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The Mass Flux of Non-renewable Energy for Humanity

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The Mass Flux of Non-renewable Energy for Humanity

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Abstract

The global energy supply relies on non-renewable energy sources, coal, crude oil, and natural gas, along with nuclear power from uranium and these finite resources are located within the upper few kilometers of the Earth's crust. The total quantity of non-renewable energy resources consumed relative to the total quantity available is an essential question facing humanity. Analyses of energy consumption was conducted for the period 1800 – 2014 using data from the *U. S. Energy Information Administration (EIA)* and *World Energy Production, 1800-1985* to determine the balance between non-renewable energy resources consumed and ultimately recoverable reserves. Annual energy consumption was plotted for each non-renewable resource followed by analyses to determine annual growth rates of consumption. Results indicated total energy consumption grew approximately exponentially 3.6% per year from 1800 – 1975 and was linear from 1975 – 2014.

The ultimately recoverable reserves (URR) plus the total quantity consumed to date equals the total energy resource reserve prior to exploitation (7.15 x 10^{18} grams). Knowing the original resource quantity and the annual consumption and growth rates, we can forecast the duration of remaining resources using different scenarios. Alternatively, we can use population growth models and consumption trends to determine the per capita allocation trends and model that into the future. Alternative modeling of future resource allocation on a per capita bases suggests that resource lifetime may be significantly less than that predicted from consumption and production dynamics alone.

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List of Abbreviations

BP	British Petroleum
BTU	British Thermal Unit
C	Celsius
EIA	U. S. Energy Information Administration
g	grams
g/mol	grams per mole
IAEA	International Atomic Energy Association
J	Joule
K	Kelvin
m^3	Cubic meters
mol	moles
n	number of moles
OPEC	The Organization of the Petroleum Exporting Countries
P	Pressure
Pa	Pascal
R	Universal Gas Constant
T	Temperature
URR	Ultimately Recoverable Reserves
V	Volume

I. Introduction

Energy sources are either non-renewable or renewable. Non-renewable sources are considered so since their regeneration time maybe hundreds of thousands to many millions of years. Renewable energy sources, on the other hand, are the energy sources which can be replenished quickly such as solar or wind. Humanity relies on four major non-renewable energy sources: (1) coal, (2) crude oil, (3) natural gas, and (4) uranium. Coal, crude oil, and natural gas are considered fossil fuels because they were formed from buried organic carbon. Uranium, a metal which is mined and refined to a fuel used in nuclear power plants, is not a fossil fuel. However, it is also classified as a non-renewable energy source because uranium also has a long regeneration time as that of coal, crude oil, and natural gas.

These non-renewable energy sources provide a considerable amount of energy for humanity. Across the world, fossil fuels and nuclear energy generate electricity through thermoelectric power plants by heating water in a boiler until it is evaporated into steam. The steam is then used to spin a turbine which generates electricity. After the steam has spun the turbine, it is sent to a condenser to be cooled back into water so it can be converted to steam once again to produce more electricity. As global population growth continues and developing nations become more industrialized, more energy will be consumed leading to diminishing non-renewable energy resources worldwide.

II. Resources vs. Reserves

The current method used to determine the time until non-renewable energy resources are depleted is by evaluating the proved reserve quantity and dividing it by the observed current consumption rate. The quantity of proven reserves plays the greatest role in determining the longevity of the global non-renewable energy resources. By definition, the total proven reserves are those quantities of non-renewable energy which, by analysis of geological and engineering data, can be recovered with reasonable certainty in the future from known reservoirs under current economic and geological conditions (BP, 2015). Because proven reserves fluctuate due to economic conditions, nations may see large increases or decreases in proven reserves as prices fluctuate allowing uneconomic reserves to become economically producible and vice versa. According to British Petroleum (BP), over the past decade, global proved reserves have increased by 24%, or more than 330 billion barrels, and OPEC countries continue to hold the majority of the global reserves, accounting for 71.6% of the global total. The British Petroleum Statistical Review of World Energy (2015) shows the global total proved reserve levels of fossil fuels are: 1700 billion barrels of crude oil, 891.5 billion tonnes of coal, and 187 trillion cubic meters of natural gas. At the current levels of extraction, British Petroleum estimates that the proved reserves of crude oil would be depleted by 2068, coal would be exhausted by 2125, and natural gas by 2069. If we, as a global population, want to continue to rely on non-renewable energy as a primary resource, then we must start now to sustain the non-renewable energy or start developing alternative energy methods.

III. Previous Work

Many studies have predicted when fossil fuels will be ultimately depleted. In 1928, as it was becoming clear that oil generated more energy than coal, Ludwell Denny discussed the geopolitics of oil and how nations fight to control it. He explained that more conflicts will arise as developing nations establish themselves economically resulting in inevitable oil wars. Denny said, “The nation which controls oil and other raw materials, foreign markets, and credits will rule the world” (Denny, 1928). Without these, nations cannot continue, therefore conflict will arise.

Following Denny, in 1956, the idea of "peak oil" coined by M. King Hubbert, a Shell geologist, predicted that the United States oil resources would peak between 1965 and 1970. By observing the bell-shaped curves of oil production from different oil fields, he could predict that a peak in production would occur when approximately half of the available resource had been extracted followed by the production declining over the next decades. He concluded that of the global non-renewable energy reserves 75% are represented by coal and the remaining 25% are approximately divided equally between oil and natural gas (Hubbert, 1956). Hubbert also estimated that coal would ultimately be depleted around 2160 and crude oil and natural gas around 2010. These estimates were based on the available data in 1956 when recovery methods were not as efficient as they are today. However, he does state that improved methods of recovery would most likely cause the rate of decline to be less steep (Hubbert, 1956).

In 1968, Garrett Hardin examined a unique link to population and resources, and recognized that population must be brought under control in order to sustain non-renewable energy resources. Hardin stated, "A finite world can support only a finite population; therefore, population growth must eventually equal zero" (Hardin, 1968). As population increases, the finite resource share per person must decrease. His solution was that we, as a population, must abandon the freedom to breed before it ruins humanity.

Albert Bartlett, an emeritus professor at the University of Colorado at Boulder, United States of America also attempted to predict when non-renewable energy would be exhausted by using the concept of doubling time. For example, if a quantity grows at a fixed rate of 5% per year, a constant time will be required for the growing quantity to double its size or increase by 100% (Bartlett, 1978). By using this concept, he was able to calculate resource lifetime in years based on present and future annual growth rates of production. He concluded that decreasing the annual consumption rate of each resource would be the only way to extend each resource's lifetime.

A more recent study of projected fossil fuel depletion was done by Shafiee and Topal (2008) based on consumption and price of fossil fuel. Their calculations used two different methods. The first method used a compound rate formula assuming that fossil fuel consumption was constant and the second method calculated the ratio of world consumption to reserves. The first model estimated that coal, crude oil, and natural gas would be exhausted by 2112, 2040, and 2042, respectively. As for the second model, it approximated that coal, crude oil, and natural gas would deplete by 2205, 2045, and 2075, respectively, assuming 2006 consumption rates (Shafiee and Topal, 2008). They determine the reason why the coal lifetime increased is because coal reserves were not very accurate in the last two decades due to political policies against releasing the real data.

IV. Research Hypothesis

It was assumed in this research that the non-renewable energy that was produced, was consumed. This is because the most economical way of storing non-renewable energy, is within the reserves themselves. The question "how much fossil fuel is left on Earth to be consumed for the global energy demand" is an essential question in determining how much longer these finite resources will last. The objective of this research was to estimate the initial quantity of non-renewable energy mass on Earth prior to consumption and how much mass remains to be consumed. The estimate of the total non-renewable energy mass will be an approximation, generally to the correct order of magnitude of the actual total non-renewable energy mass that was initially on Earth.

V. Methods

An analysis of non-renewable energy production was conducted from data publically available data from the *U. S. Energy Information Administration (EIA)*, *World Energy Production, 1800-1985* (Etemad and Luciani, 1991), and enerdata.net (Enerdata, 2016). These data sources were the most comprehensive tabulations of energy resources produced since the beginning of the 19th Century. The annual production data was plotted for each non-renewable resource followed by regression analyses to determine the trend of resource consumption over time. The predictive value of analyzed trends was assessed by optimizing for R^2 (i.e. correlation). The R^2 value is a statistical measure of how well a regression line approximates the data points. An R^2 of 1 indicates that the regression line perfectly fits the data.

The production data from historical data can be incomplete, or poorly documented. I attempted to improve historic estimates by hindcasting production trends from modern (20th and 21st century) data where quantity and accuracy was more certain. But in order to include the years with incomplete data into the estimation, I projected the trend line backwards to achieve a generalized trend line across the years with incomplete data.

VI. Non-renewable Energy Production Data

The production data for each non-renewable energy resource was publically available data from *World Energy Production, 1800 – 1985* (Etemad and Luciani, 1991), the *U. S. Energy Information Administration* (EIA), and enerdata.net (Enerdata, 2016). Each non-renewable energy resource uses different units when they are measured; coal is in metric tons per year, crude oil is in barrels per day, and natural gas is in cubic meters per year. Therefore, for this study, I converted each energy resource into common mass units (grams) per year so accurate comparisons between each resource can be made.

The unit conversion into grams required different methods for each energy resource. Coal is already in a mass unit of metric tons per year and is the easiest of the three energy resources to convert into grams. By using 1 metric ton equaling 1,000,000 grams, coal was quickly converted into grams by multiplying the metric tons per year values by 1,000,000 to achieve the grams per year value. Converting crude oil from barrels per day into grams per year sounds complex but in fact is simple. The crude oil conversion starts by multiplying barrels per day by 365 days resulting in barrels per year. According to British Petroleum, 1 metric ton equals 7.33 barrels of crude oil, so dividing barrels per year by 7.33 barrels of crude oil yielded metric tons of crude oil per year (BP, 2015). Once that the crude oil was converted into metric tons per year, it was just a matter of multiplying by 1,000,000 to finish the conversion for a final unit of grams per year. Finally, the conversion of natural gas from cubic meters per year into grams per year was the most complex conversion of all the energy resources, but understanding simple chemistry made it a less daunting task. The natural gas conversion required using the several different chemical components forming natural gas and their molar masses to convert from a volumetric unit to a mass unit.

VII. Converting Natural Gas to a Mass

The conversion of natural gas from a volumetric unit to a mass unit is a matter of performing simple chemistry. By assuming the Ideal Gas Law, then the equation $PV=nRT$ can be used to solve for n (number of moles) and then multiply by each chemical's molar mass to achieve a mass value for natural gas per year. According to Union Gas (2016), typical natural gas composition is primarily methane, ethane, and propane and they also provide the typical range for the mole percentage for each chemical component (Table 1). For this study, the typical mole percentage for each major chemical component was 96% Methane, 3.5% Ethane, and 0.5%

Propane.

The industry has established standard conditions for referring to volumetric measurements for natural gas because natural gas is very compressible and expands significantly as it moves from a high pressure state in a reservoir to a low pressure state at the Earth's surface. For this reason, there are two different standard measurement units that are used when measuring natural gas during pumping; the Standard Cubic Foot and the Normal Cubic Meter. The Standard Cubic Foot is measured at 60°F and at one atmosphere or 14.73 pounds per square inch (psi) of pressure, while the Normal Cubic Meter is measured at 0°C and at one atmosphere of pressure (101,325 Pa). The only difference between the two standard measurement units are the temperatures at which they are measured. For this study, I will use the Normal Cubic Meter as the standard measurement unit because the natural gas production data are in cubic meters.

Chemical Component	Typical Mole % Range	Assumed Mole %	Molar Mass
Methane	87% - 97%	96%	16.04 g/mol
Ethane	1.5% - 7%	3.5%	30.07 g/mol
Propane	0.1% - 1.5%	0.5%	44.1 g/mol

Table 1: According to Union Gas, the typical mole percent range is given for each major chemical component of natural gas (Union Gas, 2016). The assumed mole percent range for this study is also given along with the molar mass for each major chemical component.

For example, let's take the year 1882, which is the first year for which natural gas production is obtained in cubic meters and convert it into a mass (grams).

Starting with the equation:

$$PV = nRT$$

Now, the equation can be rewritten to solve for n (number of moles):

$$n = \frac{PV}{RT}$$

Next, assign each variable with the correct values:

P = Pressure = 1 atmosphere = 101,325 Pa

V = Volume per year = 96,000,000 m^3

R = Ideal Gas Constant = 8.31441 J/mol*K (J = Pa*m^3)

T = Temperature = 0°C = 273.15 K

Now that all of the variables have the correct values, solving for the number of moles can be calculated:

$$n = \frac{(101{,}325 \text{ Pa})(96{,}000{,}000\text{m}^3)}{(8.31441 \text{ Pa} \cdot \text{m}^3)(273.15 \text{ K})}$$

n = 4,283,070,312 moles for the year 1882

Next, is the conversion of moles per year to mass per year value. First, determining how many moles are in each chemical component of natural gas for the year 1882 must be done. This involves using the assumed mole percent from Table 1:

Methane % = (4,283,070,312 moles) (0.96) = 4,111,747,500 moles of Methane

Ethane % = (4,283,070,312 moles) (0.035) = 149,907,460.9 moles of Ethane

Propane % = (4,283,070,312 moles) (0.005) = 21,415,351.56 moles of Propane

Once the mole values have been calculated for each chemical component of natural gas for the year 1882, the conversion of moles into a mass requires multiplying the mole values by the molar mass of each chemical component:

Grams of Methane = (4,111,747,500 moles) (16.04 g/mole) = 65,952,429,898 g

Grams of Ethane = (149,907,460.9 moles) (30.07 g/mole) = 4,507,717,350 g

Grams of Propane = (21,415,351.56 moles) (44.1 g/mole) = 944,417,003.9 g

Finally, the total mass value for the year 1882 can be calculated by summing all of the chemical component's mass values together:

Total natural gas produced in 1882 = 7.1405×10^{10} grams

This process was completed for every year of production for natural gas in order to covert the data from a volumetric value into a mass value. A test calculation was performed using 15°C and compared it with the results of the 0°C value. There is 5.5% overall decrease of the final value when using 15°C instead of 0°C, but this change is so small compared to the overall data set that using either temperature would result in roughly the same answer.

VIII. Non-renewable Energy Production

Now that all three non-renewable energy resources were in the same units, it is possible to compare the production/consumption of each resource and the growth rates through time. The production data for each energy resource had differing years in which the production ultimately began but all the production data ended in the year 2014, the most recent year of available data.

