity prices. Faced with uncertainty and delay in its ability to obtain rate recovery for these anticipated claims costs, the company decided to seek bankruptcy protection. That decision puts at risk PG&E equity investors. As might be expected, there is a raging debate regarding what fire related costs should be borne by PG&E. Some critics argue the company should be responsible for all of them because it acted imprudently. However, even if the PG&E executives acted imprudently, the equity investors did not, and they were the ones who ended up bearing most of the costs.

What the experience of PG&E makes clear is that the risk associated with investing in electric utility stocks is determined more by politics than by market forces. Furthermore, although investors may be fooled once, such as those who invested in PG&E equity, they cannot be fooled repeatedly. Before making similar investments, they will insure that the expected returns are high enough to compensate them for all the investment risk, including the political risks.

Political risks are not limited to those experienced by PG&E equity holders. To date the efforts of many governments, including that of the United States, have engaged in a series of start and stop special programs and subsidies designed to promote the transition to renewable energy. One example is the 30% tax credit the U.S. federal government offers for the installation of rooftop solar panels, which is expected to expire in 2020. Although the subsidy may seem to be a plus for renewable energy, it has a dark side in that it favors the production and installation of silicon panels over other technologies that may prove superior over the long-run such as perovskite. By subsidizing the current technology, government efforts tend to lock in the use of silicon panels. This is politically expedient because voters are aware of solar panels making the program easier to sell to them, but it may be the wrong long-run choice. Government subsidies of electric vehicles could end up playing a similar role. Voters are well aware of electric cars via the public fascination with Tesla, so electric car subsidies are popular with green energy advocates, but this does not mean that they are wise energy policy.

These specific examples are illustrations of a broader problem. The political importance of energy provision makes it subject to start-stop risks as the political winds change. For instance, Schmalensee (2015) reports that the United States steeply ramped up funding for solar energy in response to the oil crisis in the 1970s only to have the funding plunge even more quickly in the 1980s. This start-stop approach adds significant risk for investors in renewable energy. For example, the subsidization of silicon panels led to bankruptcies of many companies attempting to develop competing technologies.

The risks associated with unpredictable government policies are compounded by the fact that politicians have a better idea of what they might do than investors. This leads to an asymmetric information problem of the type articulated by George Akerloff in a paper that served as the basis for his Nobel Prize.[9] Akerloff's basic idea can be illustrated with a simple example. Assume that there are equal numbers of two types of used cars: good ones which have a value of $10,000 and lemons which are worth $5,000. Current car owners know whether the used car they are selling is a lemon, but the buyers do not. At first blush, it may appear that a buyer would be willing to pay $7,500 for a used car on the grounds because he is equally likely to get a good one or a lemon. But that cannot be the market equilibrium, because owners of a good car would reject the offer, whereas the owner of a lemon would accept it. Thus, buyers would end up paying $7,500 for cars worth $5,000. Furthermore, if buyers were offering only $7,500, owners of good cars would start withdrawing from the market. As owners of good cars withdraw, and buyers come to realize the make-up of the market is no longer fifty-fifty, they offer lower prices. Akerlof shows that this problem leads to a quick collapse of the market to a situation in which the only cars available for sale are the lemons at $5,000.

Investors face a similar conundrum when investing in the energy infrastructure required to move the great transformation forward. The returns on their investments ultimately depend on the price at which energy, basically electricity, will be sold to final customers. But that price will be greatly impacted, if not directly determined, by political

[9] The market for lemons: Quality uncertainty and the market mechanism.

entities. This puts investors in a position akin to used car buyers. The value of their investment depends on the decisions of governmental bodies who are encouraging them to invest. But the investors know less about how the government will behave than the government itself.

The risks and the information problems associated with unpredictable policies would not be so serious if the required investment were not so large. However, given that the scale of required investment limits the returns on the upside, investors, like the holders of PG&E equity, are put in a heads I lose, tails I get only a "fair" return situation. The rational response is to withhold investment. But risks associated with unpredictable policy, unlike fundamental risks such as whether the product will work are risks that, at least conceptually, can be avoided. The challenge for financing the great transformation is to overcome the policy risk and asymmetric information problems so that large investors will find renewable energy investments attractive.

The role of a carbon tax

A critical first step is a stable, predictable carbon tax. Such a tax, if properly administered, could both properly reflect the social costs of using carbon-based fuels and provide investors with the incentives they require to invest in renewal energy enterprises. The idea is simple. For the market to function properly, the price of using fossil fuels must reflect *all* the costs, including the environmental and scarcity costs, of using them. To the extent that it does not, there will be inappropriate incentives to overuse fossil fuels. To overcome those incentives, a tax should be levied on the use of carbon-based fuels.

