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The American Energy Security Crisis Solution—Space Solar Power

By James Michael "Mike" Snead

Introduction

It is 11:39 pm, April 14, 1912 and you are comfortably enjoying a transatlantic voyage from England to New York on the world's newest, largest, and safest ocean liner—the *RMS Titanic*. The weather outside has turned clear and brisk due to air and water temperatures having rapidly fallen in the last few hours. Stepping outside, the sky is awash in stars from horizon to horizon on the moonless night. The water is almost flat due to the absence of wind. The unrivaled power of the Titanic can be felt through the decking as it steams at near its maximum speed. Unknown to you, disaster is less than a minute away, your live or die moment at the hands of the heartless Atlantic less than three hours away; the cause yet unseen, however, by the forward observers.

The captain—an experienced mariner of these Transatlantic voyages—has made a fatefully wrong assumption. In 1912, eyes were still the herald of danger ahead. The captain has assumed that, with such clear viewing conditions, his observers in the crow's nest and his bridge crew will have twenty minutes or so of warning should an iceberg or ice pack appear ahead of the ship. With that amount of warning, stopping or turning the ship to avoid the ice can easily be accomplished.

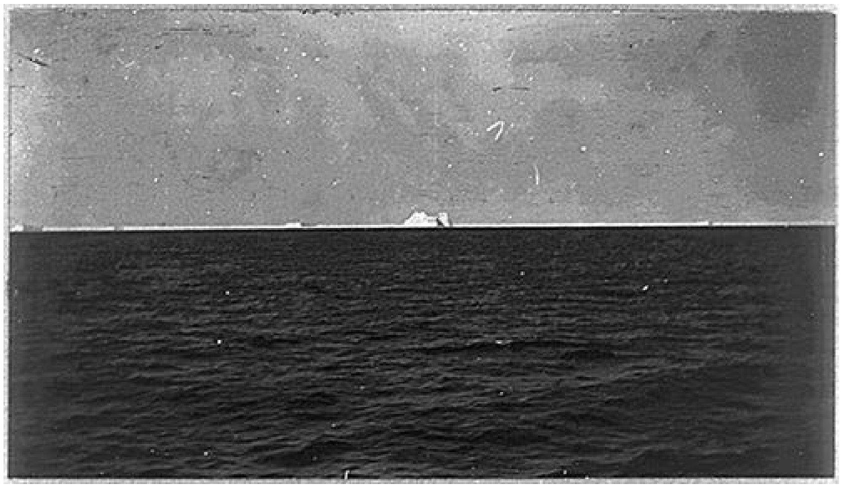

Fig. 1. View from S.S. CARPATHIA of the iceberg which sank the Titanic. Note the other ice and sea condition. http://www.loc.gov/pictures/item/2002721381/

What the captain did not understand was that nature was playing a trick on him that evening. A mirage had formed, due to the difference in air and water temperatures ahead of the ship, which hid the iceberg from view. The mirage brought the image of stars down to the horizon ahead, masking the iceberg from sight. Only too late did the observers in the crow's nest spot the iceberg. No matter what could then have been done by even the most experienced crew, the 40 seconds or so available to respond from first sighting was simply insufficient. The ship and well over a thousand souls were lost. In this small bubble of human civilization crossing an ocean in the leading edge of human technology, its leader judged poorly by ignoring radioed warning messages of ice ahead. He thought he had plenty of time to respond. In reality, he did not understand the dire circumstances his ship faced. Entirely within his control, he let his ship steam into disaster.

Just as the Titanic had blindly entered an ice field that fateful night, its captain confident that he controlled his ship's future, American civilization has entered a new energy security crisis as it blindly pushes forward in the 21st century. Simply put, the United States lacks sufficient technically recoverable, affordable fossil fuels to sustain its increasingly energy-hungry culture through the end of this century. Consequently, absent the building of substantial new sustainable energy sources, in time to transition smoothly from fossil fuels, American culture will undergo disaster. Only the foolish will shrug off this disaster-in-the-making.

The facts supporting this contention are quantifiable and easily understandable. The conclusion is simple arithmetic showing that the U.S. energy security ledger is substantially in the red. While our leaders—our politicians, our government officials, our leading businessmen—probably know this information, it is very clear that they do not understand the severity of the very real threat and the "ice" ahead into which they are steaming. Because of this, American culture—and civilization—is at very serious risk.

The purpose of this paper is to provide the quantitative information needed to understand the seriousness of this crisis, to examine the technological alternatives available to resolve this crisis, and to make clear why space-based solar power is, at this time, the only alternative to pursue. With this information, a new generation of American leadership can arise to lead America out of this crisis.

Section I – The Importance of Energy to our American Culture

Cultural anthropology provides the needed framework for understanding the energy security challenge now squarely facing Americans—specifically, the anthropological study of the relationship of culture to energy undertaken by American anthropologist Leslie White.

White's Law Provides the Framework for Understanding our Energy Security Challenge

White establishes these two key thought anchors:

- **Culture**, as White defines it, "consists of tools, implements, utensils, clothing, ornaments, customs, institutions, police, rituals, games, works of art, language, etc."[1] In other words, culture is what separates modern man from living in a cave, gnawing at uncooked food, and living a short and brutish existence. Culture can be defined as standard of living. Almost everything Americans do is done within the physical expression of culture.

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[1] Leslie A. White, *The Evolution of Culture* (New York: McGraw-Hill, 1959), 3.

- **Energy**, as White uses this term, is "the capacity for performing work."[2] Work (whether by humans, animals, or machines) is what produces the products and supplies the services that constitute culture and enable us to live prosperously.

Bringing culture and energy together, White defines his law of cultural evolution as "Other factors remaining constant, culture evolves as the amount of energy harnessed per capita per year is increased, or as the efficiency of the instrumental means of putting the energy to work is increased."[3] "Instrumental means" is a fancy way of describing the technology embodied in the products and services forming our standard of living and the industry producing these products and services.

His arguments are summarized on Wikipedia as:

1. Technology is an attempt to solve the problems of survival.
2. This attempt ultimately means capturing enough energy and diverting it for human needs.
3. Societies that capture more energy and use it more efficiently have an advantage over other societies.
4. Therefore, these different societies are more advanced in an evolutionary sense.

While this line of thinking is exceptional, White expressed his law with a simple symbolic expression that is very understandable:

$$E \bullet T \Rightarrow C$$

Where:

- **E** is the energy used to produce the goods and services consumed. E can be expressed either as the energy used per person (per capita) or the total energy used by the political unit (e.g., the United States).
- **T** are the technologies, using modern energy forms, used to produce the goods, services, and energy at a particular point in time, as well as the technologies embedded in the products. Technology is the application of science through engineering and manufacturing.
- **C** is the standard of living achievable, at a point in time, using available design, manufacturing, and product/service technologies when supplied with sufficient energy of the correct type.