Once again, it was assumed that whatever has been produced, has been consumed; because the cheapest way to store non-renewable energy is in the reserve itself.

A. Coal Production

During the Industrial Revolution, the British found that coal burned hotter and cleaner than wood charcoal. This discovery would shape the Industrial Revolution by providing power to steam engines, but there is little data recording the quantity of coal mined during the 19^{th} Century. However, we can determine from consumption curves that the quantity mined was actually negligible when compared to the overall quantity that was mined since its discovery, therefore our data has reasonable coal production records starting in 1800 and data records improve significantly over time to the present day.

B. Crude Oil Production

Modern day crude oil production was attributed to Edwin Drake's first oil well in 1859. Following his discovery, the oil industry boomed toward the end of the 19^{th} Century in Texas, Oklahoma, Ohio, and California. Although there were most likely small amounts of oil seeps that were exploited before the first oil well, just like coal, the quantities were so negligible compared to the rest of the production data that it would have very little impact on the entire crude oil production data set. Our data records begin in 1860 and appear to become more accurate in the early 1900's because as technology improved, the accuracy of the measurements increase.

C. Natural Gas Production

As early as 1626, French explorers discovered naturally occurring natural gas in America, when they observed natives igniting gases that seeped into and around Lake Erie. However, not until 1821 was the first successful natural gas well invented by William Hart in Fredonia, New

York, United States. Natural gas was used almost entirely as a source of light during most of the 19th century, but an invention known today as the Bunsen burner was created in 1885 by Robert Bunsen which opened immense new opportunities for the use of natural gas. In the 20th century, pipelines were engineered and the use of natural gas extended into the homes for heating and cooking, manufacturing at industrial plants, and boilers for the generation of electricity. Even though the first natural gas well was developed in 1821, data recording of natural gas production started in 1882 (APGP, 2015).

IX. Results

A. Coal

To further interpret the production data, I analyzed the production data by observing the different growth rates that occur throughout time. Coal had an overall exponential growth throughout time of 2.9% per year. However, embedded in the overall pattern of consumption growth there are varying rates that can be detected (Figure 1). From 1800 – 1913, the exponential growth rate was 4.2% followed by a period of rebuilding from 1914 – 1945, then from 1945 – 1990 the exponential growth rate decreases to 2.5% per year. The 4.2% annual exponential growth was due to countries' consumption rapidly expanding after the start of the Industrial Revolution and then production flat-lines during World War I, the Great Depression, and World War II. After this slump, the annual exponential growth rate slows to 2.5% but is fairly consistent until 1990. There was another slump in production during 1990 – 1998 followed by another exponential growth rate of 4% per year from 1998 – 2014. The total production of coal from 1800 – 2014 was 3.50×10^{17} grams.

B. Crude Oil

The production growth rates for crude oil are completely different than those of coal (Figure 2). The average annual growth rate during the total period of production was 6.3% per year, but from 1860 – 1975 the exponential growth rate was 7.7% per year and from 1975 – 1979 was 3.8% per year. After 1975, the growth rate declined by half to 3.8% per year due to the OPEC Oil Embargo of 1973 – 1974. The growth then becomes linear instead of exponential at a rate of 1.1% per year from 1980 – 2014. Total crude oil production from 1860 – 2014 amounts to 1.72×10^{17} grams.

C. Natural Gas

The production data for natural gas correlates closely to that of crude oil. The average annual growth rate during the total production period was 6.2% per year, but it grows exponentially at 7.2% per year from 1882 – 1975 and exponentially again at 2.4% per year from 1975 – 2014 (Figure 3). Overall the global natural gas production sums to 8.15×10^{16} grams.

D. Total Non-renewable Energy

Each non-renewable energy source mass (coal, crude oil, natural gas) was tabulated and the total quantity of non-renewable energy mass was calculated by summing together each resource mass (Figure 4). The total sum of all the masses equaled 6.04×10^{17} grams and this number will be used in the next section as the mass consumed as of 2014. Also, a calculation was completed to determine the quantity of each resource contribution to the global energy demand since 1800. This was achieved by dividing each energy resource total production mass by 6.04×10^{17} grams. The global energy demand for non-renewable energy from 1800 – 2014 was satisfied with 58% coal, 28.5% crude oil, and 13.5% natural gas.

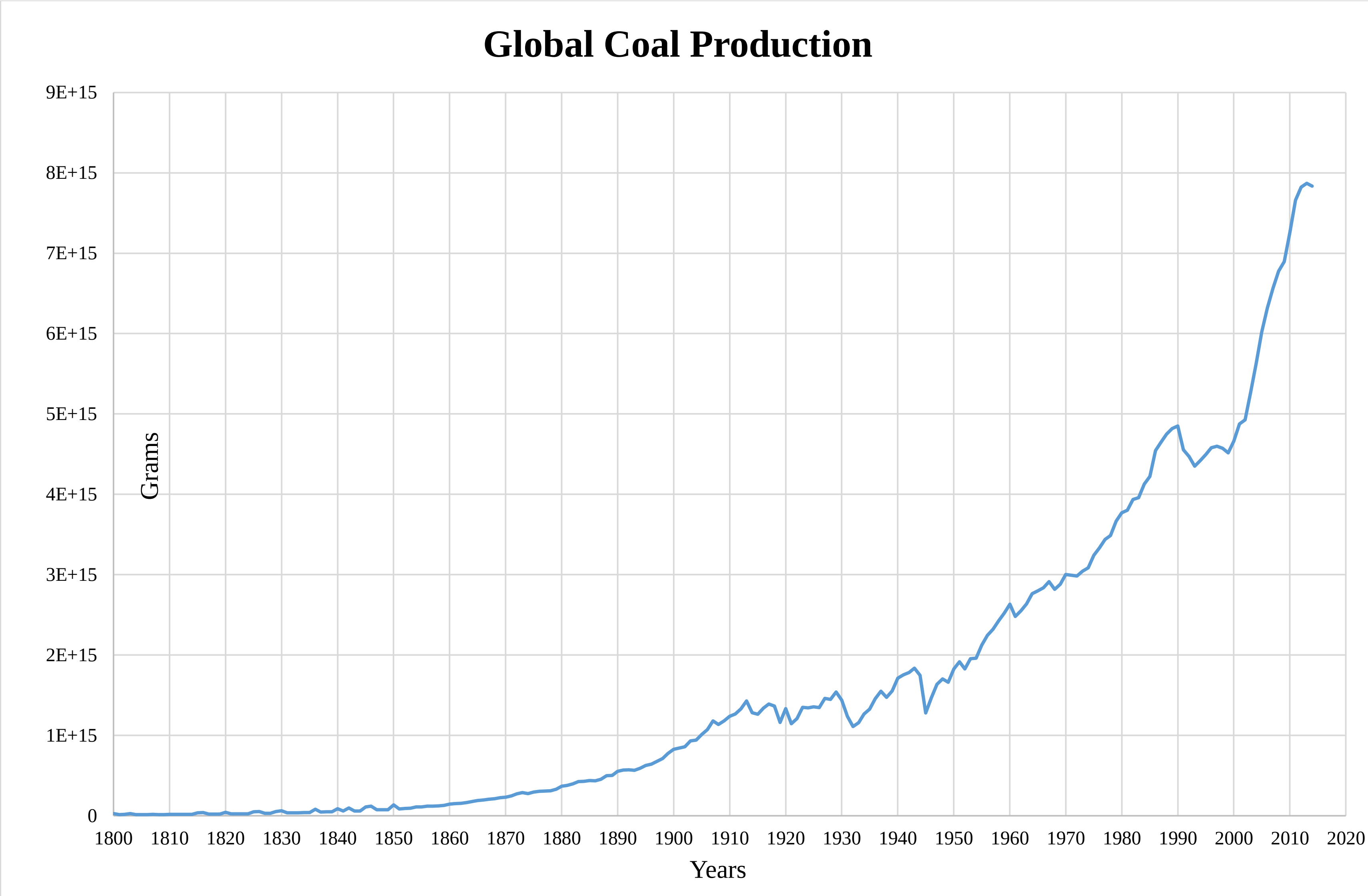

Figure 1: Global coal production data from 1800 – 2014 with a total production since 1800 of 3.50 x 10^{17} grams (EIA, 2015b, Etemad and Luciani, 1991, and Enerdata, 2016a).

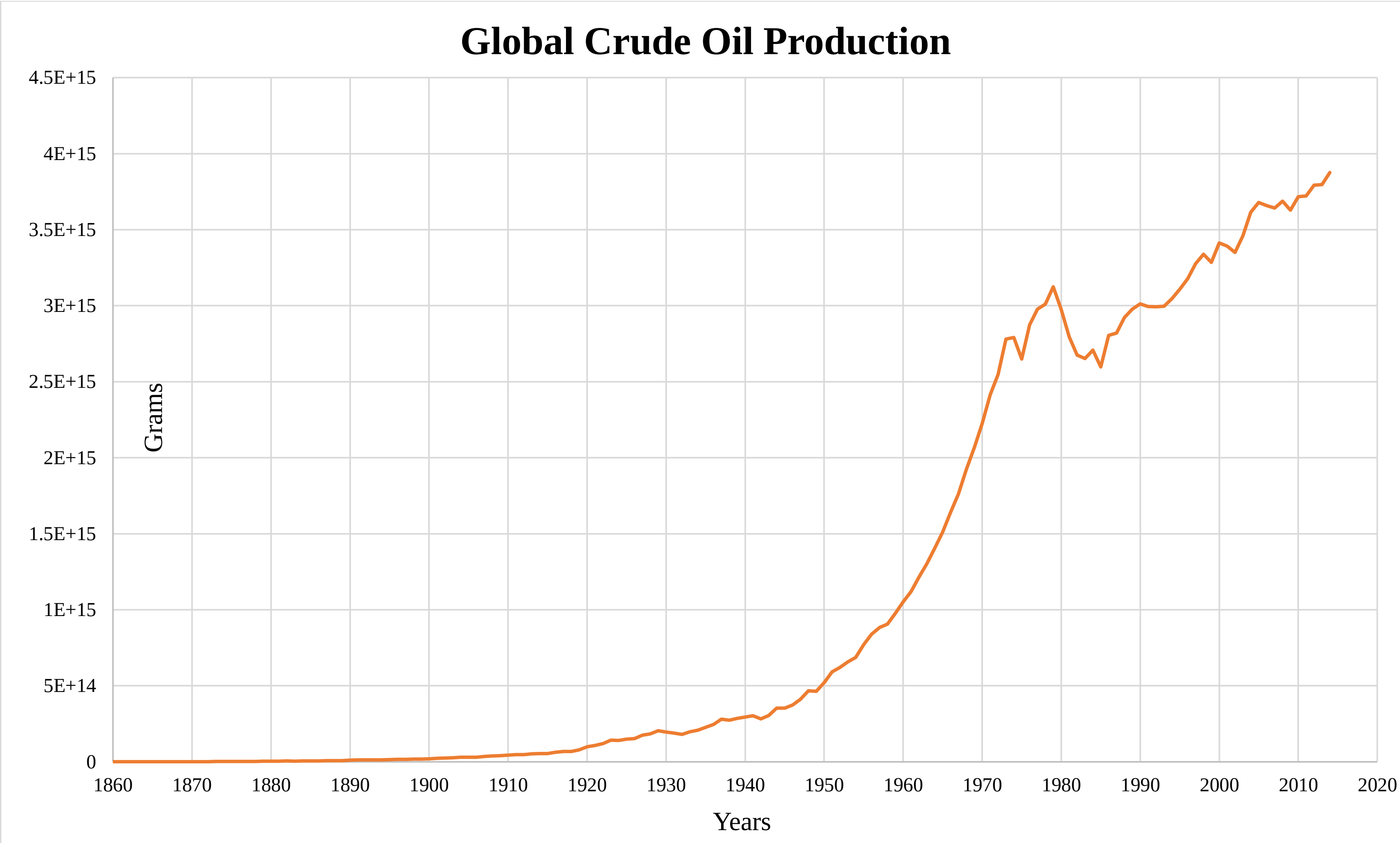

Figure 2: Global crude oil production from 1860 – 2014 with a total production since 1860 of 1.72 x 10^{17} grams (EIA, 2015d, Etemad and Luciani, 1991, and Enerdata, 2016b).

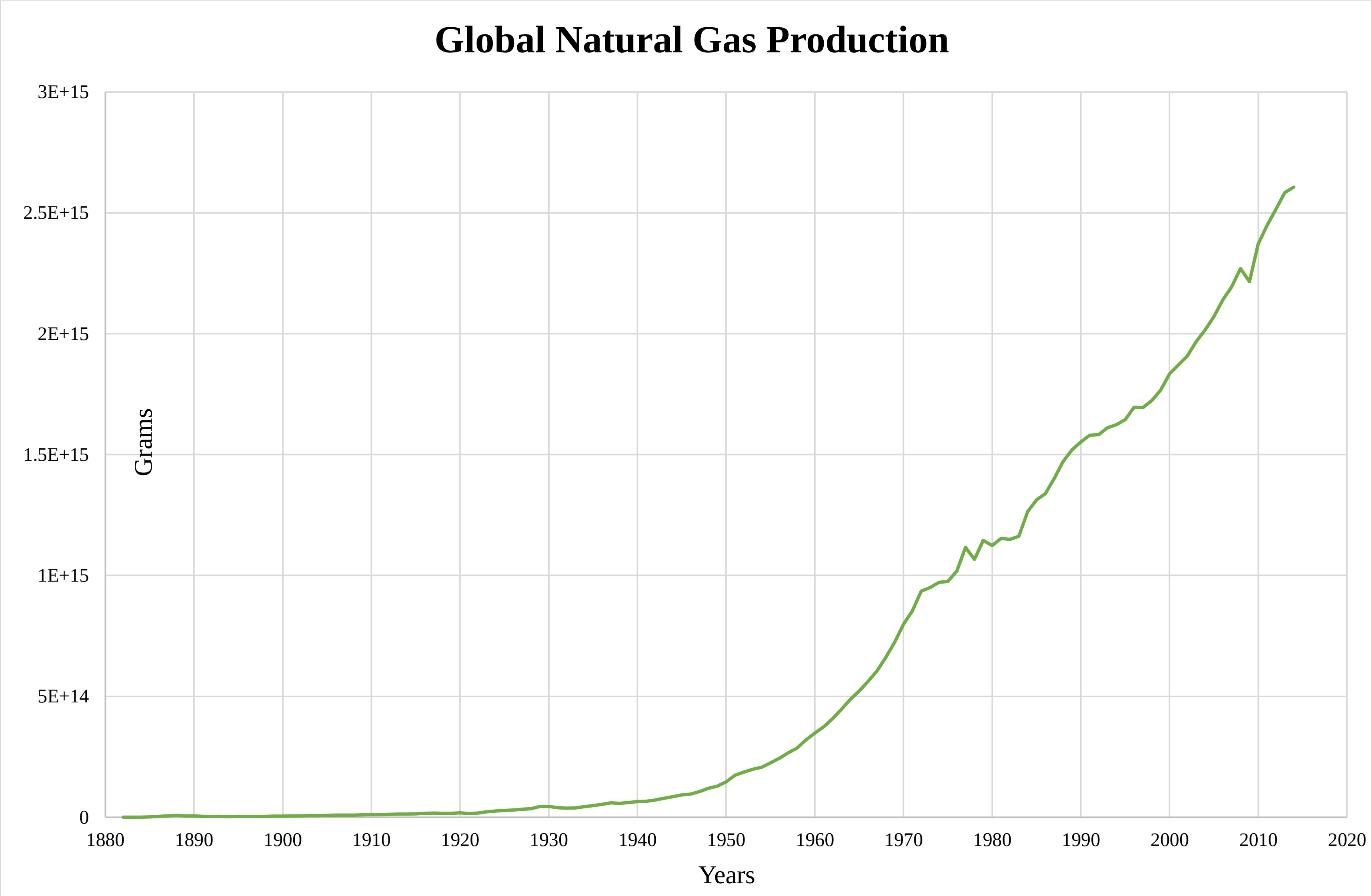

Figure 3: Global natural gas production from 1882 – 2014 with a total production since 1882 of 8.15 x 10^{16} grams (EIA, 2015c, Etemad and Luciani, 1991, and Enerdata, 2016c).