A carbon tax not only constrains excessive use of carbon-based fuels, it also provides an incentive to invest in alternatives. To the extent that the carbon tax raises the prices of fossil fuels, it allows alternatives to charge higher prices as well. This increases the revenues of alternative enterprises without affecting their costs, thereby adding to the estimated value of an investment and increasing the likelihood that it will be undertaken.

As an indication of how widespread the acceptance of a carbon tax is within the economics profession, on January 16, 2019 the 27 living Nobel laureates in economics, along with all four former chairs of the Federal Reserve, 15 former chairmen of the Council of Economic Advisers, and two former Treasury secretaries produced a statement endorsing a carbon tax that was published as an op-ed piece in the *Wall Street Journal*. The economists' statement is attached as Exhibit 32. For current purposes, the statement makes three key points. First, that a carbon tax offers the most efficient way to reduce carbon emissions. Second, that the tax should be predictable in that it increases at a predetermined rate. Third, substituting a price signal for cumbersome regulations will provide the regulatory certainty companies need for long-term investment in clean-energy alternatives.

EX.32 ECONOMISTS' STATEMENT ON CARBON DIVIDENDS

Global climate change is a serious problem calling for immediate national action. Guided by sound economic principles, we are united in the following policy recommendations.

I. A carbon tax offers the most cost-effective lever to reduce carbon emissions at the scale and speed that is necessary. By correcting a well-known market failure, a carbon tax will send a powerful price signal that harnesses the invisible hand of the marketplace to steer economic actors towards a low-carbon future.

II. A carbon tax should increase every year until emissions reductions goals are met and be revenue neutral to avoid debates over the size of government. A consistently rising carbon price will encourage technological innovation and large-scale infrastructure development. It will also accelerate the diffusion of carbon-efficient goods and services.

III. A sufficiently robust and gradually rising carbon tax will replace the need for various carbon regulations that are less efficient. Substituting a price signal for cumbersome regulations will promote economic growth and provide the regulatory certainty companies need for long- term investment in clean-energy alternatives.

IV. To prevent carbon leakage and to protect U.S. competitiveness, a border carbon adjustment system should be established. This system would enhance the competitiveness of American firms that are more energy-efficient than their global competitors. It would also create an incentive for other nations to adopt similar carbon pricing.

V. To maximize the fairness and political viability of a rising carbon tax, all the revenue should be returned directly to U.S. citizens through equal lump-sum rebates. The majority of American families, including the most vulnerable, will benefit financially by receiving more in "carbon dividends" than they pay in increased energy prices.

From the standpoint of energy investing, the predictability of the tax is more important than its precise form. Investors evaluate risks over the entire life of an investment by incorporating the risks into the discount rate. In the case of energy investments, that lifetime can be decades. An on-again, off-again carbon tax, or a tax whose rate keeps changing unpredictably, could be worse than no tax at all. The added risk due to the uncertain tax could offset the incentive benefits associated with the increase in the price of carbon.

As the economists' statement stresses, the carbon tax also has the benefit that it gets the government out of the business of trying to pick the winners in the race to develop renewable technologies. As noted earlier, specific subsidies, such as those for rooftop solar, not only produce added investment risk for competitors, they may counterproductively lock in what proves to be an inferior technology. If the carbon tax is set properly, so that it reflects the full social costs of utilizing carbon fuels, the playing field will be leveled and there will be no need for the government to make added attempts to subsidize certain technologies.

This primary reliance on a carbon tax runs counter to the argument that because of social benefits they provide, small startups involved in clean energy should receive special subsidies.[10] But with a proper carbon tax, there is no reason why such companies could not attract adequate investment. Because most of them are start-ups, they offer the possibility of huge upside returns if their business model and its underlying technology turn out to be a success. There is already an extensive venture capital industry, aided and abetted by hedge

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[10] See, for example, Gaddy, Sivaram, Jones and Wayman (2016).

funds and private equity firms, designed to invest in such companies. If there has been inadequate investment due to the fact that such companies had to compete with the massive fossil-fuel infrastructure in a world in which the consumption of carbon-based fuels was significantly underpriced, that asymmetry would be removed by the carbon tax.

Where a carbon tax is likely to have the most immediate, and perhaps largest impact is on the demand side. In the previous section, I noted that due to increased efficiency aggregate U.S. energy usage had remained approximately constant with gains in efficiency offsetting increasing population and economic growth. But that was with carbon-based fuels being underpriced because they fail to reflect the true social costs. When the price rises to reflect total costs, there are a myriad of ways that efficiency can be increased in industry, residences, transportation and agriculture. These include obvious things like new design for building, more efficient lighting, insulating homes, relocating near to work places, using more efficient devices, and so on virtually ad infinitum. While few of these changes may be large individually, when added across tens of millions of businesses, farms, vehicles, buildings and residences the estimated that the savings could be as large as 25% to 50% of current energy uses. Furthermore, those savings are achievable by relying on the ingenuity of millions of Americans without the need for direct government intervention. In fact, the government does not even need to guess what changes will be made. All the government needs to do is give people the proper incentives, in terms of proper prices for fossil fuels, and get out of the way.