The symbol "•" is used to express the ***interaction*** of energy with technology. It is not a symbol indicating multiplication. Likewise, the symbol "⇒" is not an "=" expressing equality; it is better understood as indicating ***yields***.

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[2] Leslie A. White, "Energy and the Evolution of Culture," *American Anthropologist* 45, no. 3 (July-September, 1943): 335.

[3] Leslie A. White, *Energy and the Evolution of Culture* (New York: Grove Press, 1949), 111.

America's Energy Security Challenge is to meet our Children's Energy Needs

White's Law, with just five common symbols, captures the fundamental essence of the challenge America (and the world) has this century to REMAIN civilized. America's energy security challenge this century is: *Will America have enough energy of the right type, combined with sufficiently capable technology, to yield an acceptable standard of living for our children and grandchildren?*

With the life expectancy of Americans now commonly stretching into the 80s, many of today's newborns will easily live to see the opening of the 22nd century. Thus, as a society of responsible adults/parents/grandparents understanding the clear implications of White's Law, our national energy security planning horizon now stretches at least to 2100. In terms of White's Law, we are, therefore, responsible to see that the following relationship holds true:

$$E_{\text{America in 2100}} \bullet T_{2100} \Rightarrow C_{\text{America in 2100}}$$

where:

$$C_{\text{America in 2100}} \geq C_{\text{America today}}$$

Expressing this in terms of per capita energy consumption (e) and the U.S. population:

$$(e_{\text{American in 2100}} \times \text{Population}_{\text{United States in 2100}}) \bullet T_{2100} \Rightarrow C_{\text{America in 2100}}$$

The philosophical beauty of this formulation of America's energy security dilemma/challenge is that it allows us to dissect this dilemma/challenge into its pieces, study them, understand them, and use this information to formulate an implementable engineering solution that will make the above expression valid. The starting point is to understand America's population growth through 2100. Population size is the primary consideration in assessing U.S. energy security.

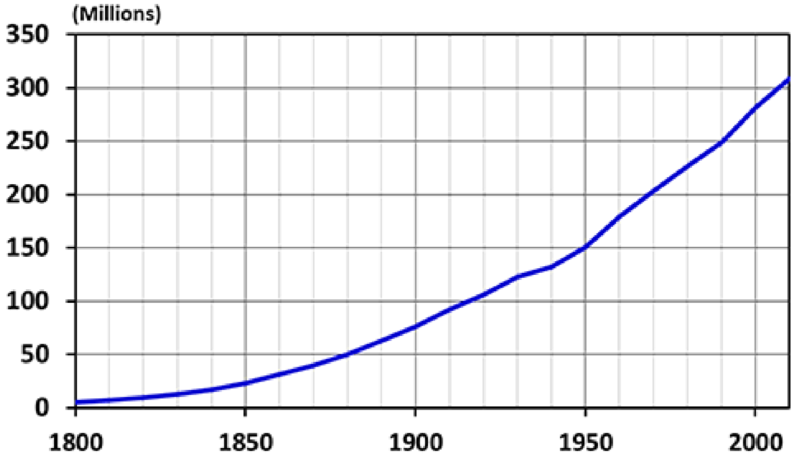
Section II – Forecasting America's Energy Needs in 2100

While politicians may wish to speak in generalities, engineers prefer to express our thinking quantitatively. Fortunately, the critical issue of planning for America's energy needs in 2100 easily lends itself to being defined quantitatively. In fact, it is a matter of simple arithmetic. The two important pieces of information needed to forecast America's energy needs in 2100 are the size of the population and the expected energy supply needed per person (per capita) each year to maintain a prosperous standard of living.

America's Population Will Likely More Than Double By 2100

America's demand for natural resources is driven by its population size. Over the last two centuries, America's population has climbed steadily from around 5-8 million in 1800 to around 307 million in the last census in 2010 (Fig. 2).

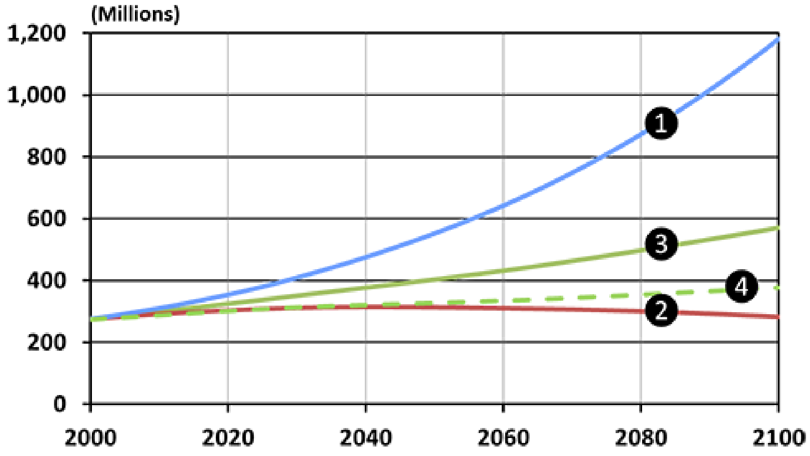
Fig. 2 - U.S. population (1800-2010)



(Original data source: U.S. Government)

In 1999, the U.S. Census Bureau made several forecasts of the U.S. population through 2100.[4] Figure 3 shows three of these forecasts establishing an upper ❶, a lower ❷, and a middle ❸ series projection based on assumptions of fertility and death rate, along with continued immigration.[5] Of these three forecasts, the middle series is used in this paper as the basis for projecting American population size in 2100.

Fig. 3 - U.S. population projection (2000-2100)



(Original data source: U.S. Census Bureau, 1999)

In 2008, the Census Bureau updated the 1999 projection through 2050. This is shown in Fig. 4. Using this update, a linear extrapolation is then used to establish a ballpark

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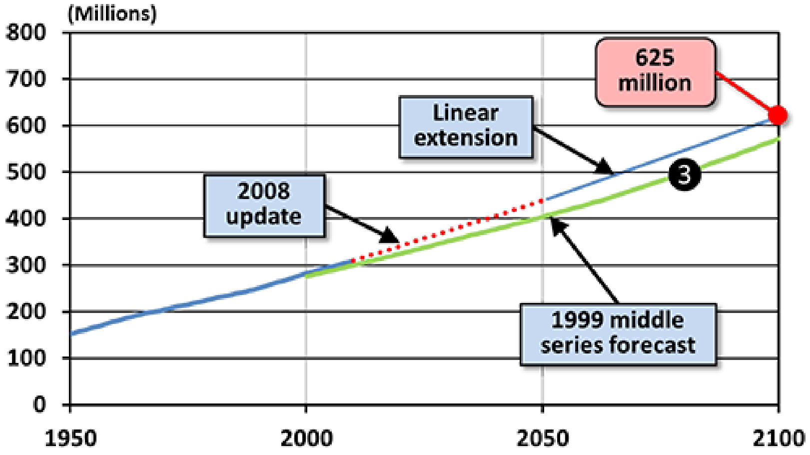
[4] http://www.census.gov/population/projections/files/natproj/summary/np-t.txt; http://www.census.gov/population/projections/files/natproj/summary/np-t1.txt.