X. Discussion

The early production data of energy resources accounted for only a small percentage relative to the rest of the data where the production is much greater, so overall errors should be negligible. This is due to the exponential growth function. As you hind cast the exponential growth back into time the quantities become very small (Bartlett, 1978) compared to the entire data. All non-renewable energy was produced (consumed) prior to the Industrial Revolution so we can neglect the early production data somewhat. To demonstrate how the exponential growth function operates, since 1850, the global population has consumed 99.7% of the total non-renewable energy mass that has been ultimately produced which means that only 0.3% was consumed between 1800 and 1850.

A. Coal

Coal is the most abundant non-renewable energy resource on Earth. The production of coal has been going the longest of all the non-renewable energy resources. The majority of the total production data is coal production, even though coal production extends back to 1800, mostly in European countries, humanity still consumes it the most. If we were to continue consuming coal at the same rate, this would destroy our Earth due to the large amounts of atmospheric pollution.

B. Crude Oil

The first century of oil production was completely open to whoever wanted to drill, but a huge historical crude oil event would occur in 1973 that would shape oil production growth forever. The Arab members of the Organization of Petroleum Exporting Countries (OPEC) imposed an embargo against the United States, Netherlands, Portugal, and South Africa due to their decision to re-supply the Israeli military. The oil embargo banned crude oil exports to the targeted nations and began a series of crude oil production cuts. The embargo more than quintupled the price of oil from $2.09 a barrel to $11.65 a barrel; however, after the embargo was lifted in March 1974, the higher oil prices remained (Merrill, 2007).

Following the oil embargo, crude oil production peaked in 1979 and then started falling until 1985. During this time, the Iranian Revolution started in 1979 followed by the Iran – Iraq War in 1980. These conflicts greatly reduced the amount of oil that was being produced in the Middle East which caused the large drop in production. Since the OPEC Oil Embargo, the Iranian Revolution and Iran – Iraq War, oil production appears to be increasing but instead of an exponential growth, it is linear growth to 2014. This suggests that politics and private organizations have controlled the amount of oil production since 1985. Major historical conflicts can still be seen in this linear data including: the Gulf War in 1990, the War on Terror in 2001, and the Recession in 2009.

C. Natural Gas

Natural gas does not become prevalent until World War II is over. It grows exponentially like crude oil and then the growth slows drastically due to the OPEC Oil Embargo in 1973 and the control of politics coming into play. After the OPEC Oil Embargo, natural gas growth becomes linear at 1.1% mirroring crude oil production but in a smaller quantity. The flux of the natural gas production data is not as great as that of crude oil but one can still see the major historical conflicts within the natural gas data.

D. Total Non-renewable Energy

Since all production data are in the same units, a visual comparison between each non-renewable energy resource can be shown along with the sum of all the energy resources (Figure 4). The total non-renewable energy production figure displays some interesting features that are difficult to perceive in the individual figures. First, one can observe how coal is the dominant energy resource throughout the 1800's but crude oil starts to directly replace coal as the primary energy resource in the early 1900's then, in 1920, natural gas begins to supply energy for the global energy demand. Next, there appears to be consistent growth rate that occurs after 1945 in the total production data but upon further observation the growth rates were disrupted by major historical events.

Major historical events have shaped the total production data throughout time causing disruptions in the data which can be easily correlated on the total production figure. Figure 5 shows the total production was increasing exponentially at 4.2% per year until the first major historical event occurred. World War I, from 1914 – 1918, was the first disruption in total production and it caused a slight dip in the production data followed by the Great Depression from 1929 – 1939 which triggered a more drastic dip in production. During this period, total production seems to flat line but also at this time, crude oil is becoming a more dominant energy resource. The next major historical event was World War II from 1939 – 1945 that caused the total production to increase until 1944 followed by a huge decrease in 1945.

After World War II, total production increases exponentially at 4.3% per year until 1979 when another significant decrease in total production occurs from 1979 – 1983. However, before the decrease in 1979, the OPEC Oil Embargo occurred in 1973 which mostly impacted the crude oil production to grow linearly and this affected the total production to grow exponentially at a slower growth rate of 2.9% per year because crude oil is the more dominant energy resource at this time. The decrease of total production in 1979 correlates directly to the Iranian Revolution of 1979 and the start of the Iran – Iraq War in 1980 that would last until 1983. After these events, the total production would begin to grow exponentially again but at a slower rate of 2.9%

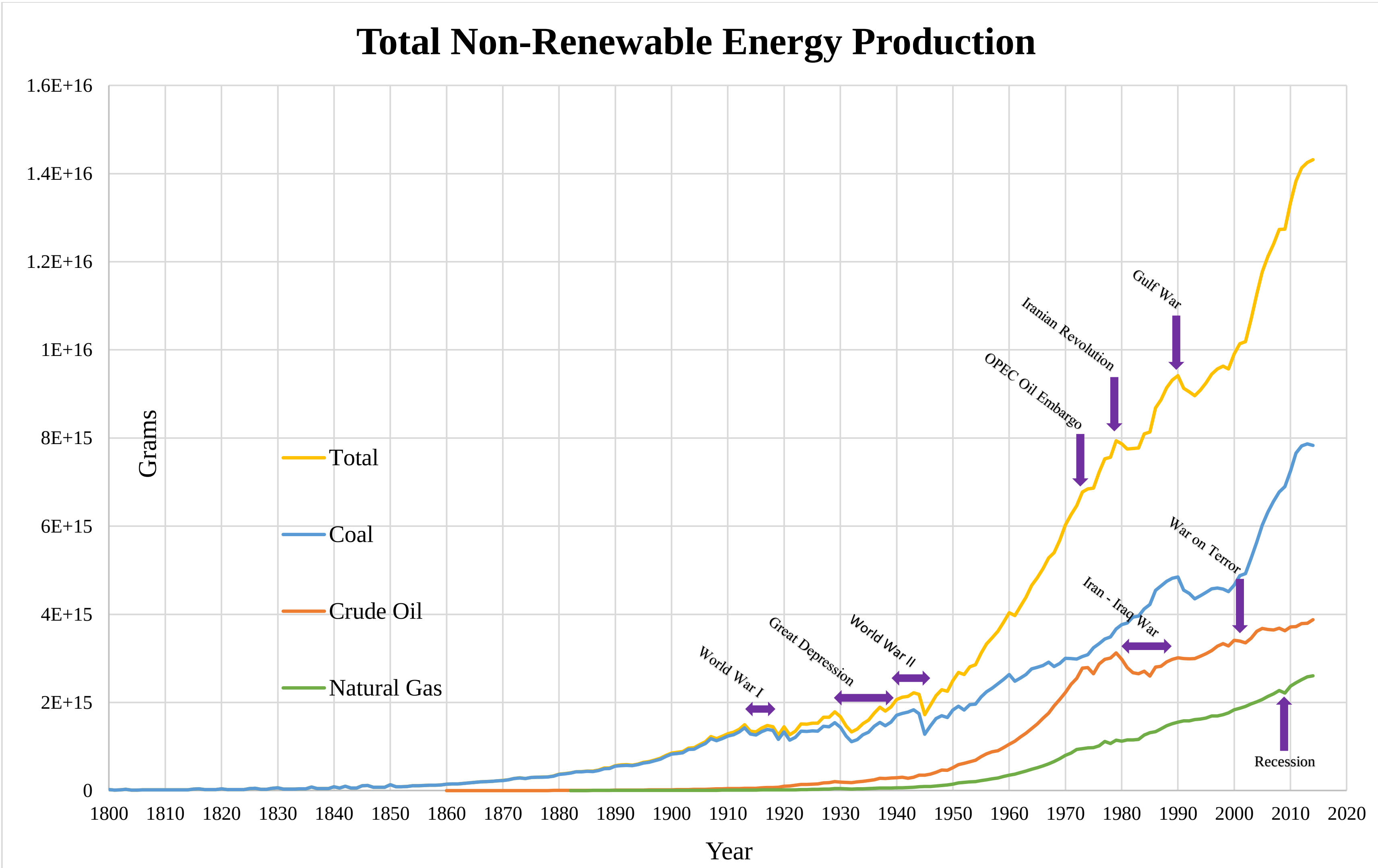

Figure 4: Total non-renewable energy production from 1800 – 2014 with a total production of 6.04 x 10^{17} grams (EIA, 2015, Etemad and Luciani, 1991, and Enerdata, 2016). Major historical events have been correlated to production declines as discussed in the text.

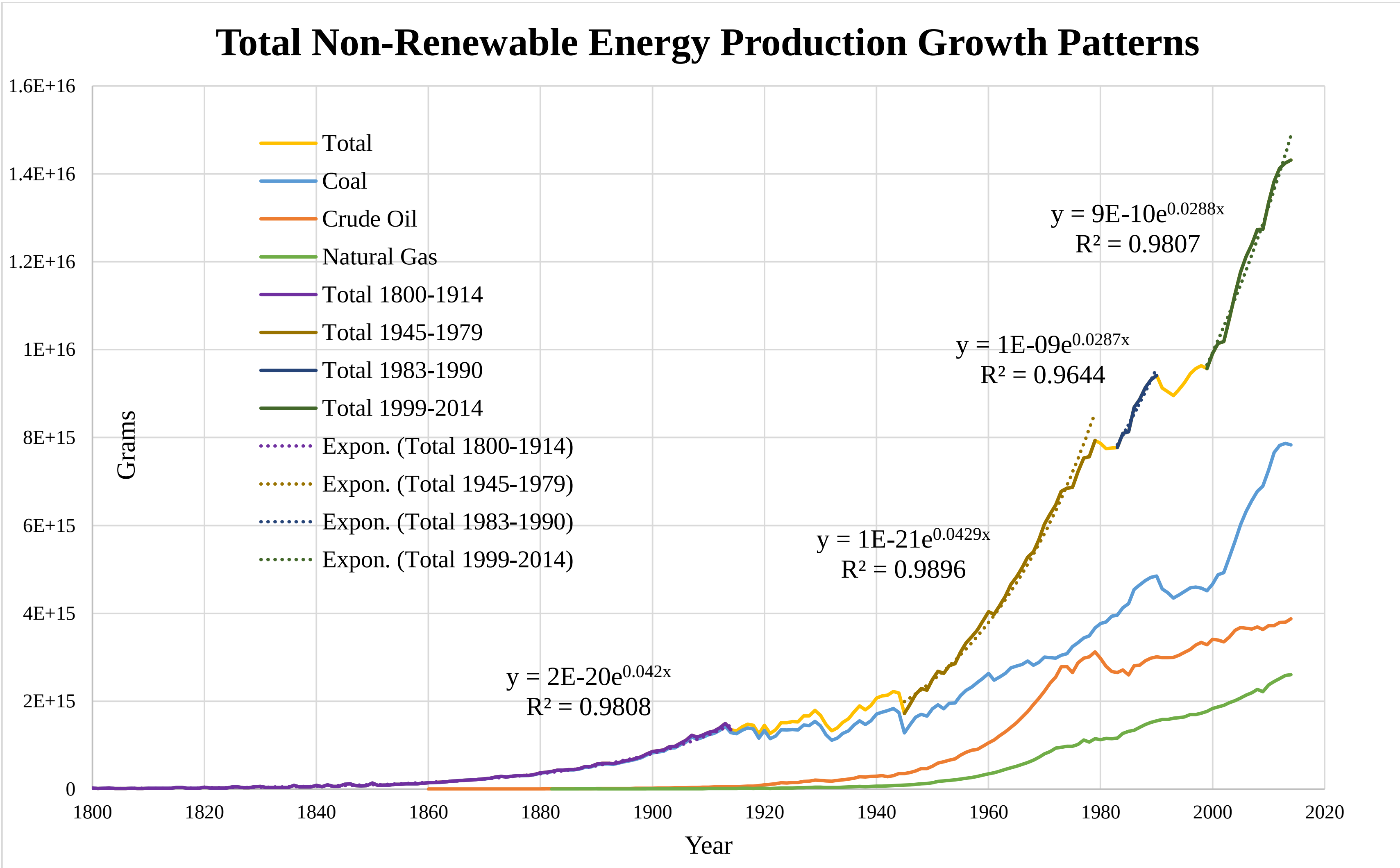

Figure 5: Exponential trend lines indicate the constant growth interrupted by the major historical events discussed in the text. (EIA, 2015, Etemad and Luciani, 1991, and Enerdata, 2016).

per year due to the OPEC Oil Embargo.

The last significant decrease in total production occurred in 1990 – 1999 with the start of the Gulf War. This decrease can be seen mostly in the coal production presumably due to natural gas becoming more abundant and cheaper. Following the Gulf War, total production starts to grow exponentially again from 1999 – 2014 at 2.9% per year and there are some slight disruptions during this time that can be observed. In 2001, the War on Terror begins which causes a very slight dip in the total production followed by the Recession in 2009. These events do not overly interrupt the total production to cause another drastic decrease but they should be noted.