A common criticism of the carbon tax is that it is not politically feasible, but that is probably a short-term concern. Given the current inertia, people of both right and left political persuasions have been able to avoid coming to terms with key facts. In the case of those on the right, it is admitting how large the social costs of continuing to rely on fossil fuels are likely to be. On the left, it is failing to come to terms with the immense costs of the great transformation. For instance, one of the most profligate uses of fossil fuels is air travel. Enthusiasm for green energy tends to dim if one is told that a good start would be to reduce planned air travel by 50% or more. As David MacKay reports it, during an impassioned speech calling for transition to green energy British Prime Minister, Tony Blair, said

> *Unless we act now, not some time distant but now, these consequences, disastrous as they are, will be irreversible. So, there is nothing more serious, more urgent or more demanding of leadership.*

Two months later, responding to the suggestion that he should show leadership by not flying to Barbados for holidays, Mr. Blair stated,

> *a bit impractical actually. . .* [11]

Hopefully, this will all pass. The carbon tax is a key step in establishing the proper environment for energy investing.

Financing large scale projects

Even a well-designed carbon tax leaves unresolved the second issue regarding the financing of large-scale projects such as the reconstruction and expansion of much of the electric grid and the provision of large-scale electrical storage. As stressed previously, size alone limits the returns that can be expected from major renewable investments. But more importantly, the investment returns will ultimately depend on the price of electricity. Given that electricity generated from renewables will become the primary source of energy as the great transformation proceeds, its price will be of critical importance for consumers

[11] MacKay (2009), page 222.

worldwide. As a result, the price of electricity will be a continuing front and center political issue. Few governments are likely to be willing to contemplate electricity prices that provide for returns to investors much above the risk-free rate of interest. Furthermore, once funds are committed, government agencies have an incentive to act opportunistically on behalf of consumers because there are more votes among consumers than investors. The result is the risk of continued variation in policies that affect the price of electricity and, thereby, the investment performance of securities whose values depend on that price. To make the relatively low returns that massive infrastructure investments will offer palpable to investors, the risk associated with variable government policies must be eliminated. The only practical way to assure that is with a carefully crafted government guarantees, not on the limited scale provided by some development banks today, but on a scale running into the tens of trillions of dollars.

Some may argue that such guarantees are not necessary. For instance, the wholesale market for renewable power appears to be relatively free of government interference. Electric utilities, whose primary assets are distribution systems, bid for power sold by renewable generators and then pass that cost on to final consumers as part of the state regulatory process described earlier. This makes is seem as if the market determines the wholesale price of renewably generated electricity. But dig deeper and you find that is not the case. Investment in renewable generation has been supported by a variety of ever-changing subsidies. A study by the University of Texas projected that in 2019 U.S. energy subsidies per megawatt hour would be in the range of $15 to $57 for wind and $43 to $320 for solar. Based on these prices, the wind production subsidy covers 30% to 60% of wholesale electricity price. Furthermore, the utilities are often required to purchase minimum specified amounts of renewably generated electricity. The point here is not to debate the specifics of the subsidies or the purchase requirements, but to highlight the even today government bodies are deeply involved in most every aspect of the provision and pricing of electricity. As the great transformation proceeds, it is hard to imagine that such involvement will not increase.

Assuming that government guarantees will be required, they could be fashioned in a manner similar to the guarantees offered by the Government National Mortgage Association (or Ginnie Mae). Ginnie Mae guarantees securities created by approved issuers and backed by mortgages covered by other federal programs. The Ginnie Mae guarantee ensures that investors in those securities do not experience any disruption of the timely payment of principal and interest, thus shielding them from losses resulting from borrower defaults. As a result, the securities appeal to a wide range of investors and trade at a price like that of U.S. government bonds of comparable maturity. The Ginnie Mae program has been immensely successful and there is currently over $2.1 trillion in principal outstanding. As large as this sounds, the renewable program would have to be an order of magnitude larger. Designing and implementing such a program will be a key step in planning for the great transformation.

The guarantees need not be a threat to the federal budget. The reason once again is the price of electricity. Analogous to state utility regulation, the price can be set at the minimum level sufficient to ensure that payments on the outstanding securities can be made. In this fashion, the guarantees also provide protection against after-the-fact political efforts to manipulate the price of electricity.