[5] For comparison, the dashed line ❹ represents the middle series forecast but with zero immigration. Used as a point of reference, it shows that about two thirds of the U.S. population growth through 2100 will be due to immigration.

estimate of the 2100 U.S. population size of 625 million used in this paper. As seen in Fig. 3, this is about 60 million greater than the 1999 forecasted 2100 population, indicating that, as the century unfolds, even this 625 million forecast may prove conservative—a point to keep in mind![6]

Fig. 4 - U.S. population projection to 2100 used in this paper



(Original data source: U.S. Government)

With a planning estimate of 625 million Americans in 2100 as the starting point, the next step in assessing White's Law is to examine U.S. per capita energy use.

Per White's Law, American Culture is Quantitatively Defined by Its Per Capita Energy Use

At the heart of the American industrial revolution of the later 19th century was the expenditure of increasing amounts of energy per person (per capita) to make life better. In a general sense, per capita energy use is a good quantitative measure of our culture or standard of living since, by White's Law, they are related.

To discuss per capita energy use, we need a readily understandable unit of measure. For this paper, the barrel of oil equivalent or BOE is this unit. An actual barrel of oil contains 42 U.S. gallons. By international agreement, this amount of oil is assumed to contain 5.8 million British Thermal Units or BTUs of energy.[7]

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[6] The reader should consider the implications of liberalized U.S. immigration policy, as proposed by some, on any estimate of the size of the U.S. population in 2100. Most immigrants come to America to "adopt" our standard of living which, by White's Law, means they and their children are adding to our future energy needs. There is nothing in White's Law granting them a waiver with respect to their impact on future U.S. energy needs.

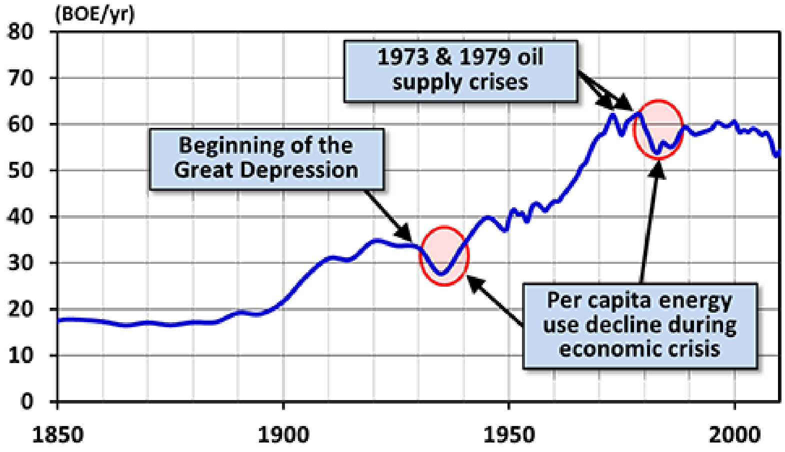
[7] A British Thermal Unit or BTU is the amount of thermal energy required to increase the temperature of one pound of water by 1°F. The BTU was defined in the early days of steam engine development to quantify how much thermal energy was released by the combustion of fuels such as wood and coal. To understand better how much heat is involved, heating a cup of tap water to the start of boiling to make a cup of tea requires about 70 BTU.

1 BOE = 5.8 million BTU

All forms of energy production or consumption can be expressed in terms of the BOE of gross thermal energy produced or consumed. This is true even for production methods such as hydroelectricity that do not involve any form of combustion. In such cases, the actual electrical energy generated is replaced by the amount of oil that would be required to generate the same quantity of electrical energy using an oil-fired power plant.

The U.S. Government has kept reasonably good energy production and consumption statistics since the 1850s. By summing up the types of energy produced, converting this to the common unit of BOE, and then dividing by the U.S. population at the time, an historical per capita energy use, expressed in BOE/yr., can be determined. The calculated annual U.S. per capita energy use from 1850-2010 is shown in Fig. 5.[8]

Fig. 5 - U.S. per capita energy use (1850-2010)



(Data source: Composite of publicly available data)

Up until the Civil War, non-food per capita energy consumption was primarily for cooking and space heating. The 17 BOE/yr. of per capita energy consumption was almost entirely from wood fuel—around five cords of seasoned hardwood per person per year. While there was a modest amount of steam-powered transportation and industry, prior to the Civil War this did not significantly impact per capita energy use. For example, in 1850 there were only about 9,000 miles of railroad. Also, during this mid-century period, building construction and heating technology (T) improved, especially with the introduction of cast iron stoves to replace open hearths for cooking and heating. This increased the efficiency of the use of wood fuel, allowing more work to be performed per cord of wood fuel.

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[8] Note that annual energy production/consumption data reporting did not start until 1950. Prior to that year, reporting was at 5-year intervals creating the impression of less year-to-year variation.

The impact of the American industrial revolution began to be reflected in increased per capita energy use about 1890 as the nation shifted from wood fuel and human/animal power to steam-powered transportation and industry; to electricity generation; to coal, oil, and natural gas fuels; to oil-fueled transportation; and to electricity-powered communications, entertainment, homes, and industry. As seen in Fig. 5, with the exception of the Great Depression, per capita energy use climbed fairly continuously from 1900 until the early 1970s—rising from about 22 BOE/yr. in 1900 to the historic peak of about 62 BOE/yr. just prior to each of the two oil supply crises of 1973 and 1979.

Despite 30 Years of Intense Emphasis on Conservation, American's Per Capita Energy Use Has Only Very Modestly Declined

To forecast the average U.S. per capita energy need in 2100, a baseline representative of the future American culture is needed. The period of 1960-2010—roughly the last half-century—is used. This covers the period of the rapid rise in per capita energy use during the 1960s, the peak in domestic oil production in 1970,[9] the twin historic peaks in the 1970s, the two oil crisis-induced economic recessions,[10] the subsequent two decades of a very modest decline in per capita energy use, and the beginning of the current recession. It was during this half century that the modern American lifestyle was established—a lifestyle that, it is presumed, Americans in 2100 will wish to continue if not improve.