The major historical events disrupted the growth rate for about 5 years and then production started growing exponentially again until another major event occurred, disrupting the growth rate once again, causing these shifts of growth rates within the data. On average, the total production grew exponentially at 3.4% per year from 1945 – 1979, 1983 – 1990, and 1999 – 2014 and the overall exponential growth rate of the total production is 3.3% per year mostly because coal by mass was the most produced.

E. Renewable Energy Transition

The global energy demand has relied primarily on fossil fuels: coal, crude oil, and natural gas. The problem with fossil fuels is they are non-renewable and limited in supply and will be ultimately depleted one day. Humanity now looks toward electric power generation from renewable energy primarily from wind and solar power with zero carbon emissions. Wind turbines are generally 200 feet or more above the ground and harnesses energy by the wind blowing and turning the turbine blades. Solar energy is generated from photovoltaic cells which converts sunlight directly into electricity.

The EIA has data records of electricity generation through renewable energy worldwide since 1983 until present. The electricity generation data was originally in units of BTU, but I have converted the BTU data into the gram equivalent of coal, crude oil, and natural gas. Since 1983, the fossil fuel mass equivalent of the total electricity generated from wind and solar power is 9.67×10^{14} grams of coal, 9.37×10^{13} grams of crude oil, and 5.67×10^{13} grams of natural gas with a total mass equivalent of 1.12×10^{15} grams. The mass equivalent of electricity generated through solar and wind accounts for 0.19% of the total non-renewable energy mass that was produced since 1800.

Despite this tremendously small percent, renewable energy has been increasing its percent share of the global energy demand since 1983. In 2014, renewable energy grew by 12%, providing 6% of the world's electricity (BP, 2015). Renewable energy will likely grow into the future and make a drastic impact on the global energy demand. Humanity will begin to transition to renewable energy and it will start to replace fossil fuels as the primary energy supplier, therefore extending the lifetime of use for each fossil fuel.

XI. Ultimately Recoverable Reserves (URR)

The total ultimately recoverable reserve is an estimate of the total quantity of a resource that existed before exploitation began. Since the total production of each resource has been calculated, we can now estimate when each resource will be ultimately depleted by subtracting the annual production from the ultimately recoverable reserves (URR) quantity for each resource and projecting scenarios based on variable depletion rates. The best estimates of the remaining URR for each energy resource were determined by Ekins and McGlade (2010). Their data was separated into each remaining resource quantity as well as their respective remaining reserve quantity. For this research, their data were converted from the normal energy resource units into common mass unit of grams using the same conversion techniques described previously. In order to estimate how much mass was initially on Earth before exploitation, we can add the cumulative production of each resource to the 2010 URR values, as well as calculating a new URR for 2014 by subtracting the production data of 2011 – 2014 for each resource from the same 2010 URR values. The ultimate quantity of non-renewable energy prior to exploitation was determined to

Years	Coal	Crude Oil	Natural Gas	Total	Percent Remaining
Before Exploitation	5.41×10^{18} g	1.03×10^{18} g	7.16×10^{17}g	7.15×10^{18}g	100.0%
2010	5.09×10^{18} g	8.68×10^{17} g	6.45×10^{17} g	6.60×10^{18} g	92.3%
2014	5.06×10^{18} g	8.53×10^{17} g	6.35×10^{17} g	6.55×10^{18} g	91.6%

Table 2: Best estimates of the ultimately remaining reserves as of 2010 (Ekins and McGlade, 2010) with approximation of URR before exploitation and as of 2014.

be 7.15×10^{18} grams; but more specifically, 5.41×10^{18} grams of coal, 1.03×10^{18} grams of crude oil, and 7.16×10^{17} grams of natural gas (Table 2). I believe that these estimates of the total URR and the URR of each energy resource states the correct order of magnitude of the actual URR that exist.

XII. URR Depletion Scenarios

Since we do not know exactly when non-renewable energy will be completely exploited, we can use a variety of production growth rates to model the production into the future and then subtract the annual production from the remaining URR per year to achieve different URR depletion scenarios. As more non-renewable energy resource is produced, less resource is left and as more and more production occurs, the depletion grows until the resource declines to zero. In practice, most resources will be abandoned prior to their complete exhaustion simply because they will become economically unexploitable, being too scarce and too expensive to continue exploiting. Nonetheless, it is informative to project various depletion scenarios into the future to determine the range of possible resource lifetimes. I am assuming that the global energy demand will still rely solely on non-renewable energy and not alternative energy sources and that as population continues to grow, more and more energy will be required simply because more people will use more energy. Of course, various improvements in energy efficiency over time are possible (even likely) however, exploitation of these fossil energy reserves will continue at rates greater than their natural regeneration rates, so they will ultimately deplete.

As an example, the total production of all the resources grew exponentially on average at 3.3% per year. Subtracting the annual production from the total URR results in the remaining URR per year. In Figure 6, from 1800 – 2014, the actual total production per year data was used and then from 2015 – 2098, when total exploitation occurs, a projected annual production of 3.3% per year was used, which causes the total URR to deplete at the same rate of 3.3% per year. But, as more and more non-renewable energy resources are produced, the resource will become harder and harder to exploit. This requires models to have more than one depletion rate to achieve a greater range of possible years of total exploitation. To declutter Figure 7, the projected annual production data has been left out and only the remaining URR per year is present. A range of depletion rates from 1% – 4% was used, because the total production growth rate never exceeded 4%. By using different depletion rates, an estimated year at which total exploitation occurs can be perceived. At 1% depletion total exploitation occurs in 2185, 2% depletion in 2130, 3% depletion in 2104, and 4% depletion in 2088. More precisely, this same model can be used for each non-renewable energy resource because the total URR for each resource is known. The same assumptions discussed earlier are applied to each energy resource depletion scenario, except for the depletion rates

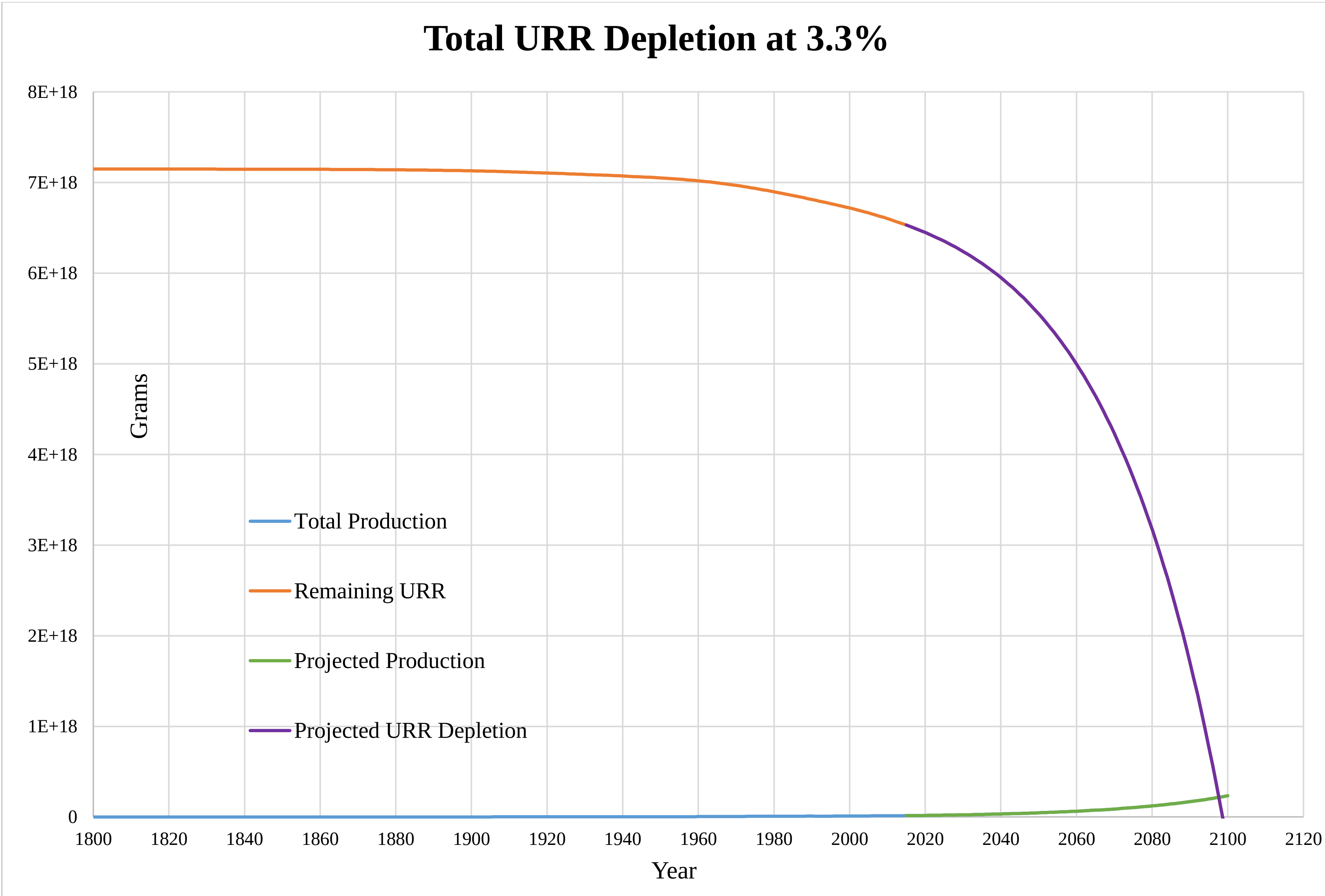

Figure 6: Total URR depletion at 3.3% per year with depletion of the URR occurring in 2098.

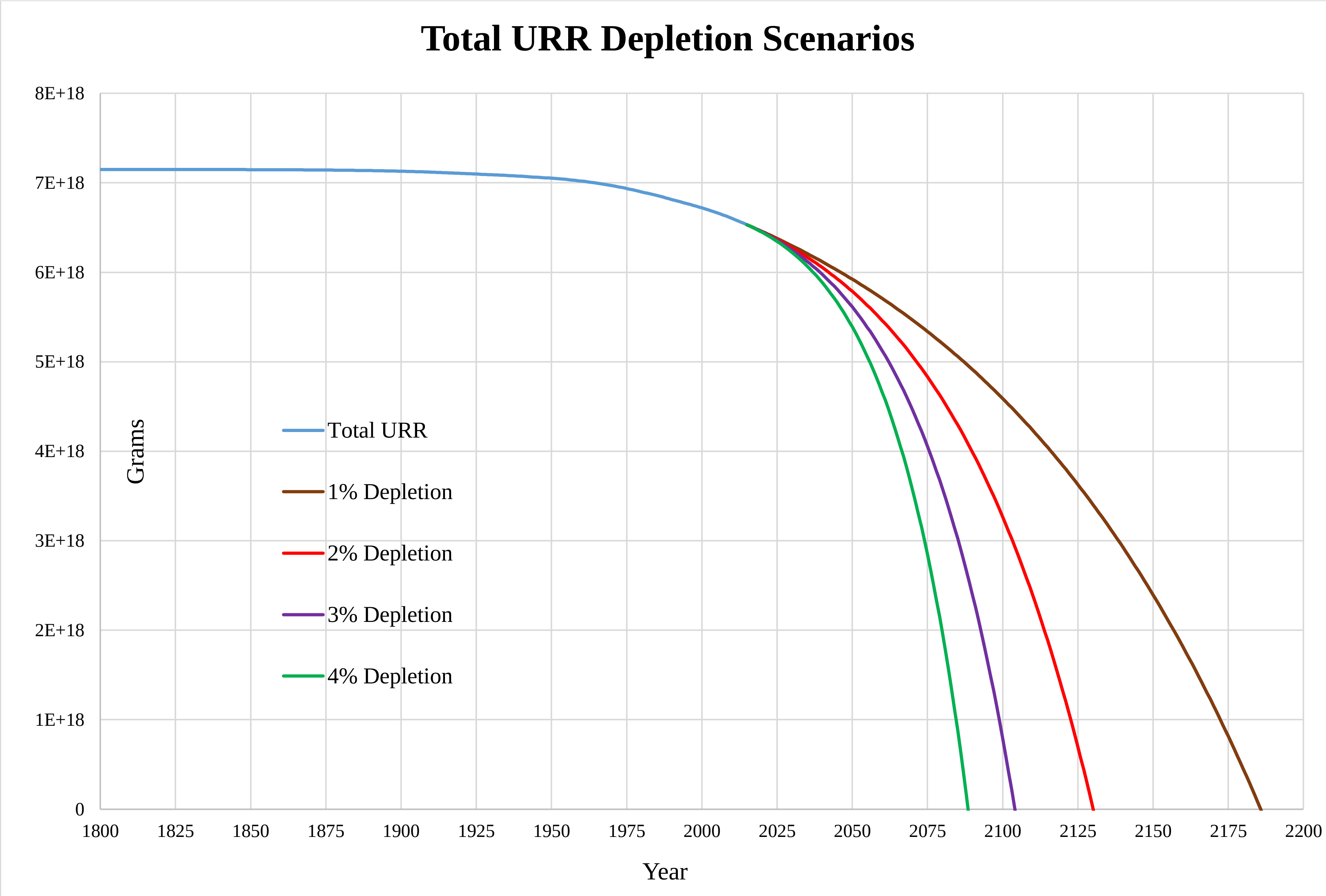

Figure 7: Total URR depletion based on 1% – 4% projected annual total production rates.

A. Coal URR Depletion Scenarios

Coal is the most abundant non-renewable energy resource by mass. The total URR of coal before exploitation was 5.41×10^{18} grams and the total quantity that has been produced since 1800 is 3.50×10^{17} grams. This indicates that as a global population we have produced (consumed) 6.5% of the total available coal and 93.5% remains to be exploited. To determine the lifetime of coal, a URR depletion rate scenarios of 1% - 5% was used since the maximum rate of production for coal was slightly over 4% (Figure 8). The same URR depletion process as discussed earlier was used which gave a wide range of possible years of total depletion. The total URR depletion for coal ranges from the year 2215 at 1% depletion to 2084 at 5% depletion. Table 3 displays all the years of total URR depletion for the given production rates.

