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The Basic Arithmetic of the Global Energy Transition

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Abstract

The point of this short paper is to argue that any discussion of energy and climate policy should begin with a clear presentation of the basic arithmetic of energy transition. The basic arithmetic highlights the fact that the numbers must add up – projected energy consumption must equal future energy production. In that regard, this paper has a simple objective – to lay the basic arithmetic of a transition of the world's energy economy to one more based on renewables. Analysis of a few simple scenarios illustrates the importance of starting policy analysis with the basic arithmetic.

Introduction

The goal of the energy sector of the economy is to provide reliable, affordable power to support the lifestyles of citizens and to provide for economic productivity and growth without causing undo environmental damage. As society becomes more complex, integrated, and reliant on technology, the importance of reliable power grows. However, simultaneously concerns have arisen regarding the external social costs of energy consumption, particularly the climate related effects associated with the release of greenhouse gases. This has led to a variety of proposed objectives such as "net zero carbon" or "carbon neutrality" designed to transition energy provision and consumption so that it is less environmentally damaging. The point of this short paper is to argue that the starting point for any policy discussion should be a clear presentation of the basic arithmetic of energy transition. The basic arithmetic highlights the fact that the numbers must add up – projected energy consumption must equal future energy production. Nature does not negotiate, and she cannot be cajoled. She has her laws, one of which is the conservation of energy. The only decision left to us is how we choose to obey them. Making that choice wisely begins with an understanding of the basic arithmetic of any proposed energy transition.

In that regard, this paper has a simple objective – to lay the basic arithmetic of a transition of the world's energy economy to one more based on renewables. As such, it includes four sections. The first describes where we are now in terms of energy consumption and how we got there. The second calculates how much added energy the world economy is likely to consume by 2050. It also provides several scenarios regarding the way that consumption could be satisfied. These scenarios are meant to be illustrative. Predicting what the breakdown of primary energy sources will be in 2050 is beyond the scope of this report.

For those who are interested, there are numerous entities such as the Energy Information Administration (EAI), the Intergovernmental Panel on Climate Change (IPCC), Exxon, and McKinsey that provide detailed long-term projections. Section three offers some observations on the scenarios and concludes the global analysis. To add perspective, section four repeats all the calculations for the United States.

For simplicity, the calculations in this paper are done at the gross level. There are no adjustments for conversion losses or for the fact that there is a gap between the gross energy consumed and the useful work performed. For example, to generate 100 kwh of electricity requires roughly 250 kwh hours of energy stored natural gas. Renewables avoid these conversion loses but have a different drawback. For renewables, average generation at the rate of 100 kw requires capacity in excess of 300 kw and a storage system because much of the time the wind does not blow, and the sun does not shine. There are other similar issues throughout the energy economy. As one more example, it takes almost 400 kwh of energy in the form of gasoline to produce 100 kwh hours of kinetic energy for an automobile. Electrical energy is much more efficient that way because only about 130 kwh hours is required to produce the 100 kwh hours of kinetic energy. However, the electricity must be generated from some other primary source. In general, energy flow charts such as those produced by Lawrence Livermore (2020) show that about two-thirds of primary energy is lost to wasted energy and only one-third is converted into useful work.

Where we are now (the end of 2019) and how we got there

Exhibit 1 plots the world's consumption of primary energy of all types, measured in trillions of kilowatt hours, from 1965 through 2019. The data are taken from British Petroleum's (2020) *Statistical Review of World Energy* and converted to kilowatt hours. The kilowatt hour is used as a measure of energy because it is familiar. It is not meant to imply a reference to electrical energy. By definition, none of the primary energy in Exhibit 1 is electrical because electricity is derived from other primary sources. The exhibit shows that over the fifty-four-year period primary energy consumption increased by nearly a factor of four, rising from 43.25 trillion kilowatt hours in 1965 to 162.19 trillion kilowatt hours in 2019. This represents a compound growth rate of 2.48% per year.

Over the same time frame, the World Bank (2020) reports that world population grew from 3.32 billion to 7.67 billion, a growth rate 1.56% per year. Putting the two pieces together, primary energy consumption per capita was 13,010 kilowatt hours in 1965 and rose to 21,140 kilowatt hours by 2020, a growth rate of 0.90%. The numbers show that about two-thirds of the growth in primary energy consumption was due to increased population. The other one-third represents the net effect of two competing forces. On the one hand, growth in real GDP per capita led to increased energy consumption, while on the other hand improved energy efficiency reduced consumption. The net growth 0.90% per year reflects the fact expanding GDP outweighed improving efficiency during the fifty-four-year period. These data are summarized in a waterfall chart in Exhibit 2. In the exhibit, the compounding term is equally divided between population growth and per capita increase in energy consumption. The waterfall also projects the continued growth in energy consumption through 2050. Those projections are discussed below.