Figure 6a shows the total annual gross thermal energy used over the last half century more than doubling from 8 billion BOE/yr. in 1960 to nearly 18 billion BOE currently. The key point of this figure is emphasizing the fact that the U.S. total energy consumption continued to increase at a fast pace despite, as seen in Fig. 6b, a leveling off and modest decline in per capita energy use. This emphasizes the major influence of population size in defining America's energy needs in the future.

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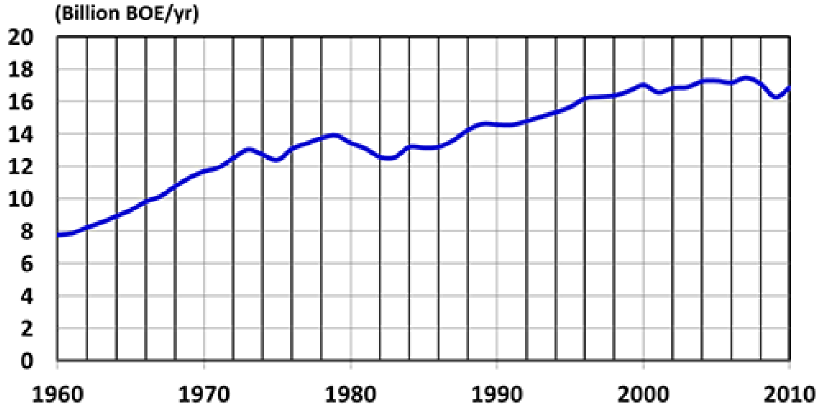
[9] Beginning in the late 1950s, the United States began to import large quantities of oil as demand outpaced domestic production. In 1970, domestic oil production peaked even as domestic demand continued to grow. At this point, the U.S. vulnerability to a disruption in oil imports became significant as oil imports surged from about 1 billion BOE in 1970 to over 2 billion BOE in 1973 at the time of the first oil supply crisis.

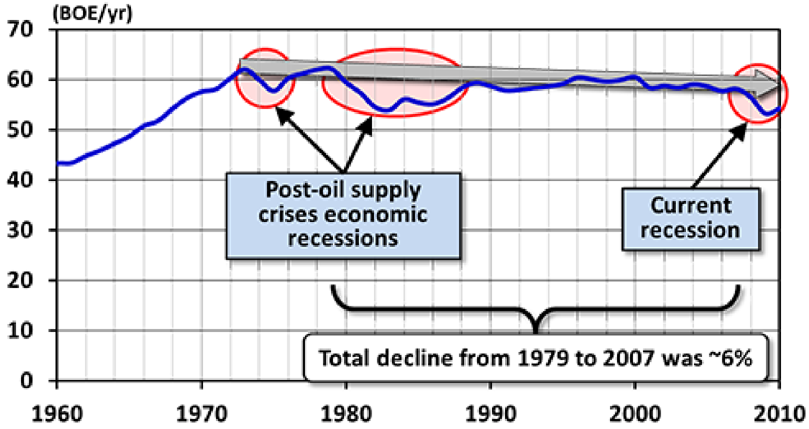
[10] The first oil supply crisis arose in 1973 during the 4th Arab-Israeli War, also known as the Yom Kippur War. Due to a reversal of fortunes on the battlefield by the attacking Arab forces, some oil-exporting countries in the region initiated an embargo of the United States in an attempt to dissuade U.S. military support for Israel during the conflict. World oil prices more than doubled. While the military aspects of the conflict were resolved in fairly short order, the economic consequences persisted in the United States for nearly five years before per capita energy use returned to pre-crisis levels. The second oil supply crisis started following the hostage-taking of U.S. citizens in Iran in 1979. The hostage situation persisted for well over a year. In response, the United States embargoed oil imports from Iran. This drove world oil prices to near $100/barrel in 2010 dollars. With oil supplies constrained, with natural gas supplies also constrained due to over-regulation by the government, and with high world oil prices, the United States entered a severe recession with high unemployment, high interest rates, and high inflation. It took nearly a decade for per capita energy use, as a measure of the standard of living, to return to near pre-crisis levels.

Fig. 6a – Annual U.S. gross thermal energy consumed (1960-2010)



(Data source: U.S. Government and author's projection)

Fig. 6b - U.S. per capita energy use (1960-2010)



(Data source: Composite of publicly available data)

The chart of U.S. per capita energy use over the last 50 years, seen in Fig. 6b, is a remarkable example of a civilization adapting to circumstance. Imagine it is still the early 1970s and you are plotting per capita energy use since 1900 in order to forecast America's energy needs in the 21st century. What would you have forecast for 2010? A simple linear extrapolation would put per capita energy use somewhere in the range of 100-120 BOE/yr. The United States would today be annually consuming about 31-37 billion BOE. Given the standard of living Americans have today at about 58 BOE/yr., it is difficult to visualize what standard of living would need 100-110 BOE/yr.—flying cars, perhaps? The point of this thought exercise is to appreciate the fundamental transformation that America underwent in the 1970s and 1980s as the near-continuous century-long growth in annual per-capita energy use halted, leveled off, and then began a modest decline.

The twin oil-supply crises of the 1970s obviously triggered this transformation. The severity of the back-to-back recessions, the increased energy costs, the accompanying inflation, the imposition of Government mandates with new energy efficiency standards (e.g., car mileage), and, especially, the emergence of new technologies ended the pre-crisis year-over-year growth in per capita energy use. In effect, Americans became content with the standard of living they had achieved by 1980 and, going forward, were content to let technological improvements, rather than increased per capita energy use, achieve future increases in their standard of living. In essence, Americans made White's Law work for them, instead of against them. Of course, it helped immensely that the United States had affordable replacement energy sources to turn to.[11]

The historic peak of U.S. per capita energy use occurred in 1979. After that, the United States has seen a modest long-term decline in per capita energy use even during prosperous times. While many in the environmental movement had advocated for significant reductions, the reality is that over the nearly thirty-year period of 1979 to 2007, per capita energy use declined only a total of a 6%. Obviously, there has been an improving energy efficiency technology component of White's Law responsible for part of this reduction, e.g., car mileage standards. However, there are also social and consumer trends of an aging population, more single households, larger homes, longer commutes, more electronic communications, larger TVs, a higher standard of living at the lower end of the economic spectrum and during retirement, etc., which also have impacted per capita energy use.

The very important historical lesson learned from these past 30 years is that despite significant government and societal emphasis on achieving substantial decreases in per capita energy use through energy conservation and technological energy utilization efficiency improvements, <u>the actual real reduction in per capita energy use was only about 0.2% per year</u>. It strongly argues against the proposition that America can be expected voluntarily to "conserve" its way out of the pending energy crisis absent draconian Government mandates.