B. Crude Oil URR Depletion Scenarios

Crude oil is the dominant non-renewable energy resource today. The total URR of crude oil before exploitation was 1.03×10^{18} grams while the total quantity which has been produced since 1860 is 1.72×10^{17} grams. Globally, we have produced (consumed) 16.8% of the total available crude oil with 83.2% remaining to be exploited. Since crude oil is the dominant energy resource, it is pertinent that a URR depletion scenario be calculated. A wider range of possible URR depletion scenarios was used because the maximum production rate of crude oil was 7.7% (Figure 9). Reaching 8.8% crude oil production again seems unlikely, so URR depletion rate scenarios of 1% - 8% were calculated. If production of crude oil remains at 1% then it would be completely exploited in the year 2130 but if production jumps to 8%, total exploitation would occur in 2051. For an enhanced analyses, Table 3 has the years when total exploitation would occur based on different production rates.

C. Natural Gas URR Depletion Scenarios

Natural gas mirrors crude oil very closely in terms of growth rate but in a smaller quantity. The total URR of natural gas before exploitation was 7.16×10^{17} grams and the total quantity that has been produced since 1882 is 8.15×10^{16} grams. 11.4% of the total available natural gas quantity has been produced (consumed) leaving 88.6% to be exploited. A wide range of URR depletion scenarios for natural gas was also used because at one time, the maximum production rate was 7.2%. Although, reaching a production rate of 7.2% again seems improbable, a URR depletion rate scenarios of 1% - 8% was calculated to remain consistent to the crude oil URR depletion scenarios (Figure 10). At 1%, total exploitation of natural gas occurs in the year 2137 and at 8% total exploitation would occur in 2052. Based on the same depletion rates, total depletion of crude oil and natural gas would occur at approximately the same time.

D. Comparing URR Depletion Scenarios

The huge range of depletion scenarios gives a profound insight on the possible years of total URR depletion based on different production rates. A comparison between previous works of the year(s) when these non-renewable energy resources will be ultimately depleted can now be achieved. Table 3 displays the years of total depletion for each non-renewable energy resource which will be directly compared to previous works.

Hubbert first determined that of the global non-renewable energy reserves 75% are represented by coal and the remaining 25% are approximately divided equally between oil and natural gas (Hubbert, 1956). In my study, the global non-renewable energy reserves before exploitation were 75.6% coal, 14.4% crude oil, and 10% natural gas in good agreement with Hubbert's prediction. His reserve quantity prediction was extremely accurate in 1956 given the technology at that time but he also estimates that coal will be ultimately exploited around 2160 and crude oil and natural gas around 2010. Given the production rate of 3% - 4% of coal in 1956, Hubbert estimation was within 50 years of the estimation of this study with total exploitation occurring between 2096 – 2115. However, Hubbert wrongly estimates the lifetime of crude oil and natural gas because his estimates are based on the current data in 1956 when recovery methods were not as efficient as they are today but he does state that improved methods of recovery would most likely cause the rate of decline to become less steep (Hubbert, 1956).

Depletion Rates	**All Resources**	**Coal**	**Crude Oil**	**Natural Gas**
1%	2185	2215	2130	2137
2%	2130	2146	2098	2102
3%	2104	2115	2081	2084
4%	2088	2096	2071	2073
5%	----------	2084	2064	2065
6%	----------	----------	2058	2060
7%	----------	----------	2054	2055
8%	----------	----------	2051	2052

Table 3: The coinciding years when each non-renewable energy resource will be ultimately exploited based on different depletion rates.

Another estimation of total non-renewable energy depletion was conducted in 2008 by Shafiee and Topal. They used two models to approximate when total exploitation might occur. The first model estimated that coal, crude oil, and natural gas would be depleted by 2112, 2040, and 2042, respectively. As for the second model, it approximated that coal, crude oil, and natural gas would deplete by 2205, 2045, and 2075, respectively, assuming 2006 consumption rates (Shafiee and Topal, 2008). Their second model seems to be more accurate when compared to this study. In 2006, coal production (consumption) was approximately 4.9% per year, crude oil was being produced at 1.8% per year and natural gas at 2.8% per year. This study indicates, given 2006 consumption rates, that coal would be ultimately exploited in 2084, crude oil in 2098,

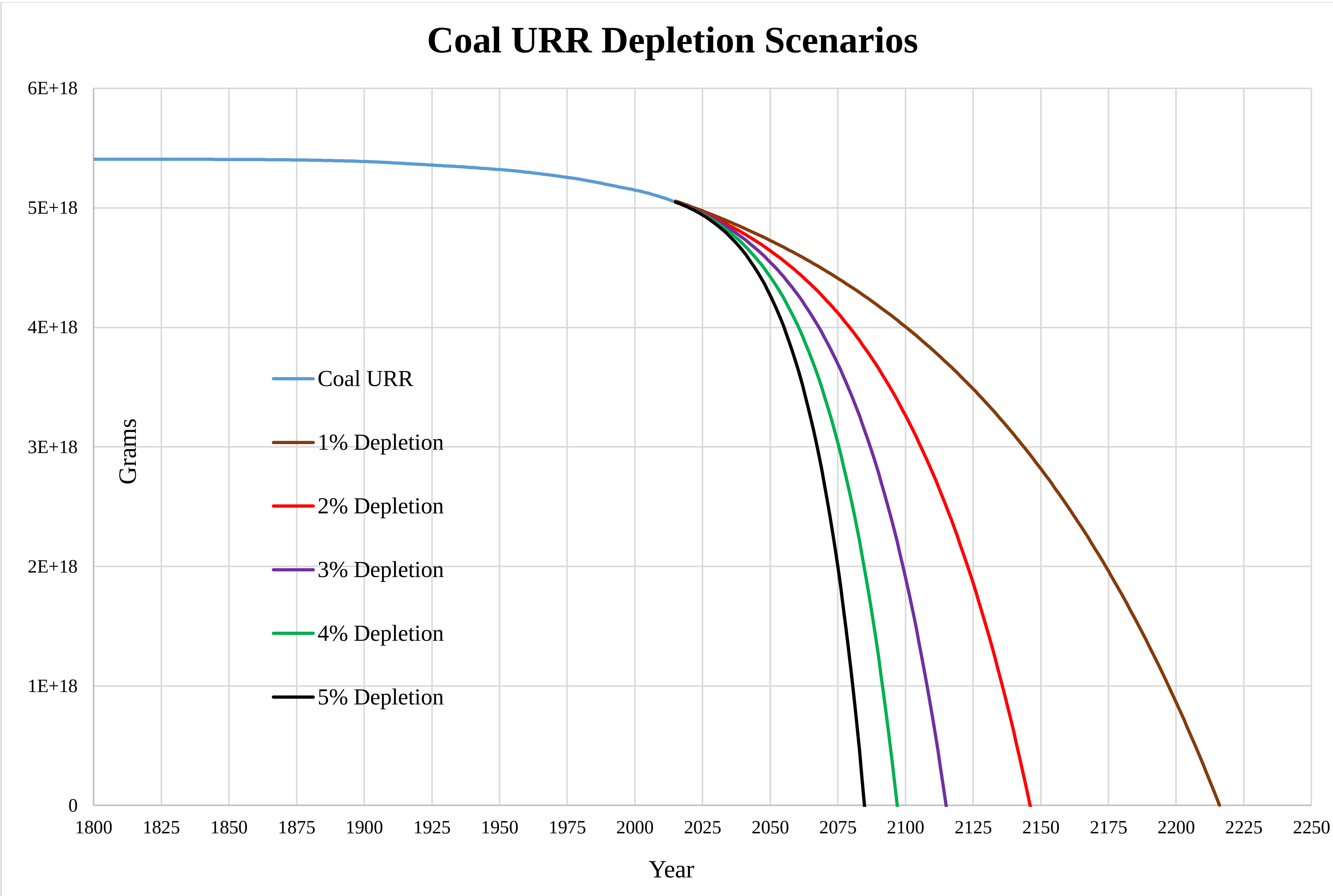

Figure 8: Coal URR depletion scenarios based on 1% – 5% projected annual production rates.

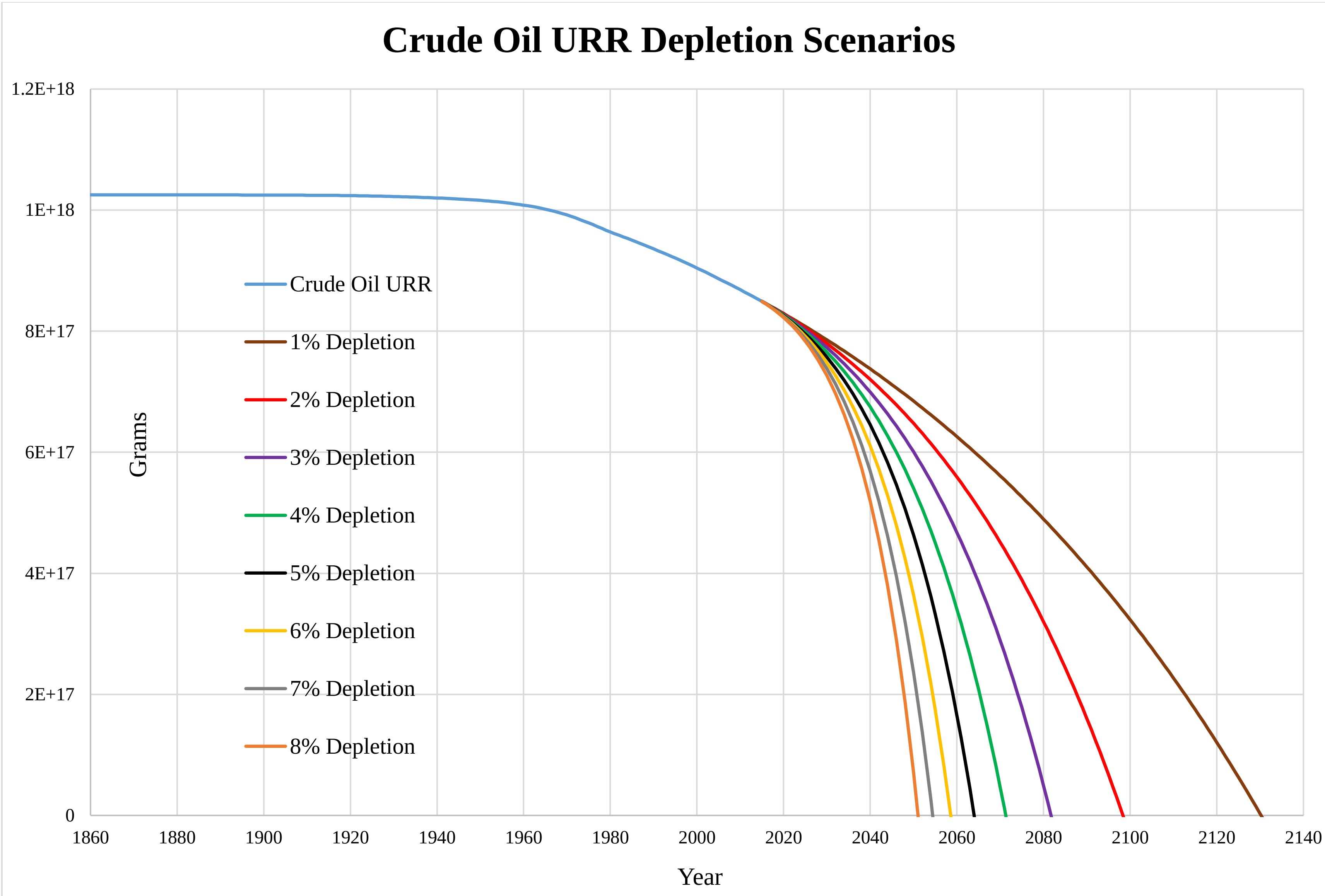

Figure 9: Crude oil URR depletion scenarios based on 1% – 8% projected annual production rates.

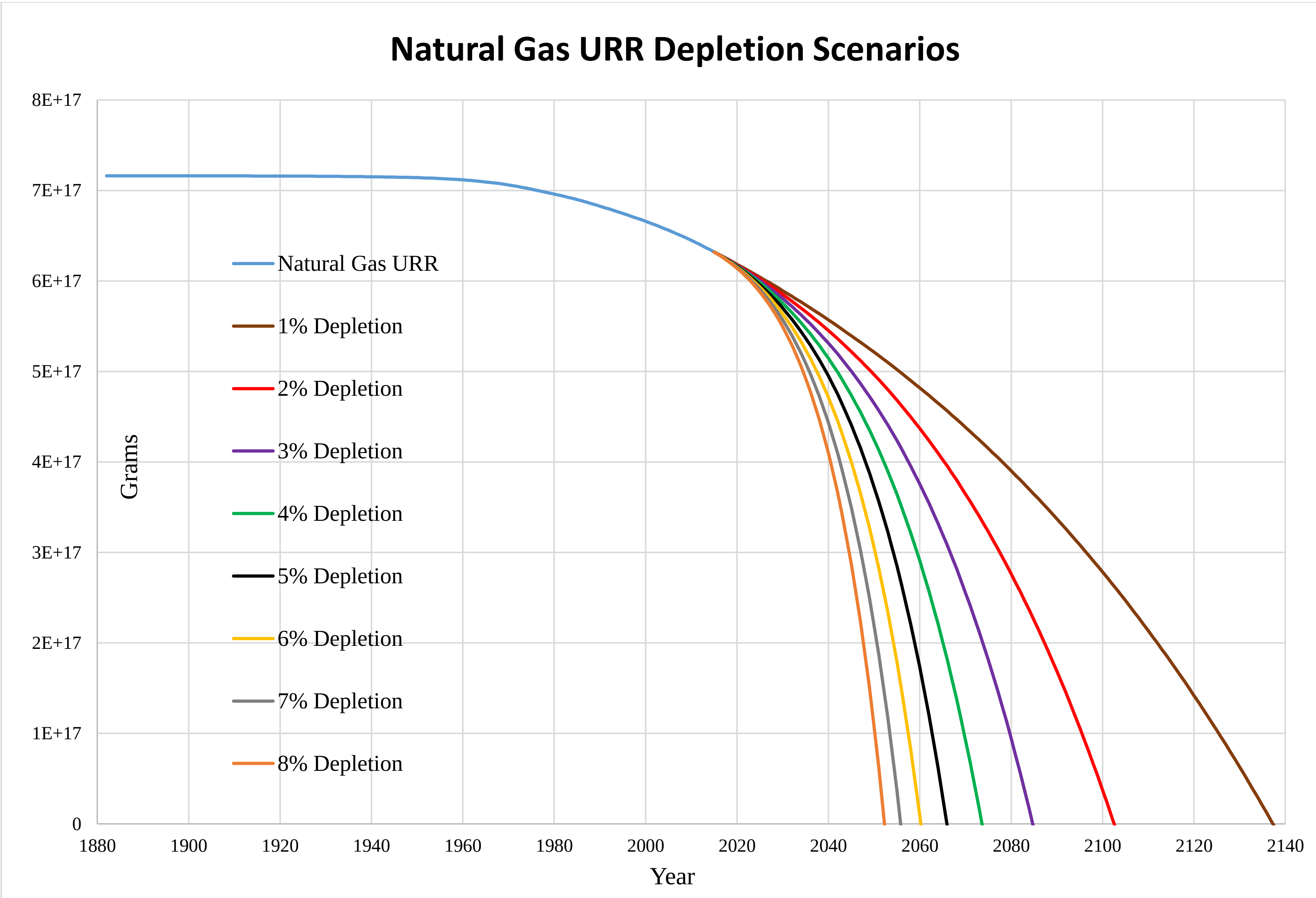

Figure 10: Natural gas URR depletion scenarios based on 1% – 8% projected annual production rates.

natural gas in 2084. Once again, the comparison is less than 50 years for crude oil and within 10 years for natural gas but the coal estimation is way off because Shafiee and Topal believe that coal reserves were not very accurate in the last two decades due to political policies against releasing the real data therefore skewing their coal data. By comparing the previous work to this study, the year in which total depletion might occur is very similar despite this study using somewhat different methodology and units of measure.