Exhibit 3 breaks down total 2019 consumption of primary energy by fuel type. The exhibit clearly shows the continued reliance on fossil fuels which accounted for 84.3% of the primary energy consumed in 2019. Renewables, although growing rapidly, accounted for only 5.0% of the total. Renewables were constrained by the fact that they cannot be consumed directly. You cannot put sun in your car or cook your dinner with wind. Most all renewable energy must be intermediated by using it to produce electricity. This means that for renewables to become a predominant source of primary energy many industrial, residential and transportation activities must first be electrified.

Although wind and solar are by far the largest and the most rapidly growing renewables, British Petroleum also includes geothermal, biofuels and biomass in their definition of renewables. It is worth noting that although biofuels are renewable, they add to carbon emissions. In addition, they require a great deal of land to produce a relatively limited amount of fuel. Biomass is also defined as renewable, but from an emissions standpoint it is the dirtiest source of energy. As regards the future, it is assumed that future growth in renewables will be exclusively wind and solar. Alternatives such as geothermal are limited in scope and wood and biomass should decline over time.

Where we will have to go by 2050 – three scenarios

With so many governments laying out energy plans for 2050 that date is used as the end point for the analysis here. The first question to answer is what will primary energy consumption be in 2050? The second is what will be the sources of that energy? As in years past, future energy consumption growth from current levels will depend on the same three basic factors; population growth, growth in real GDP per capita, and increasing energy efficiency. Following Exhibit 2, Exhibit 4 combines the final two factors into per capita growth of primary energy consumption. To project future primary energy consumption, Exhibit 4 makes two assumptions. The first is that population grows at a rate such that global population in 2050 will be 9.7 billion. The 9.7 billion figure is based on the most recent population projection produced by the United Nations. The implied growth rate of 0.67% is significantly less than the growth rate of 1.56% during the years from 1965 to 2019. This slowing growth rate meaningfully reduces the need to provide future energy. The second assumption is that the growth rate in per capita energy demand will remain at its historical average of 0.90%. This assumption hides a lot of complexity because population growth and economic development are intertwined. Rather than delve into that subject, the historical number is used. The reader is free to alter this assumption.

Using the two assumptions, Exhibit 4 shows that by the end of 2050 total global primary energy consumption will have increased to 270.97 trillion kilowatt hours. This growth is also depicted in the waterfall chart shown in Exhibit 2. The question that remains is what will be the source of those 270.97 trillion kilowatt hours? Here, three simple scenarios are developed for illustrative purposes. All three scenarios are presented in Exhibit 5.

In scenario 1, all future growth in energy consumption comes from renewables. The other sources of primary energy are held constant at their 2019 levels. Hydro, which should be considered a renewable but has its own category, is held constant because it is assumed there are few remaining opportunities for growth. As shown in the exhibit, this requires that consumption of renewables rises 1,351% from its 2019 level to become 43.1% of total primary energy consumption.

Scenario 2 eliminates the use of coal. Other than coal, all other sources of primary energy, except for renewables, are again held constant at their 2019 level. The entire shortfall is made up by additional consumption of renewables. The elimination of coal means that renewables must rise 1,896% from their 2019 level to become 59.3% of total primary energy consumption.

Scenario 3 goes one step further and assumes that like coal, nuclear power will be phased out by 2050. With no coal or nuclear the required increase in renewables jumps to 1,982% and renewables are 61.9% of global primary energy consumption by the end of 2050.

The most notable feature of the scenarios is the dramatic required growth in renewable production. The basic arithmetic makes it clear that energy transitions of the type contemplated in the scenarios will require a major restructuring of the energy sector.