U.S. Per Capita Energy Need in 2100 is Forecast to Be 50 BOE/Yr.

Drawing on the last 30 years' data, in Fig. 7, the author linearly extends the 1979-2007 trend to 2100, where the U.S. per capita energy use would be in the ballpark of 50 BOE/yr. This equals a 14% reduction from the current U.S. per capita non-recession energy use of about 58 BOE/yr. Accomplishing this modest decline would be expected to come from technological advancement with no loss of standard of living—making White's Law work for us. This means that our grandchildren living in 2100 would live in

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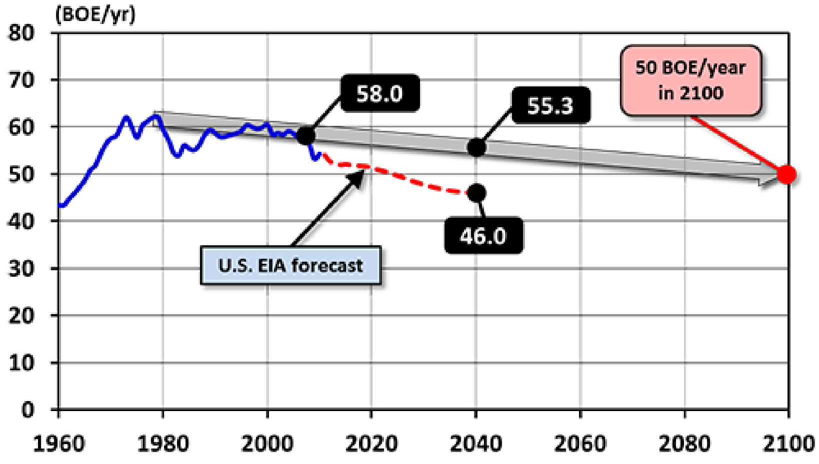
[11] One important outcome of the second oil-supply crisis is that U.S. per capita oil consumption was permanently lowered—falling about 25%—despite oil prices returning, in the mid-1980s, to near pre-crisis levels. During the six years of the recession, the United States shifted away from oil where technologically and economically feasible. Coal production expanded to replace oil for electricity generation. Natural gas production, once it was deregulated, expanded to heat homes and supply industry. Nuclear electricity, in development since the 1950s, became commercially available to help meet growing demand for electricity. In all three cases, the costs of the replacement energy sources were less than the cost of the oil they replaced. The availability and affordability of these replacement energy sources enabled the United States to return to near pre-crisis per capita energy use as the 1980s ended. Note, however, that all of these substitution energy sources were also non-sustainable. Consequently, this was only a temporary fix.

homes comparable to ours today, have personal transportation comparable to ours today, travel for business and vacation, etc. Of course, there would twice as many Americans, meaning that housing and roads would double, food and water production would double, etc.[12]

Fig. 7 - U.S. per capita energy use & EIA forecast (1960-2100)



(Data source: Composite of publicly available data)

For comparison, the U.S. Energy Information Administration (EIA) 2013 projection of U.S. per capita energy use through 2040 is also shown in Fig. 7. This EIA projection reflects a number of separate inputs including increased environmental regulation and a decreased long-term rate of economic growth. While the author's linear projection would see a 55 BOE/yr. rate of consumption in 2040, the EIA is forecasting only 46 BOE/yr.—16% lower.

Recall that the total reduction from 1979-2007 was only about 6%. Also, take note of the fact that this EIA projection begins at the current depressed mid-recession per capita energy use and forecasts a permanent, long-term decline from this depressed starting point. Compare this to the experience after the 1979-1985 recession—Fig. 6b—when, as the economy and consumer confidence improved, per capita energy use returned to near-historic peak levels. No such recovery is seen in the EIA forecast as the economy recovers. Hence, the author believes the EIA forecast to be unreasonably optimistic—yes, optimistic—for use in projecting U.S. energy needs through 2100 because projections of future total U.S. energy needs, based on this EIA forecast, are likely to be low. Energy security planning would then miss the mark in terms of having adequate future energy supplies. Draconian government mandates may then be necessary to force lower per capita consumption to meet the inaccurate forecasts and correspondingly inadequate energy supplies.

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[12] One unknown is the growth of humanoids—robots replacing humans at work or serving humans as machine butlers. It is possible there may be tens of millions of such robots in the United States in 2100, all requiring energy to operate, maintain, repair, replace, and transport.

At the author's forecast per capita energy use of 50 BOE/yr. by 2100, U.S. per capita energy use would have declined by nearly 20% from the 1970s historic peak. While more energy conservation may be achievable, it is also important to recall, as noted earlier, that the future population size projection is now trending higher, meaning that the United States may actually have more than 625 million people in 2100. Thus, the 50 BOE/yr. per capita energy use and the 625 million U.S. population in 2100 combine to provide, at least for now, a reasonable set of assumptions for assessing future U.S. energy security needs. Adjustments, of course, will be necessary as the future unfolds.

The United States Will Need About 31 Billion BOE Annually By 2100 to Maintain Its Standard of Living

The calculation of the U.S. energy need any particular year is simple:

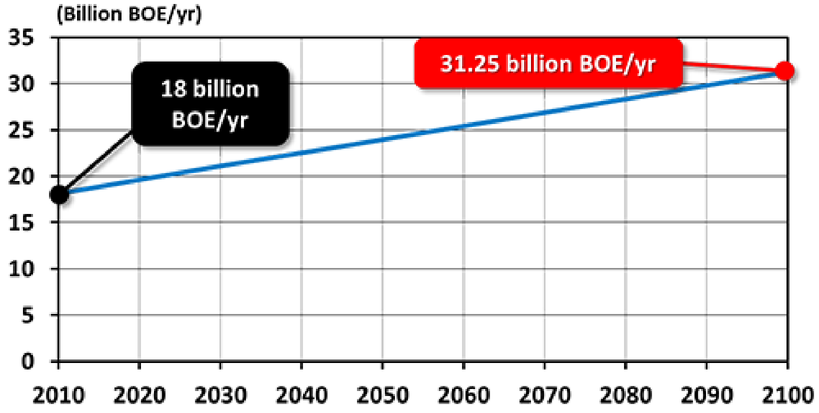
Population size x per capita energy use = total energy needed

Using the population growth data shown earlier combined with the linear decrease in per capita energy use to 50 BOE/yr. forecast for 2100, the annual U.S. energy need from 2010-2100 can be computed.