XIII. Per Capita Allocation

Another way to analyze how much longer non-renewable energy resources will last is to calculate the per capita allocation of the remaining URR of the resources. This calculation takes the remaining URR and divides it by the global population per year. The generalized population data is from Ortiz-Ospina and Roser (2016) which uses actual UN Population Division data from 1950 – 2015 and then projected population data from 2016 – 2100. The population in the past was estimated using a spline interpolation method which plotted a single series of past population estimates from every one hundred years (Ortiz-Ospina and Roser, 2016). Since the production data only goes back to 1800, only generalized population data from 1800 – 2100 will be used (Figure 11). Population increased exponentially at different rates during this time span; rapid growth occurred from 1800 – 2020 and the growth slows from 2020 – 2100. The growth is still exponential from 2020 – 2100, but it is growing at a lesser rate than the past causing the appearance that the population flattens out.

The resource allocation per capita (Figure 12) is a declining linear graph because the population is growing exponentially positive, while the remaining URR is exponentially declining and dividing the population by the remaining URR causes the converging exponential graphs to produce a linear graph. As of 2014, the remaining URR per capita allocation of the

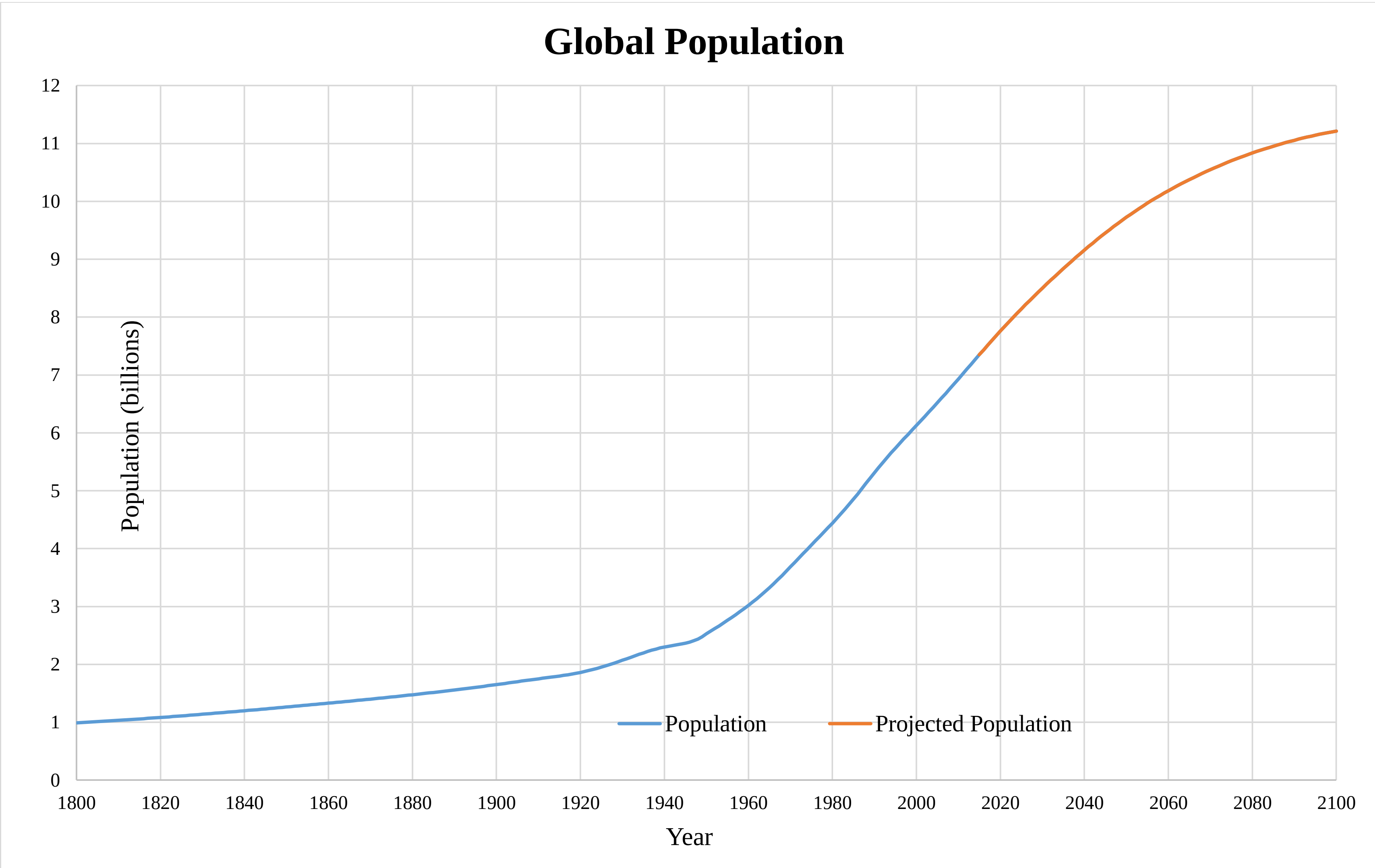

Figure 11: A generalized global population growth model based on current population up to 2015 followed by projected global population using the spline interpolation method **(**Ortiz-Ospina and Roser, 2016**).**

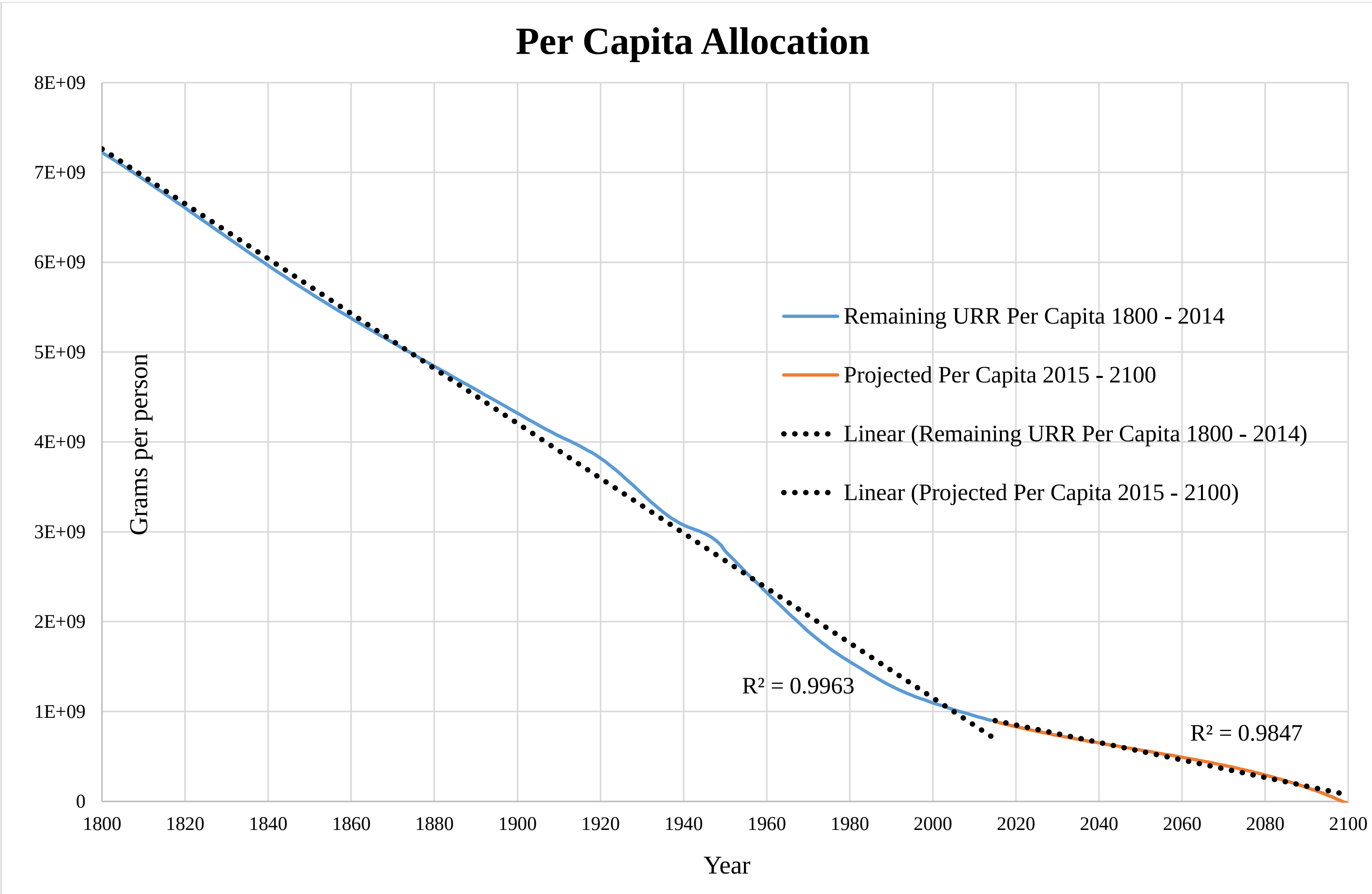

Figure 12: Per Capita allocation based on the total URR depletion of 3.3% per year. The graph is linear due to exponential growth in population and the exponential decline of the total URR.

total non-renewable energy mass is 9.0×10^8 grams which is nearly an order of magnitude lower than in 1800 when the per capita allocation was 7.2×10^9 grams. Since 1800, the per capita allocation is an 8-fold decline driven by the 7-fold increase in global population which also drives the global energy demand through time. The per capita allocation will equal zero in the year 2098. However, a resource crisis will emerge significantly before total depletion because the per capita allocation will fall below the threshold necessary to sustain civilization unless alternate energy is implemented.

In 2014, the total production of non-renewable energy resource mass per capita was 1,970,412 grams per person (approximately 2 metric tons per person) compared to 25,676 grams per person in 1800 (Figure 13). There is inequality in the distribution of the per capita allocation because industrialized nations use more energy per capita than less developed nations. This substantial increase is due to the exponential growth of population and the emergence of technological society because more people consume more energy. At some point humanity must become more efficient to not solely rely on non-renewable energy.

A. Remaining Total URR Per Capita Depletion Scenarios

The per capita allocation can also use the same URR depletion scenarios process discussed previously to forecast per capita allocation based on URR depletion rates. The same principle that were used in the URR depletion scenarios still apply but to calculate the per capita depletion scenarios, we must divide the URR depletion rates per year by the global population per year. The per capita depletion scenarios only go up to the year 2100 because that is the final year that projected global population is available. Since we are only concerned with the data that estimates the different scenarios, a zoomed in display was used from the year 2000 – 2100.

Figure 14 displays the estimated per capita of the total non-renewable remaining URR with different per capita depletion scenarios. In 1800, the per capita allocation of the total non-renewable energy remaining URR was 7.2 x 10^9 grams per person compared to 2014 where the per capita allocation was 9.0 x 10^8 grams per person. Once again, this is an 8-fold decrease in per capita allocation due to global population increasing. The per capita allocation reaches beyond 2100 when the depletion is between 1% – 3% however, if the depletion rate is 4%, the per capita allocation would reach zero in the year 2088.

B. Remaining Coal URR Per Capita Depletion Scenarios

The coal remaining URR per capita in 1800 was 5.5 x 10^9 grams per person and in 2014 it was 7.0 x 10^8 grams per person (Figure 15). The per capita allocation decrease was nearly 8-fold. If the coal depletion rate is 1% – 3%, then the per capita allocation of coal would extend beyond 2100 until it reached zero. But if the depletion rate increase to 4% or 5%, then the per capita allocation would become zero in 2096 at 4% and 2084 at 5%. The coal per capita allocation extends the longest based on the same depletion rates when compared to crude oil and natural gas because coal accounts for 75.6% of the total non-renewable energy on Earth.

C. Remaining Crude Oil URR Per Capita Depletion Scenarios

The crude oil remaining URR per capita is very different than that of coal. Since crude oil is a smaller quantity, the time when the per capita reaches zero occurs sooner given the same depletion rates. In 1800, the per capita allocation of the remaining crude oil URR was 7.7 x 10^8 grams per person and as of 2014, the per capita allocation was 1.2 x 10^8 grams per person (Figure 16). This decrease in per capita allocation was approximately 6-fold. The per capita allocation would only extend past 2100 at 1% depletion. The per capita depletion rates of the remaining URR of crude oil are almost identical than the depletion scenarios in Figure 9.