Comments on the scenarios and conclusion

The scenarios are a useful tool for calculating how much renewable energy will be required under different circumstances, but they offer no details about how that energy will be provided. Starting with scenario 1 in which renewables are only required to provide for future primary consumption growth, it is clear that the transition envisioned by the scenario will necessitate fundamental changes in the way in which energy is produced and consumed. For the provision of renewable energy to grow 1,351% to 43.1% of total primary energy without sacrificing reliability, the following will be necessary at a minimum. One, the transition will require major expansions of electric grids worldwide in terms of scope, scale, and intelligence. Two, increased reliance on renewables will require electrification of many industrial, office, residential, and transportation activities that now rely on fossil fuels. To illustrate, Exhibit 6 presents data on worldwide electricity generation in 2019 broken down by fuel type. The total amount of electrical energy generated in 2019 was only 27.00 trillion kilowatt hours, compared to total consumption of 162.19 trillion kilowatt hours.[1] Clearly, many activities that do not currently rely on electricity would have to be electrified. In

[1] Part of the discrepancy can be explained by the fact that a significant fraction of the primary energy is lost to heat in the generation of electricity.

addition, to meet the requirements of scenario 1 fossil fuels would have to be largely eliminated as sources of electricity to allow for growth in other areas, such as air travel, where fossil fuels cannot be replaced. Such electrification could possibly be intermediated by green hydrogen, but that involves using electricity to produce the hydrogen. Three, a massive expansion of storage will be necessary to insure sufficient reliability of electrical supply. With regard to storage, the basic arithmetic presented here does not consider another fundamental adding up constraint which states that supply and demand for electricity must be equated in real time. Without sufficient storage this becomes a major problem as renewables, which are inherently intermittent, account for a larger fraction of electricity generation. Four, there will have to be agreement for sharing the burden of the transition between developed countries, who have benefitted from two centuries of fossil fuel use and developing countries. Meeting these requirements is going to be immensely expensive - running into tens of trillions of dollars globally. As Cornell and Cicchetti (2020) observe, financing such a fundamental energy transition will be a major challenge requiring new combinations of public and private capital.

As one moves from scenario 1 to scenario 2 or scenario 3, the scope of the required transformation and the associated costs rise accordingly. Scenario 3 raises the question of whether it makes sense to phase out nuclear. Rather than being eliminated, the basic arithmetic suggests that it would be helpful if nuclear power grew pro rata with other non-emitting renewable energy sources. That would be a step toward solving the intermittency problem and reduce the massive land and infrastructure requirements associated with ramping up renewable production. However, detailed analysis of such alternative is beyond the scope of this short paper.

In closing, there is nothing special about the three scenarios presented here, there are a host of alternatives. However, whatever scenarios are considered, the basic arithmetic still applies. Whenever an energy policy is proposed, the starting point should be to show how it comports with the basic arithmetic. This will make it much more transparent to analyze the costs and benefits of the proposed policy and to examine the energy production and consumption tradeoffs it involves.

The basic arithmetic for the United States

The interpretation of the basic arithmetic when applied to global data is made more difficult by the fact that it aggregates results across countries with markedly different energy usage. To provide additional perspective on the application of the basic arithmetic, the calculations are duplicated in Exhibits 7 to 12 using data for the United States.

Comparing Exhibit 7 for the U.S. with Exhibit 1 shows that primary energy consumption in America grew more slowly than worldwide. In fact, since 2001 energy consumption has been largely flat in the U.S. This is a reflection of three factors. First, in 1965 the U.S. was already developed and had built a large fossil fuel based economy. For instance, in 2019 per capita primary energy consumption in the U.S. was 80,100 kilowatt hours compared to the global average of 21,140. Second, U.S. population and economic growth were slower than the world average. Third, over the years from 1965 to 2019, the U.S. economy migrated toward services and technology with more energy intensive manufacturing moving overseas. Despite these differences, the sources of primary energy in the U.S. were similar to those worldwide. In particular, Exhibit 9 shows that fossil fuels provided 83.3% of the U.S. primary energy in 2019 compared to a figure of 84.3% worldwide.

To project U.S. energy consumption in 2050, it is assumed that U.S. population growth continues at the average historical rate, but that per capita energy consumption growth drops to zero. These assumptions are reflected in the waterfall graph in Exhibit 8 and in the future consumption table in Exhibit 10. They show a much slower growth in future energy consumption in the U.S. than worldwide. This makes it easier for the U.S. to transition to renewables.

The three scenarios are shown in Exhibit 11. In each scenario, the required growth rate in renewables is high, but much less than that needed globally. Looking at Exhibit 12 which presents U.S. electricity generation by fuel type shows that much of the transition could be achieved by moving most U.S. electricity generation to renewables. This would allow the U.S. to meet the goals assumed in the scenarios while allowing for growth in those activities such as air travel that are likely to remain fossil fuel based through 2050. One other thing stands out with regard to U.S. electricity generation. Exhibit 12 shows that in 2019 nuclear accounted for 19.4%. If nuclear were to grow along with total energy consumption it would provide a big boost toward meeting the scenario requirements while simultaneously producing non-intermittent power.