The great transformation is also likely to require that energy regulation be national. The movement to renewable dominated electricity will necessitate, at a minimum, a more effective national grid to cope with intermittency. It remains possible that the generation business will remain market based if there are a sufficient number of competing generators, but even that is in doubt. With every aspect of life becoming increasingly dependent on renewably generated electricity as the great transformation proceeds, it is hard to imagine that even in market-oriented economies like the United States government will not play a pivotal role at every step in the provisioned and pricing of electricity. In many other countries, with China being the most prominent example, a central role of the government is taken as given. The Chinese system of centralized control solves many of the problems analyzed above. If the same central government both sets the price of electricity and controls the flow of funds used to finance the great transformation, then the asymmetric information problem is eliminated. In addition, without the need to face elections, Chinese leaders can sweep aside many of the bureaucratic and political roadblocks that slow the transformation in democratic societies, particularly if they are as divided as the United States is currently. Such a centralized control system does run the risk of making the wrong technological choices. Without the push and pull of market forces, it is easy to get started down a path and then fail to correct as knowledge advances and conditions change. The failure of Soviet planning to properly allocate resources is a prime example. Nonetheless, as the need to transform energy infrastructure becomes more pressing, countries around the world will no doubt compare the relative success of the United States and China to see which form of organization is more successful in coping with a problem as large and important as the great energy transformation. In this regard, the great transformation could well play a significant role in determining the predominant form of government throughout the world at the end of the 21st century. The way we use energy has already revolutionized human civilization once, there is no reason it could not happen again.

Finally, the fact that the great transformation will require a massive program of capital expenditure does not mean that it is a "bad" investment. As noted earlier, an investment must be analyzed by comparing the present value of the costs with the present value of the benefits. In this report, no effort has been made to estimate the benefits. The critical variable in that regard is the damage associated with continued global warming associated with the use of carbon-based fuels, a subject about which there is considerable debate. Without wading too far into an area in which I am not expert, the accumulating evidence suggests that the damages are enough to warrant the investment required for the great transformation, particularly in light of the fact that the transformation must occur in any event as scarcity starts to bind. Room (2018) provides an excellent, non-technical, discussion of the costs and risks of continued global warming. More technical discussions are offered by Nordhaus (2017b) and Nordhaus and Moffat (2017) as well as a host of publications available through the IPCC website (www.ipcc.ch).

4. Conclusion

If something can't go on forever, it will stop. And the use of fossil fuels which has played such a critical role in economic development and social organization since the start of the industrial revolution cannot go on forever. Even putting aside climate change, humanity has been running through a billion-year stock of fossil fuels at a rapid rate. Despite all the publicity given to green energy projects, the inertia behind the use of fossil fuels has continued largely unabated. Driven by a combination of population and economic growth, a huge infrastructure supporting their use, and political roadblocks to rapid change, the use of fossil fuels is widely projected to continue to grow through 2050. In the second half of the 21st century, the great transformation to reliance on renewable sources of energy, primarily via the generation of electricity, will have to begin in earnest. It will entail what may well be the largest capital spending program in human history. Here I have argued that the financing of such a program, if it is to be done outside of direct government control, requires two components. First, a long-term, predictable, carbon tax must be put in place as soon as possible to reflect the social cost of using carbon-based fuels and to provide the proper incentives to invest in alternatives. The predictability must also extend over the long-term given the long life of most energy investments. Any policy uncertainty increases the risk adjusted discount rate investors use to evaluate investments and, thereby, discourages investment.

Currently such a tax is considered to be politically infeasible, at least in the United States. Those on the right oppose it because they do not think it is necessary. Those on the left oppose it because they underestimate the cost of the great transformation and the importance of incentives. Both sides are wrong. Presumably that will become clear as fossil fuel scarcity increases, environmental damage accumulates, and costs come due. Both political parties will have to learn that nature does not negotiate.

Second, the size of the required investment and the importance of the ultimate product to people worldwide – namely electricity to power society – has two implications. The first is that electricity will be of such political importance that its price will be tightly regulated, if not controlled directly, by governments. The fact is that there are many more electricity consumers who are voters than there are investors. There will be immense political pressure to keep electricity prices at “fair” levels which means lower returns for investors. The problem is compounded once funds are committed, because governments then have an incentive to behave opportunistically. For low returns to be acceptable to investors, investment risk – including the risk of opportunistic behavior by the government – must be kept to a minimum. The only feasible way to accomplish that is with government guarantees on a grand scale, an order of magnitude higher than the government guarantees of mortgage securities today.

Given that inertia is going to delay the bulk of the great transformation to years beyond 2050, there is time to design the financial structure that will be necessary to fund what may well be the largest capital project in human history. But inertia extends to the financial markets as well. It is time to start preparing for the immense financial requirements of the great transformation.

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