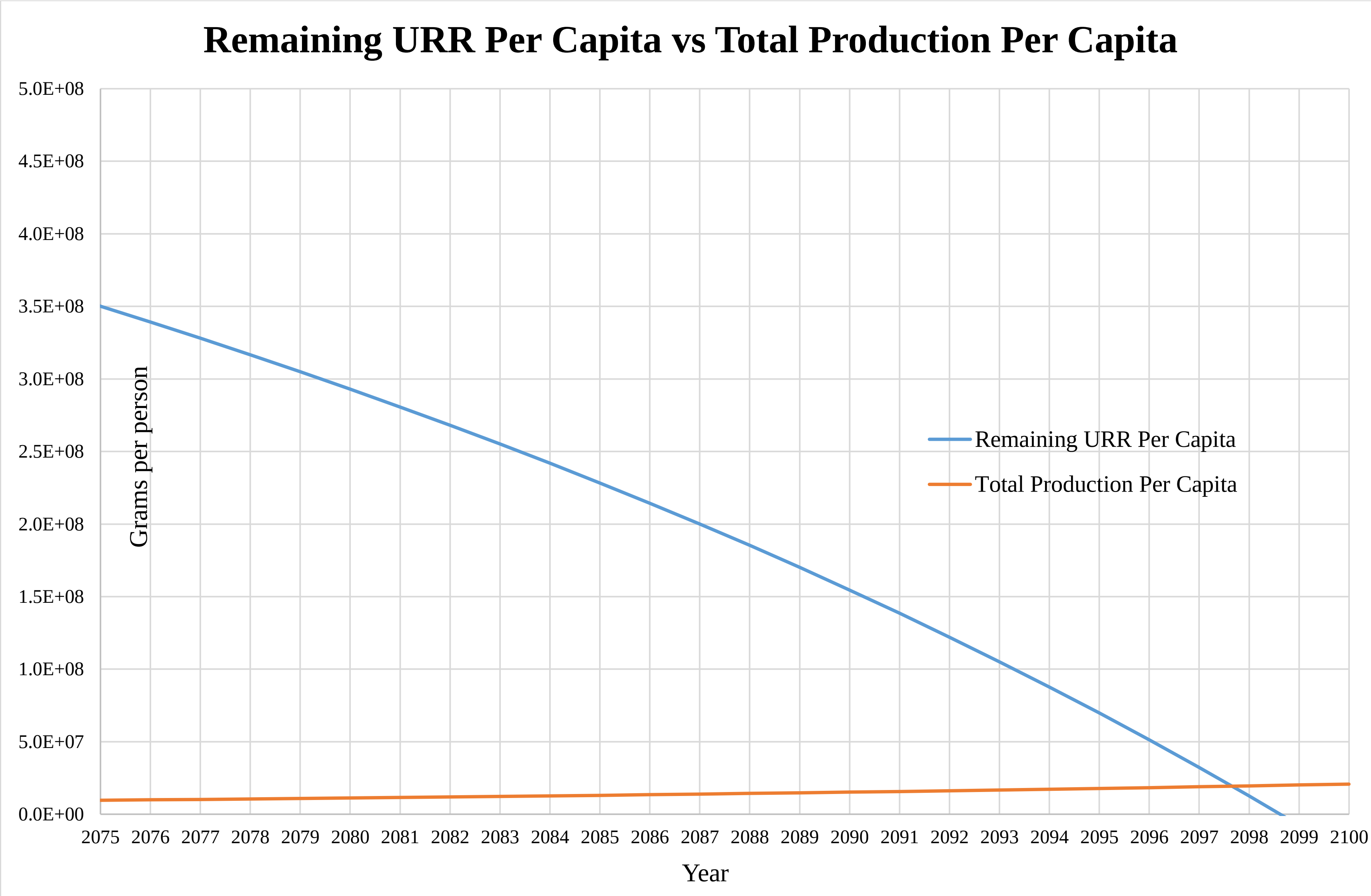

Figure 13: The threshold of the remaining URR per capita and the total production per capita with total depletion of the remaining total URR occurring in 2098.

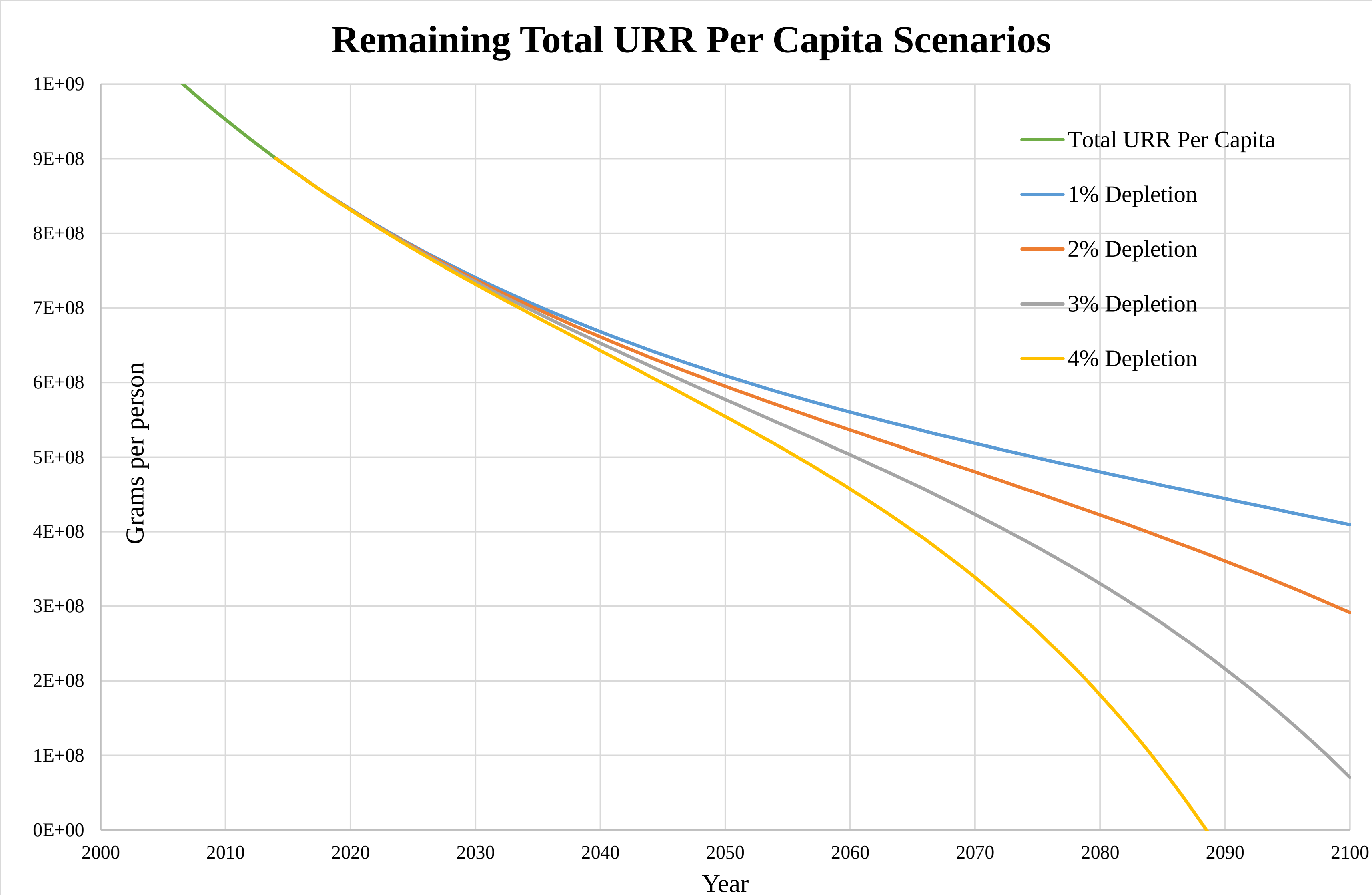

Figure 14: Per capita depletion scenarios based on different production (consumption) rates with using the same global population growth model in figure 11. Depletion rates of 1%, 2%, and 3% extend past 2100.

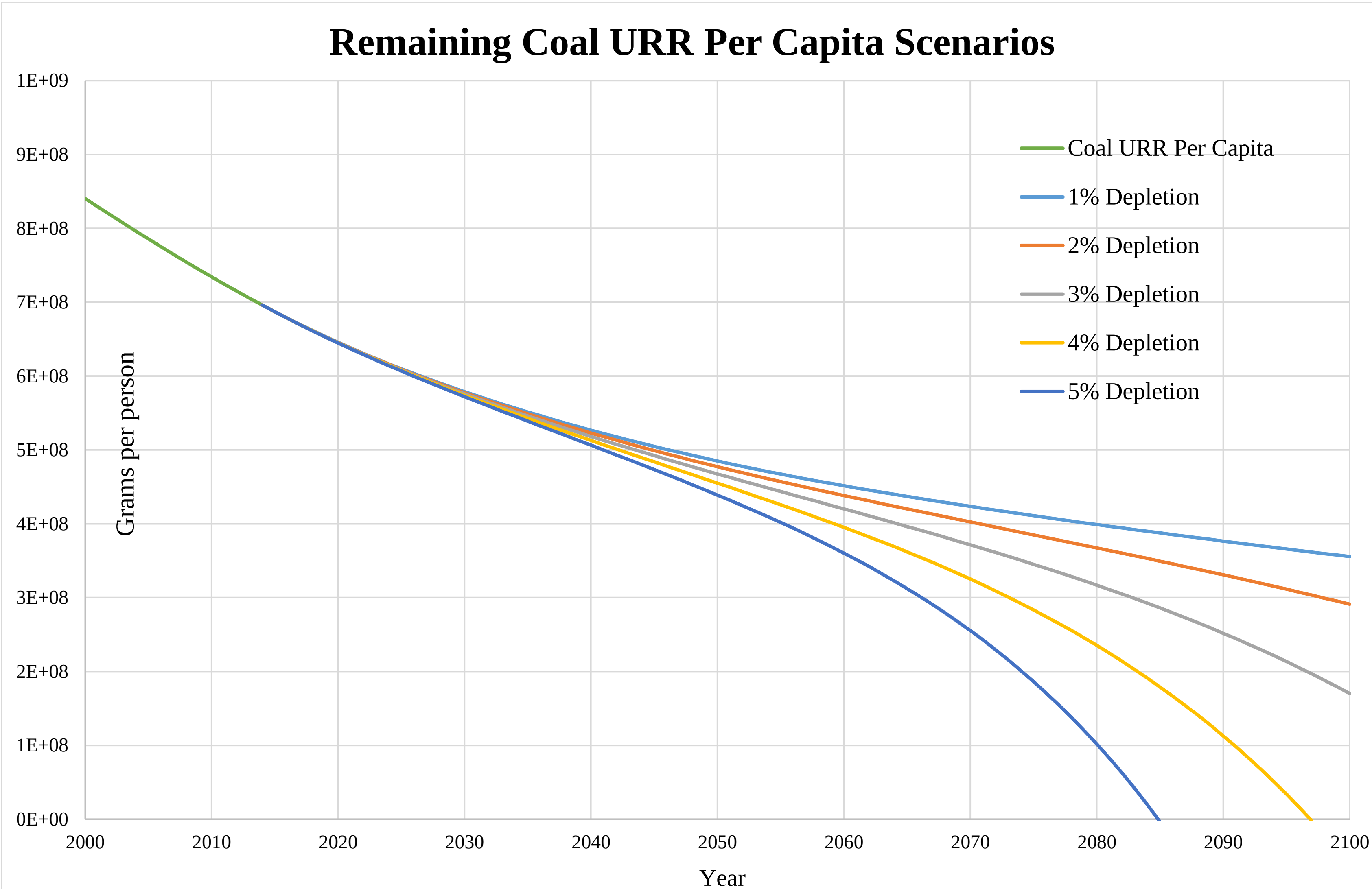

Figure 15: The per capita depletion scenarios of coal based on different production (consumption) rates with using the same global population growth model in figure 11. Depletion rates of 1%, 2%, and 3% extend past 2100.

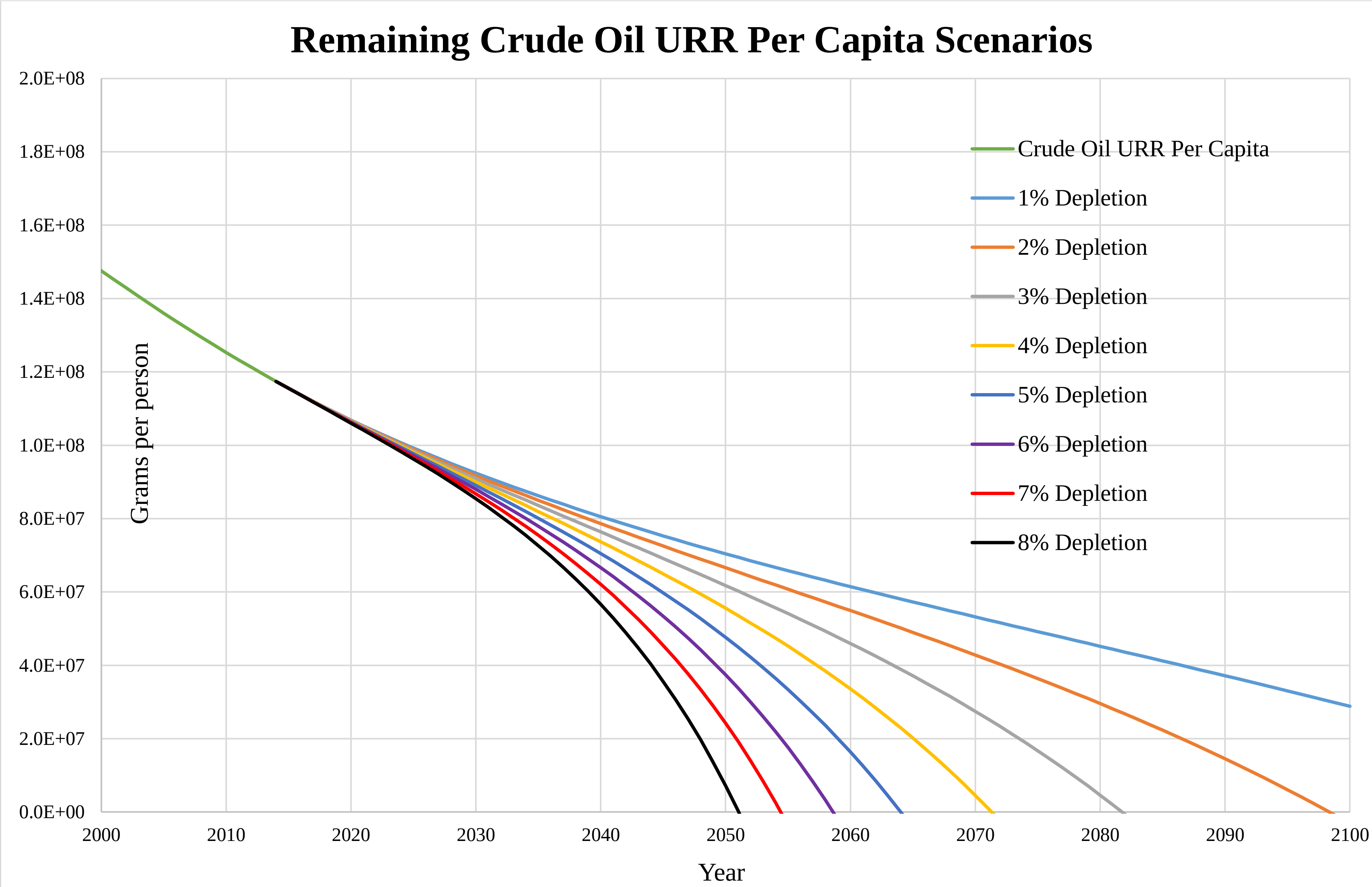

Figure 16: The per capita depletion scenarios of crude oil based on different production (consumption) rates with using the same global population growth model in figure 11. Only the depletion rate at 1% will extend past 2100.