References

British Petroleum, 2020, *Statistical Review of World Energy*, 69th edition.

Cornell, Bradford and Charles Cicchetti, 2020, Financing a sustainable energy transition, https://papers.ssrn.com/sol3/papers.cfm?abstract_id=3676703.

Lawrence Livermore Laboratory, 2020, Estimated U.S. energy consumption in 2019, https://flowcharts.llnl.gov/content/assets/images/charts/Energy/Energy_2019_United-States.png.

United Nations, 2019, *World Population Prospects*, 2019, https://population.un.org/wpp/.

World Bank, 2020, *World Bank Population Data*, https://data.worldbank.org/indicator/SP.POP.TOTL.

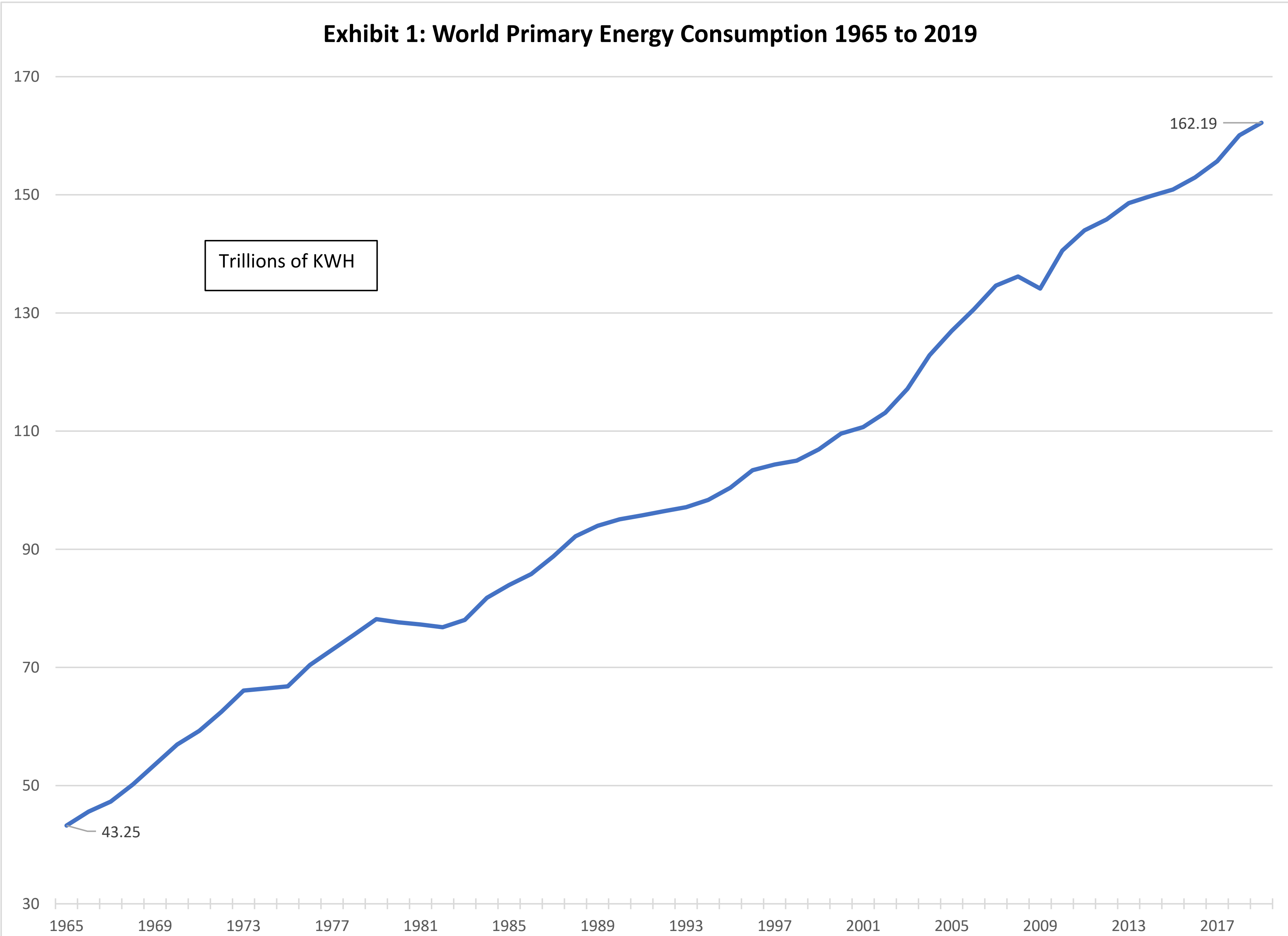
Exhibit 1: World Primary Energy Consumption 1965 to 2019
Trillions of KWH
162.19
43.25
170
150
130
110
90
70
50
30
1965
1969
1973
1977
1981
1985
1989
1993
1997
2001
2005
2009
2013
2017