625 million x 50 BOE/yr. = 31.25 billion BOE/yr. in 2100

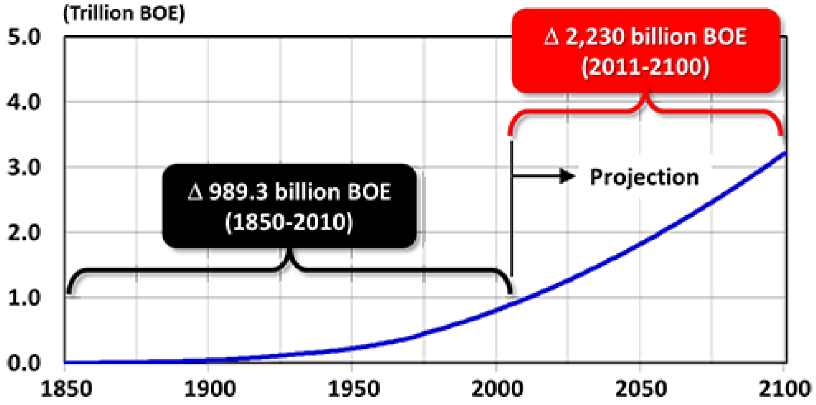
The annual need from 2011-2100, plotted in Fig. 8, will grow by nearly 75%. While this increase sounds large, as noted earlier, the U.S. total energy consumption more than doubled in the last half-century. Thus, planning for a U.S. energy infrastructure capable of supplying in the ballpark of 31 billion BOE by 2100 is prudent.

Fig. 8 - Projected annual U.S. gross thermal energy need (2010-2100)



From 2011-2100, the United States Will Need a Secure Supply of 2.23 Trillion BOE

Fig. 9 - Cumulative U.S. gross thermal energy consumed and needed (1850-2100)



(Data source: U.S. Government and author's projection)

Figure 9 shows the cumulative energy use and projected future need from 1850-2100. From 1850-2010, the United States consumed just shy of 1 trillion BOE. From 2011-2100, the forecast is that the United States will need an additional 2.23 trillion BOE. Hence, through the remainder of this century, the United States will need more than twice the amount of energy consumed since 1850.

For U.S. energy security planning purposes, there are now two targets that must be met to ensure energy security and economic prosperity:

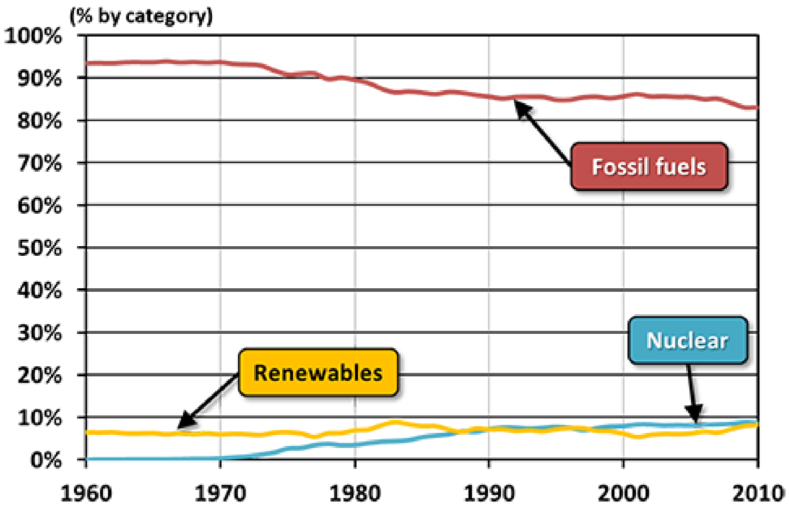
- An annual energy supply growing to about 31 billion BOE per year by 2100.
- A total energy supply of about 2.23 trillion BOE through 2100.

Of course, remember that the U.S. energy needs do not simply end in 2100. These targets are, essentially, intermediate planning milestones.

Section III – How Long Will Fossil Fuels Continue to Sustain America's Energy Needs?

Where will this 2.23 trillion BOE of energy come from? Almost everyone assumes the vast majority of this will be supplied by fossil fuels. As seen in Fig. 10, over the last 30 years, fossil fuels have provided about 85% of America's energy needs. Is it reasonable to expect this level of supply to continue, especially as the total U.S. energy need substantially increases by 2100? If the answer is no, then the United States has a serious energy security problem. To find out, the U.S. fossil fuel endowment needs to be determined and compared against the 2.23 trillion BOE needed through 2100. The starting point is to understand the terminology.

Fig. 10 - U.S. per capita energy consumption percentage by category (1960-2010)



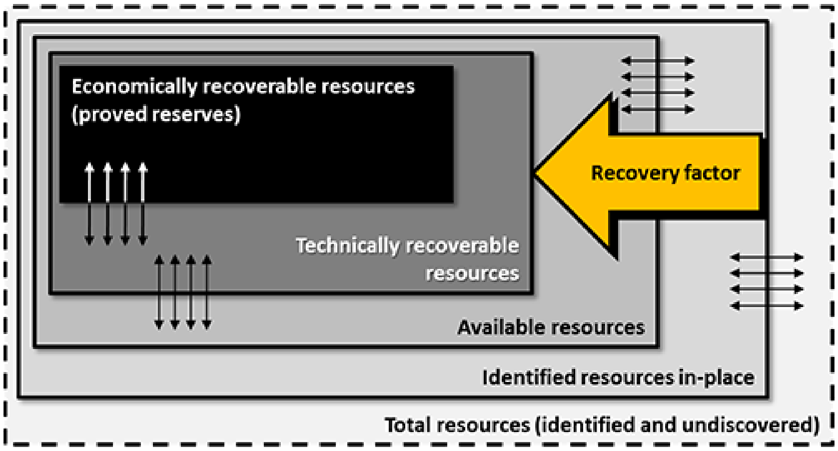
(Data source: U.S. Government)

Terminology is Important in Understanding the U.S. Endowment of Useable Fossil Fuel Resources

Prior to the start of the current recession, nuclear and renewables provided about 15% of the annual gross thermal energy supply. Fossil fuels provided the balance of about 85%. Also, as seen in Fig. 10, for the last twenty years, even as wind and ground solar energy have been emphasized, the total contribution of renewables, as a percentage of per capita energy use, has stayed about the same percentage. Thus, a substantial continued reliance on fossil fuels would be expected into the foreseeable future. The United States simply has no other choice at this time.

As estimated earlier, from 2011-2100 the United States will need about 2.23 trillion BOE of gross thermal energy. If 85% of this is to be provided by fossil fuels, the United States will need about 2 trillion BOE of coal, oil, and natural gas through 2100. Does the United States have at least this amount of available domestic resources of these fuels—what the Congressional Research Service calls the “endowment”? The starting point for answering this question is to define some terms particular to non-sustainable natural resources like fossil fuels. These are illustrated in Fig. 11.