URR in Table 3. The 2% – 8% per capita depletion of crude oil will reach zero before the year 2100.

D. Remaining Natural Gas URR Per Capita Depletion Scenarios

The natural gas remaining URR per capita also mirrors the crude oil remaining URR per capita. The per capita of the remaining URR of natural gas in 1800 was 4.8×10^8 grams per person and as of 2014, the per capita allocation was 8.7×10^7 grams per person (Figure 17). The per capita allocation decrease was approximately 5-fold due to the fact that natural gas is an even smaller quantity than that of crude oil and coal. Once again, the natural gas remaining URR per capita is virtually identical to the URR depletion scenarios of natural gas in Table 3. The depletion rates of 1% and 2% would extend past the year 2100 while the depletion rates of 3% – 8% will become zero before 2100.

XIV. Nuclear Energy

Not only are coal, crude oil, and natural gas a non-renewable energy, uranium ore is also considered a non-renewable energy. In 1938, a process called nuclear fission, which is a radioactive decay process in which the nucleus of an atom splits into smaller, lighter nuclei, was discovered. This process was proved by weighing the atomic masses of the fission products of the uranium splitting and they did not equal the original uranium's mass which indicates that the loss of mass changed to energy. Scientist began to discuss the possibility of a self-sustaining chain reaction where uranium atoms could be split to release a large amount of energy but would only happen if enough uranium was brought together under the proper conditions. By 1942, a group of scientist at the University of Chicago began construction on the world's first nuclear reactor, known as *Chicago Pile-1*, and the world entered the nuclear age (U.S. Department of Energy, 2016).

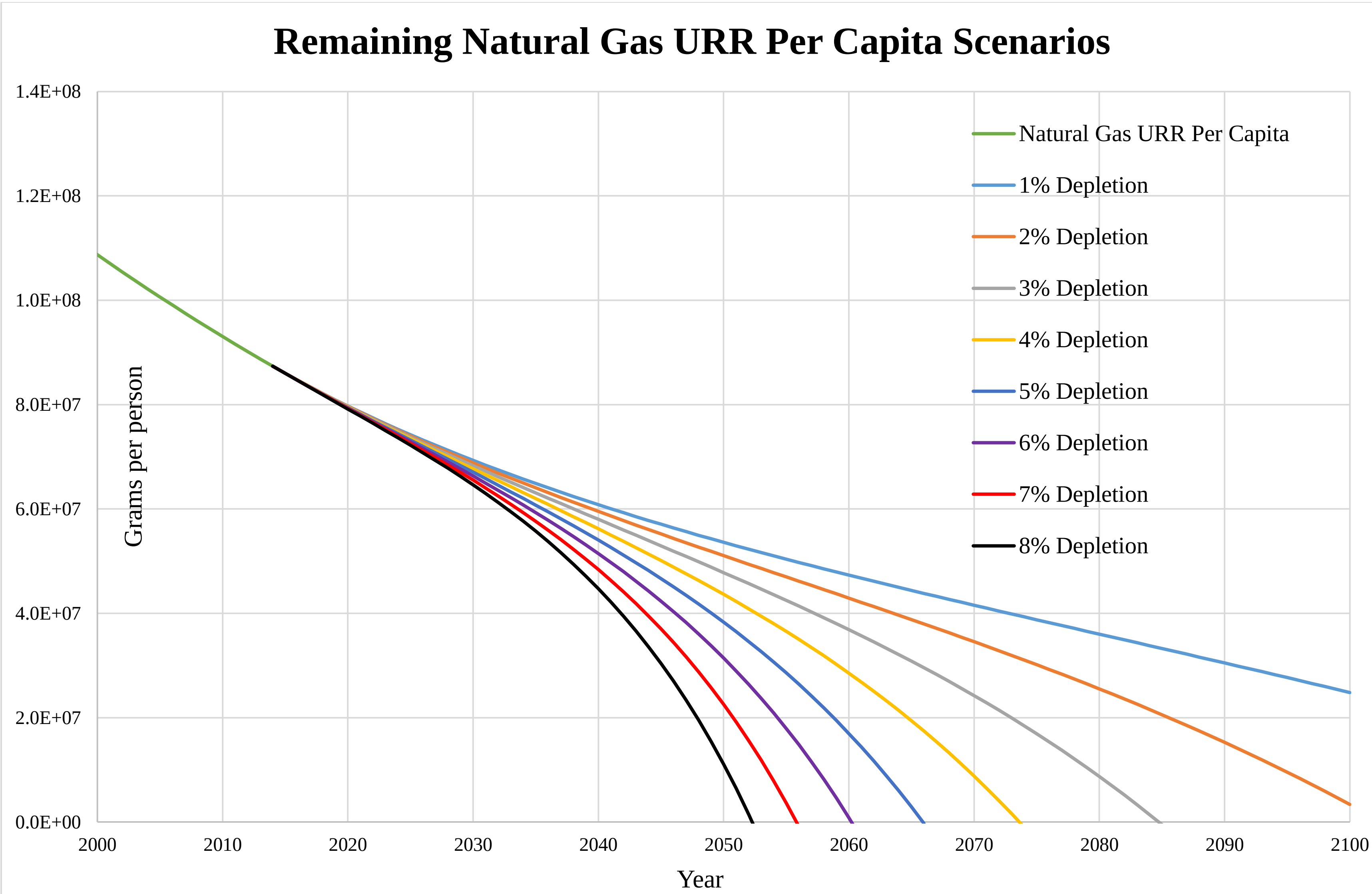

Figure 17: The per capita depletion scenarios of natural gas based on different production (consumption) rates with using the same global population growth model in figure 11. Depletion rates of 1% and 2% extend past 2100.

Under the code name *Manhattan Project*, early atomic research was focused on developing atomic bombs for use in World War II. However, after the war, on December 20,1951. The Atomic Energy Commission authorized the construction of Experimental Breeder Reactor I in Arco, Idaho, which is the first reactor to generate electricity from nuclear energy (U.S. Department of Energy, 2016). However, in 1954, the world's first nuclear power plant that generated electricity was assembled for commercial use in Obninsk, Russia with a net electrical output of 5 MW (European Nuclear Society, 2016). Nuclear energy grew rapidly in the 1960s as it was seen as economical, environmentally clean, and safe. But in the 1970s and 1980s, the growth slowed and concerns of reactor safety, waste disposal, and other environmental considerations grew.

The world produces as much electricity from nuclear energy today as it did from all energy sources combined in the late 1940s. There are about 440 commercial nuclear power plants operational in 31 countries and about 65 more power plants are under construction. These nuclear power plants supply over 11% of the global electricity as, continuous, reliable power without carbon dioxide emissions. Also, 56 countries have built 240 civil research reactors for scientific research of medical and industrial isotopes and another 180 nuclear reactors power approximately 140 ships and submarines (World Nuclear Association, 2016a). Across the world, nuclear energy generates electricity through thermoelectric power plants by heating water in a boiler until it turns into steam. The steam is then used to spin a turbine which generates electricity. After the steam has spun the turbine, it is sent to a condenser to be cooled back into water so it can be converted to steam once again to produce more electricity.

The uranium production data is from the Organization for Economic Co-operation and Development, Nuclear Energy Agency (OECD NEA, 2006) and the World Nuclear Association

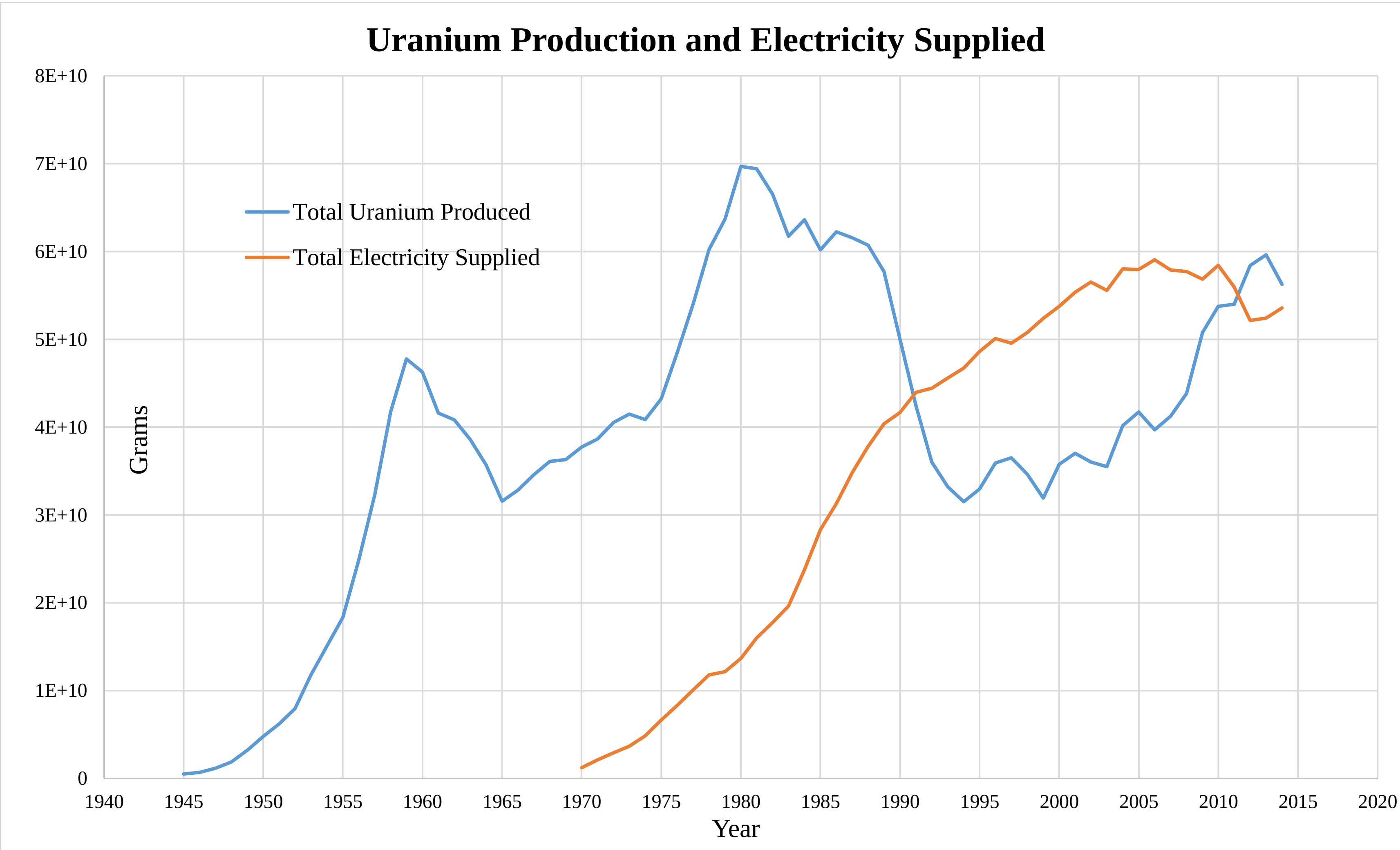

Figure 18: Uranium production data from 1945 – 2014. The total uranium produced was 2.74 x 10^{12} grams (OECD NEA, 2006 and World Nuclear Association, 2015). The global electricity supplied by nuclear power plants from 1970 – 2014. The total uranium used to generate the electricity is 1.64 x 10^{12} grams (IAEA, 2016 and World Nuclear Association, 2016a). Only 60% of the total uranium produced was used to generate electricity in nuclear power plants.

(2015). Uranium production growth is very different than that of coal, crude oil, and natural gas. Data recording of uranium production began in 1945 however, uranium was not used for nuclear energy until 1954, when the first nuclear power plant was created. It appears that uranium production does not follow any specific trends other than mining it when there is an increase in global energy demand. The total quantity of uranium is millions of times less than the total non-renewable energy from fossil fuels.

The uranium production data does not specify how the uranium was used, but we can calculate how much uranium was used to generate electricity from nuclear power plants across the world. The World Nuclear Association (2016) provided the nuclear electricity supplied (kWh) per year data from nuclear power plants since 1970 until 2008 and from 2009 – 2014, the data was available from the International Atomic Energy Association (IAEA, 2016) (Figure 18). The electricity supplied can be converted to the original mass of uranium by using the conversion factor of 1 kg of uranium produces 45000 kWh of electricity (European Nuclear Society, 2003). Dividing the electricity supplied per year by 45000 kWh equals the mass of uranium that was used to generate the recorded electricity supplied.

The total uranium produced from 1945 – 2014 is 2.74×10^{12} grams and the total electricity supplied from 1970 – 2014 is 1.64×10^{12} grams. The quantity of uranium used to generated electricity is negligible to the total produced quantity of coal, crude oil, and natural gas. Of the total uranium produced, only 60% was used to generate electricity from nuclear power plants while the other 40% has no record of where it was used. We can assume that some of the unaccounted uranium was used for scientific research in medicine with a large portion of the 40% most likely used for government programs.

XV. Conclusions

Non-renewable energy which includes crude oil, coal, natural gas, and uranium is the primary energy resource meeting global demand for energy. As world population continues to grow, more and more non-renewable energy resource is consumed and eventually will be depleted. My research attempted to estimate the total quantity of non-renewable energy mass that was present on Earth prior to consumption and the quantity remaining to be consumed. This was accomplished by fitting trend lines to known resource production data for each non-renewable energy resource and extrapolating into the future using various consumption growth scenarios. I believe the estimation of the initial amount of non-renewable energy mass is of the appropriate order of magnitude and is a reasonable estimation based on currently available data. This estimation helped determine the percentage of non-renewable energy consumed and how much remains to be consumed. Modeling production by using different growth scenarios and the impact of population aids understanding of the future allocation of resources for humanity.

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