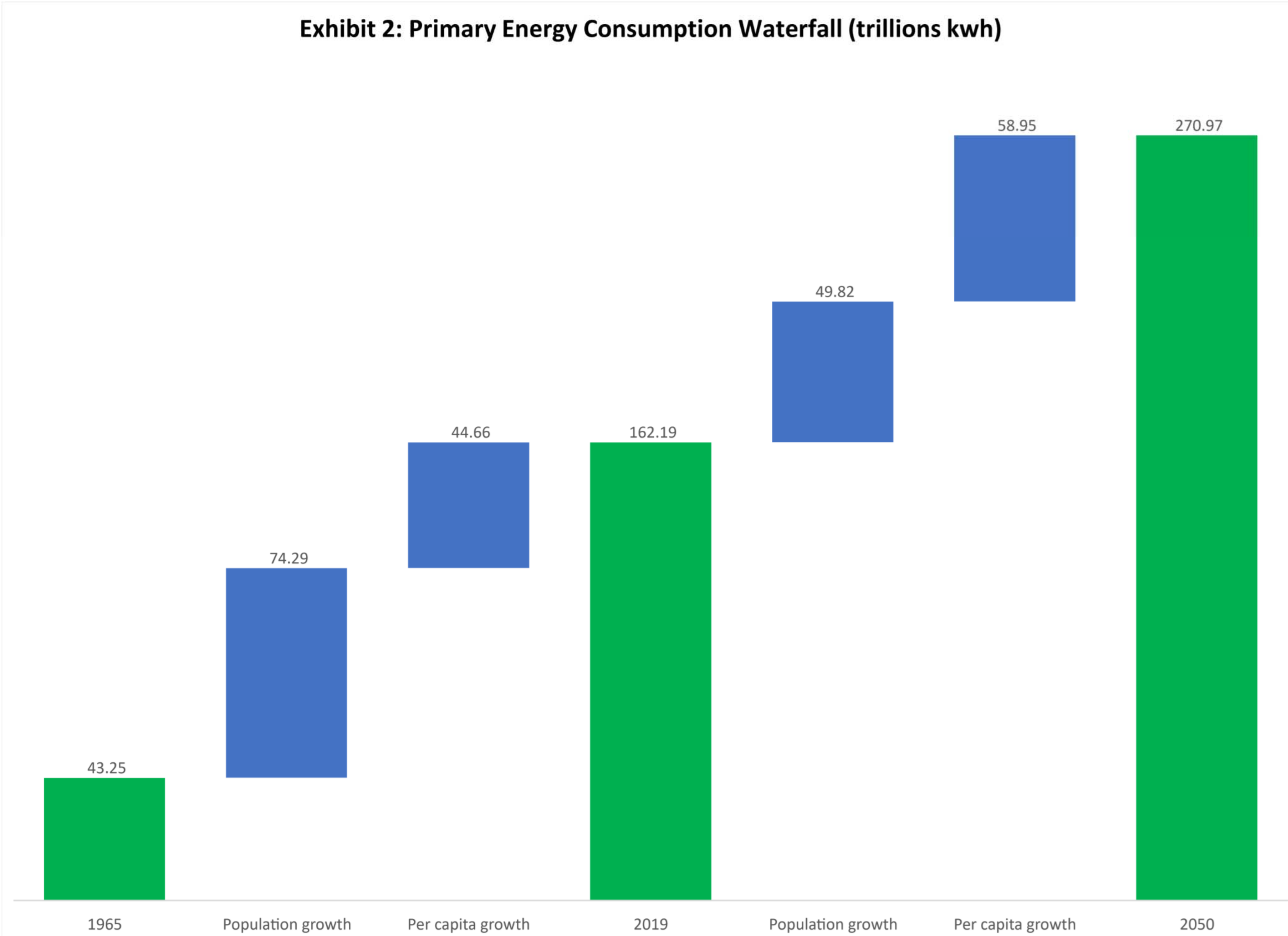
Exhibit 2: Primary Energy Consumption Waterfall (trillions kwh)
43.25
74.29
44.66
162.19
49.82
58.95
270.97
1965
Population growth
Per capita growth
2019
Population growth
Per capita growth
2050