Fig. 11 - Terms used to define fossil fuel resources



The Earth has immense stores of fossil fuels accumulated through some truly amazing geological processes over a period of several hundred million years. These range from coal, formed under tall mountain ranges, to methane hydrates stored in a unique form of water ice generally buried under the seafloor in the deep ocean.

Fossil fuels, of course, are solar energy stored as chemical energy in carbon molecules. In all fossil fuels, releasing the stored solar energy requires combustion with oxygen from the air, yielding carbon dioxide as the primary unavoidable waste product. Eventually, plants use photosynthesis to convert the carbon in carbon dioxide back into new complex carbon molecules, releasing the oxygen back into the air and beginning the natural cycle of fossil fuel formation all over again.[13]

The above illustration is of a series of nested boxes showing the relationship between the terms used to characterize fossil fuels. These terms are defined as:

- **Total resources (identified and undiscovered)** is really just a mental anchor for these discussions. Geologists can provide a rough ballpark estimate of the total resources of a particular fuel, e.g., coal, but this is really just a guess.
- **Identified resources in place** is the estimate of the known resources of a particular fuel type within a defined geographic area, generally the land area of a nation and, possibly, its surrounding ocean.
- **Available resources** is that portion of the identified resources in-place that can be extracted in accordance with political, legal, and regulatory constraints.

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[13] Currently, about two percent of the Earth's land surface is peat bog. As the plants in these bogs die, they form the peat that begins the natural cycle for fossil fuel formation leading to coal. Peat accumulates at a rate of about 1 inch in 25 years. This illustrates that the natural cycle of fossil fuel formation continues even today, although at a very slow pace compared to humanity's rate of extraction.

- **Technically-recoverable resources** is that portion of the available resources that can be extracted using available technical means and done per existing safety and environmental regulations. The ability to produce the fuel profitably may or may not be a consideration in making the estimate of the technically-recoverable resources. The size of the technically-recoverable resources is defined by the U.S. Government as the nation's "endowment" of fossil fuels and is, hence, appropriate to use in energy security planning.
- **Economically recoverable resources (proved reserves)** is the portion of the technically-recoverable reserves/resources that can be produced profitably at current market, legal, and regulatory conditions. Proved reserves—the terminology typically used— are normally owned or controlled by private industry.

In Fig. 11, the small arrows reflect the fact that these estimates change as more field data is collected and analyzed, as market, legal, and regulatory conditions change, and as new extraction technologies are introduced, e.g., hydraulic fracturing.

The large arrow represents what is referred to as the recovery factor. This is the percentage of the identified resources in place that can be permissibly extracted with available technologies. This percentage ranges from about 55% for coal, to 50-60% for conventional oil (with enhanced recovery methods), and to 80-90% for conventional natural gas. For oil and natural gas located in shale and tight rock formations—accounting for the recent boom in domestic oil and natural gas production and where guided drilling and hydraulic fracturing are required to be used—the recovery factor can be much lower—often less than 20%.

The U.S. Fossil Fuel Endowment is About 1.4 Trillion BOE

From a strategic energy security perspective, understanding how much technically-recoverable fossil fuel resources the United States has is critical. Figure 12 shows the summary table from a 2011 study done by the Congressional Research Service.[14] The report estimates that the United States has a remaining "endowment" of 1,366.8 billion BOE of technically recoverable resources. This includes economically recoverable resources (proved reserves) plus that portion of known and undiscovered technically recoverable resources thought by the Government to be profitable to produce. For example, the 261 billion short tons (2000 lbs.) of coal included in this endowment reflects only that portion of 486 billion short tons of available resources—called "demonstrated reserve base" in coal industry terminology—thought by the Government eventually to be profitable to produce.

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[14] Carl R. Behrens et al., "U.S. Fossil Fuel Resources: Terminology, Reporting, and Summary," Congressional Research Service, R40872, December 28, 2011.

Fig. 12 - U.S. Congressional Research Service estimate of proved reserves and technically-recoverable resources

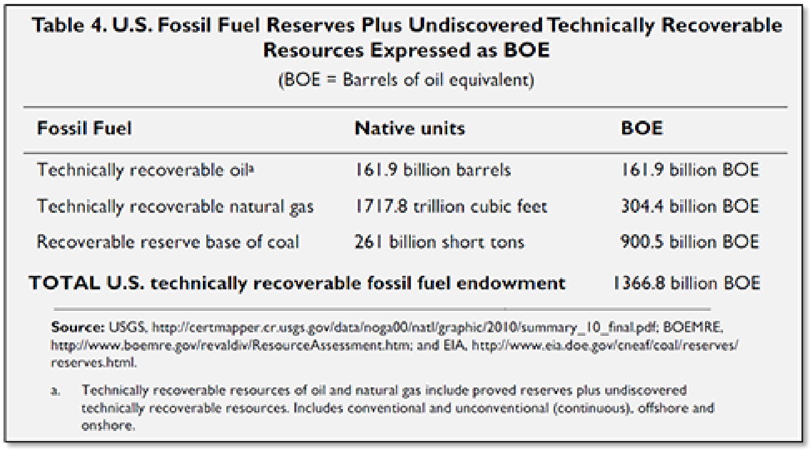


Table 4. U.S. Fossil Fuel Reserves Plus Undiscovered Technically Recoverable Resources Expressed as BOE

(BOE = Barrels of oil equivalent)

Fossil Fuel	**Native units**	**BOE**
Technically recoverable oil[a]	161.9 billion barrels	161.9 billion BOE
Technically recoverable natural gas	1717.8 trillion cubic feet	304.4 billion BOE
Recoverable reserve base of coal	261 billion short tons	900.5 billion BOE
TOTAL U.S. technically recoverable fossil fuel endowment		1366.8 billion BOE

Source: USGS, http://certmapper.cr.usgs.gov/data/noga00/natl/graphic/2010/summary_10_final.pdf; BOEMRE, http://www.boemre.gov/revaldiv/ResourceAssessment.htm; and EIA, http://www.eia.doe.gov/cneaf/coal/reserves/reserves.html.

[a] Technically recoverable resources of oil and natural gas include proved reserves plus undiscovered technically recoverable resources. Includes conventional and unconventional (continuous), offshore and onshore.

Proponents of a continued substantial reliance on fossil fuels will often point out that the endowment estimate does not include two additional resources: unconventional oil from shale (oil shale) and unconventional methane from methane hydrates.