Exhibit 3: Current Primary Energy Sources

Source	Trillions of KWH	Percentage
Oil	53.62	33.1%
Gas	39.29	24.2%
Coal	43.85	27.0%
Nuclear	6.92	4.3%
Hydro	10.46	6.4%
Renewables	8.05	5.0%
Total	162.19	100.0%
Total fossil fuels	136.76	84.3%

Exhibit 4: 2050 Consumption of Primary Energy

Population Growth Rate to 2050 (based on UN projection)	0.76%
Per Capita Consumption Growth to 2050 (based on historical average)	0.90%
Primary Energy Growth up through 2050	1.67%
2019 Primary Energy Consumption (trilion KWH)	162.19
2050 Primary Energy Consumption (trilion KWH)	**270.97**

Exhibit 5: Future Scenarios

		Scenario 1: All growth renewable			Scenario 2: Scenario 1 + No coal			Scenario 3: Scenario 2 + No nuclear		
Source	Current	Trillions KWH	Percentage	% Growth	Trillions KWH	Percentage	% Growth	Trillions KWH	Percentage	% Growth
Oil	53.62	53.62	19.8%	0.0%	53.62	19.8%	0.0%	53.62	19.8%	0.0%
Gas	39.29	39.29	14.5%	0.0%	39.29	14.5%	0.0%	39.29	14.5%	0.0%
Coal	43.85	43.85	16.2%	0.0%	-	0.0%	-100.0%	-	0.0%	-100.0%
Nuclear	6.92	6.92	2.6%	0.0%	6.92	2.6%	0.0%	-	0.0%	-100.0%
Hydro	10.46	10.46	3.9%	0.0%	10.46	3.9%	0.0%	10.46	3.9%	0.0%
Renewables	**8.05**	**116.82**	**43.1%**	**1351.2%**	**160.67**	**59.3%**	**1895.9%**	**167.59**	**61.9%**	**1981.9%**
Total	162.19	270.97	100.0%	67.1%	270.97	100.0%	67.1%	270.97	100.0%	67.1%

Exhibit 6: Soureces of Electricity Generation 2019

Source	Trillions of KWH	Percentage
Oil	0.83	3.1%
Gas	6.30	23.3%
Coal	9.82	36.4%
Nuclear	2.80	10.4%
Hydro	4.22	15.6%
Renewables	2.81	10.4%
Other (residual)	0.23	0.9%
Total	27.00	100.0%
Total fossil fuels	16.95	62.8%

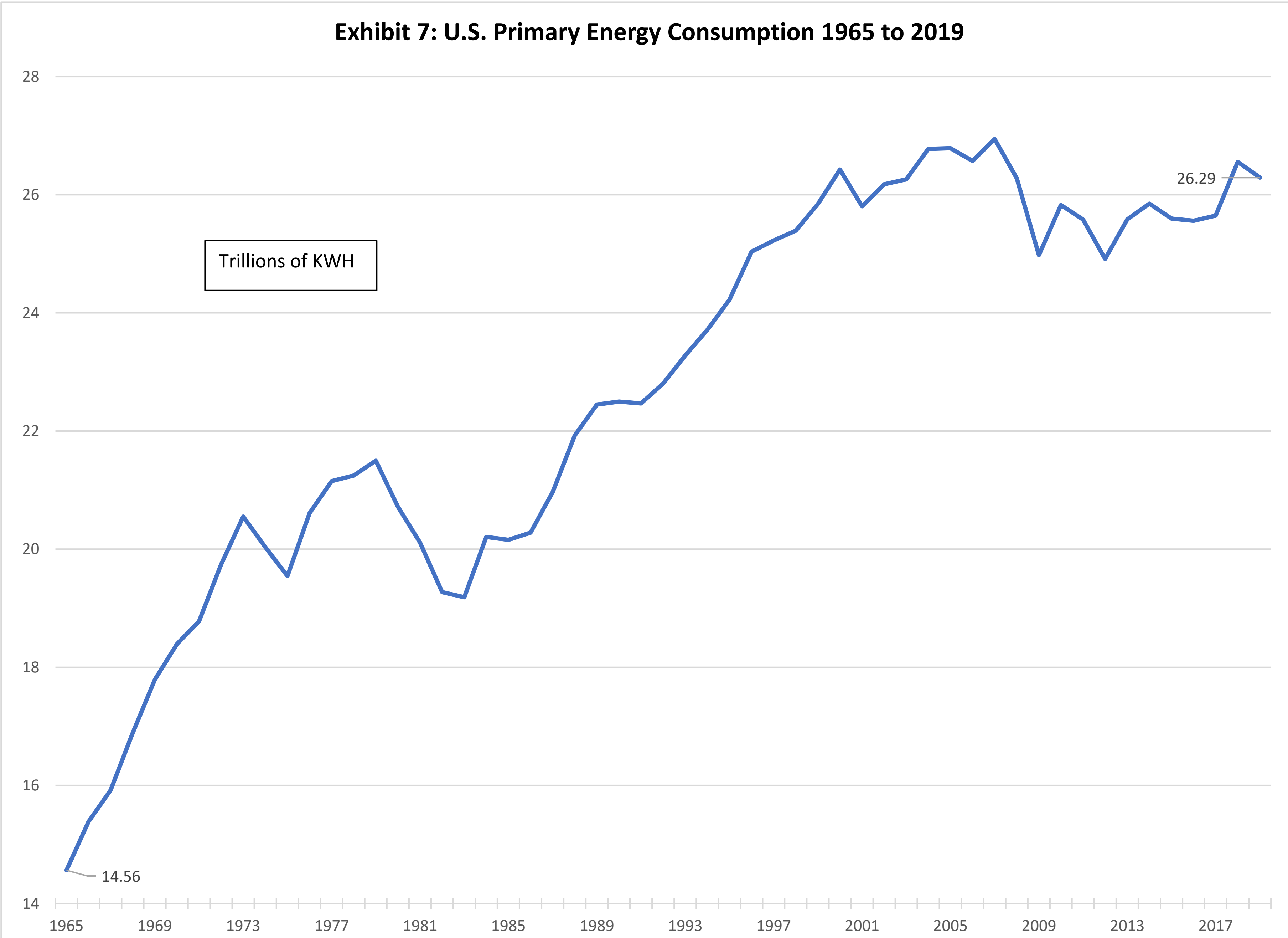
Exhibit 7: U.S. Primary Energy Consumption 1965 to 2019
Trillions of KWH
28
26
24
22
20
18
16
14
14.56
26.29
1965
1969
1973
1977
1981
1985
1989
1993
1997
2001
2005
2009
2013
2017

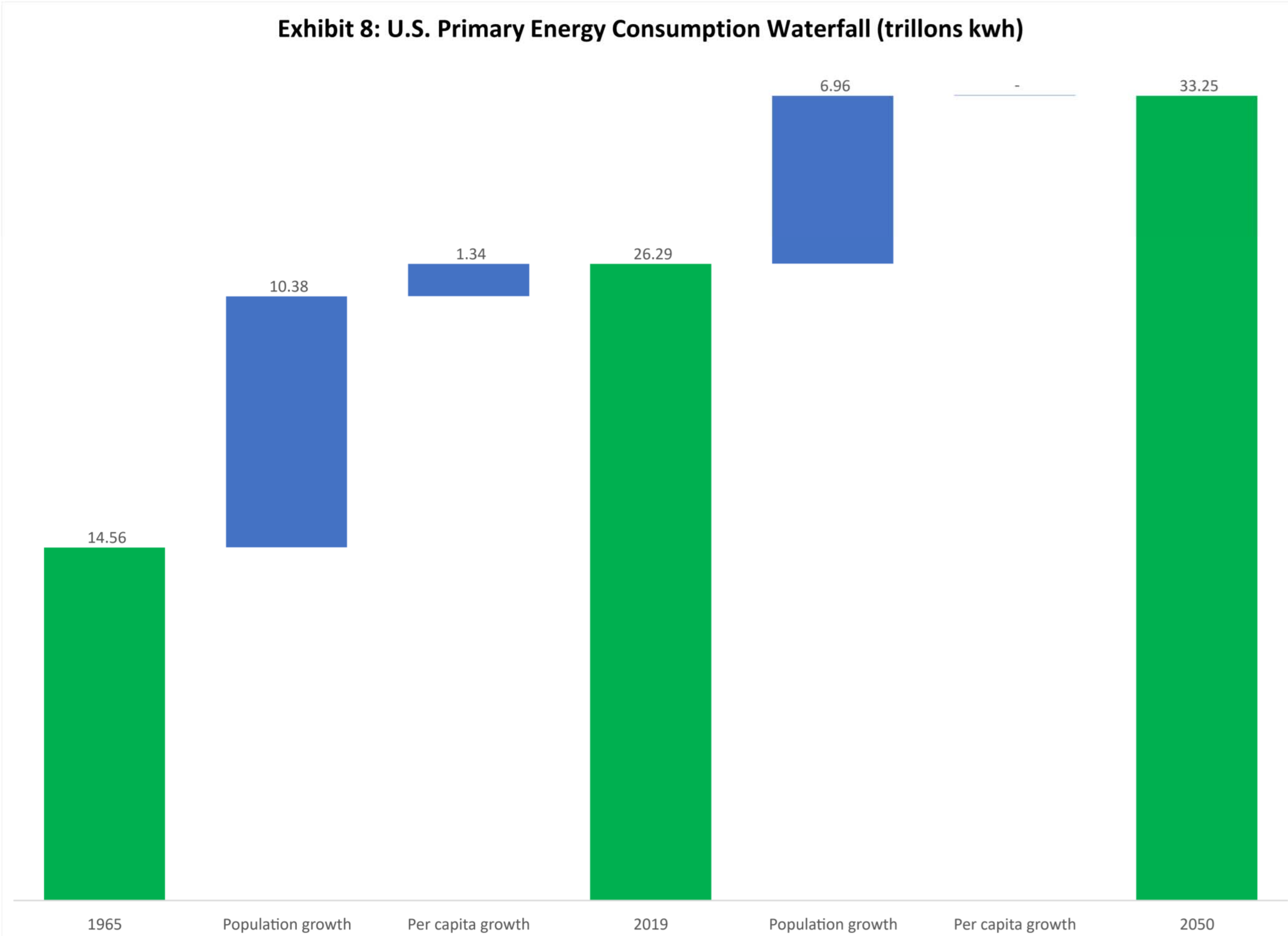
Exhibit 8: U.S. Primary Energy Consumption Waterfall (trillons kwh)
14.56
10.38
1.34
26.29
6.96
-
33.25
1965
Population growth
Per capita growth
2019
Population growth
Per capita growth
2050

Exhibit 9: US Current Primary Energy Sources

Source	Trillions of KWH	Percentage
Oil	10.28	39.1%
Gas	8.47	32.2%
Coal	3.15	12.0%
Nuclear	2.11	8.0%
Hydro	0.67	2.6%
Renewables	1.62	6.2%
Total	26.29	100.0%
Total fossil fuels	21.89	83.3%

Exhibit 10: 2050 US Consumption of Primary Energy

Population Growth Rate to 2050 (based on UN projection)	0.76%
Per Capita Consumption Growth to 2050 (judgemental entry)	0.00%
Primary Energy Growth up through 2050	0.76%
2019 Primary Energy Consumption (trilion KWH)	26.29
2050 Primary Energy Consumption (trilion KWH)	**33.25**

Exhibit 11: US Future Scenarios

Source	Current	Scenario 1: All growth renewable			Scenario 2: Scenario 1 + No coal			Scenario 3: Scenario 2 + No nuclear		
		Trillions KWH	Percentage	% Growth	Trillions KWH	Percentage	% Growth	Trillions KWH	Percentage	% Growth
Oil	10.28	10.28	30.9%	0.0%	10.28	30.9%	0.0%	10.28	30.9%	0.0%
Gas	8.47	8.47	25.5%	0.0%	8.47	25.5%	0.0%	8.47	25.5%	0.0%
Coal	3.15	3.15	9.5%	0.0%	-	0.0%	-100.0%	-	0.0%	-100.0%
Nuclear	2.11	2.11	6.3%	0.0%	2.11	6.3%	0.0%	-	0.0%	-100.0%
Hydro	0.67	0.67	2.0%	0.0%	0.67	2.0%	0.0%	0.67	2.0%	0.0%
Renewables	1.62	**8.57**	**25.8%**	**429.5%**	**11.72**	**35.3%**	**624.0%**	**13.84**	**41.6%**	**754.4%**
Total	26.29	33.25	100.0%	26.5%	33.25	100.0%	26.5%	33.25	100.0%	26.5%

Exhibit 12: Soureces of Electricity Generation 2019

Source	Trillions of KWH	Percentage
Oil	0.020	0.5%
Gas	1.700	38.6%
Coal	1.054	23.9%
Nuclear	0.852	19.4%
Hydro	0.271	6.2%
Renewables	0.490	11.1%
Other (residual)	0.014	0.3%
Total	4.401	100.0%
Total fossil fuels	2.774	63.0%