- Oil shale is not the same as the “shale oil” being recovered from shale and tight rock formations using guided drilling and hydraulic fracturing. Oil shale is actually a primitive form of petroleum called kerogen. This is viscous goo found in some porous rock formations. While the United States is thought to have on the order of 1 trillion BOE of oil shale, the technologies to produce this economically with adequate environmental protections have not yet been developed. This author believes that oil shale is best thought of as a true strategic oil reserve to be tapped only if energy supply circumstances become dire.
- Exploration has determined that the world has immense stores of methane locked in a form of water ice called methane hydrates. When formed under high pressure in the presence of methane in the water, the water ice forms around a methane molecule, locking the methane into the ice. To recover the methane, the ice needs to be melted. The typical deep locations of the methane hydrate under the seafloor, the diffuse distribution of the methane hydrate, and the likely significant environmental impact of methane recovery is thought, by the author, to make this fossil fuel resource uneconomical/socially unacceptable to produce in substantial quantities. Hence, it is not appropriate to include this in U.S. energy security planning.

With these perspectives on oil shale and methane hydrates, the Congressional Research Service’s endowment estimate of 1.4 trillion BOE is a reasonable estimate to use in assessing U.S. fossil fuel energy security.

The U.S. Fossil Fuel Endowment is Far Less Than Needed to Remain Energy Secure Through 2100

Recall that the United States used just shy of 1 trillion BOE of gross thermal energy from 1850-2010. With this in mind, the endowment of nearly 1.4 trillion BOE does sound like the United States has satisfyingly large remaining useable fossil fuel resources. But is this really the case considering that the U.S. population will likely more than double by 2100?

Of the 1.4 trillion BOE endowment, 261 billion short tons or 900 billion BOE comes from coal. The United States is currently producing about 1 billion short tons of coal per year with almost all used for electricity generation. Keeping this rate of coal production constant would consume about 90 billion short tons—about 310 billion BOE—of coal through 2100.

If we assume that all of the endowment's oil and natural gas—shown in Fig. 12—would be extracted by 2100, the total fossil fuels produced through 2100 would total about 776 billion BOE.

162 billion BOE of oil + 304 billion BOE of natural gas + 310 billion BOE of coal
= 776 billion BOE

Of the 2.23 trillion BOE needed through 2100, let us assume that nuclear and terrestrial renewables continue to provide 15%. The balance of 85% would need to come from fossil fuels. As shown in the following computation, the United States would have an energy supply shortfall of 1.2 trillion BOE—about 53% of what is needed.

2,230 billion BOE needed through 2100 x 0.85
– 776 billion BOE of fossil fuels extracted through 2100
= **1,179 billion BOE shortfall**

Not good enough is it?

Let us assume a crash program—and a substantial relaxation of environmental regulations—to boost coal production so that the entire coal endowment of 900 billion BOE is extracted by 2100. In other words, let us assume the entire fossil fuel endowment of 1,367 billion BOE would be extracted by 2100. This still yields a shortfall of 529 billion BOE or about 24% of the total needed.

2,230 billion BOE needed through 2100 x 0.85
– 1,367 billion BOE of fossil fuels extracted through 2100
= **529 billion BOE shortfall**

This "what if" analysis indicates that even with a crash program to mine all of the technically-recoverable coal, the United States would exhaust its useable/affordable fossil fuel supplies well before 2100—within the lifetime of our children and grandchildren. As a result, U.S. annual energy supplies would dramatically fall unless some means of substantially increasing imported energy were possible. But that would also increase U.S. energy insecurity, just as happened with oil in the 1970s, and would force the United States to compete with other nations of growing economic power, e.g., China, for these resources.

Consequently, continuing forward on today's path of a substantial reliance on fossil fuels with no useful transition strategy to replacement energy sources is folly, is it not? It is a sure path to catastrophe that needs to be avoided. Thus, with the information available—U.S. energy needs through 2100 and the size of the U.S. endowment of fossil fuels—what path forward makes sense?

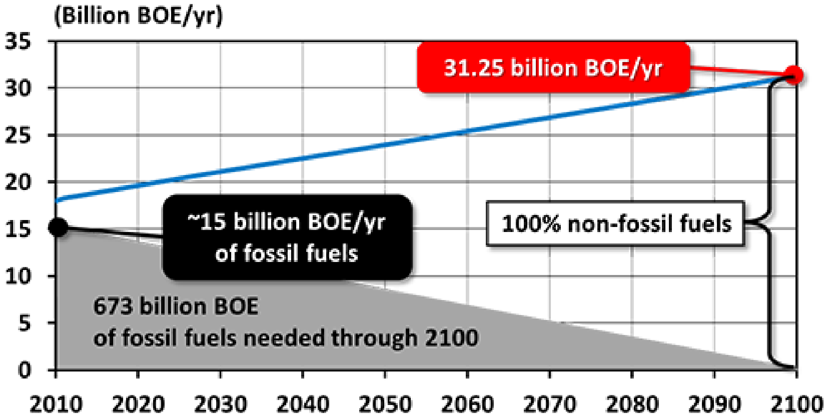
Section IV – Defining a Rational Path Forward to Achieve Energy Security

It should now be crystal clear that the age of fossil fuels is ending in the United States and America must prepare for the new future. White's Law explains the terrible consequences of failure to plan and act accordingly. Without adequate per capita energy supplies, a nation's culture or standard of living cannot be maintained. It is foolish to hope otherwise, is it not? Consequently, from a strategic energy security planning perspective, this means that the United States needs to replace fossil fuels with something else before affordable fossil fuels are no longer available.

This is where picking a planning horizon of 2100 comes into play. As will be seen in the following analyses of a hypothetical all-nuclear energy infrastructure, the size of the replacement non-fossil fuel energy infrastructure is quite large. Such a large infrastructure will not be built quickly. Thus, while picking 2100 may now appear to be impractically far in the future, as the scope of the effort required to implement a practical solution to replace fossil fuels is identified, this initial impression may change.

With 2100 being the hypothetical goal for achieving energy security with domestic non-fossil fuel energy sources, the transition would look like Fig. 13 below. By 2100, the United States would no longer be using a significant amount of fossil fuels.

Fig. 13 - U.S. transition to non-fossil fuel energy sources by 2100



Currently, the fossil fuel industry often takes great umbrage at any discussion of transitioning America to non-fossil fuel energy sources. Many see this as an either-or future. In reality, to maintain order in the U.S. energy market, it is important that both sides work together. The United States cannot make it to 2100 primarily on fossil fuels, as the earlier quantitative analysis shows. At the same time, the United States cannot simply abandon fossil fuels because the replacements are not yet available. Hence, the transition strategy shown in Fig. 13 is not only good for America, but good for the fossil fuel industry as well.

Let us put this transition into numbers. From around 15 billion BOE/yr. of fossil fuel energy consumed presently, the consumption of these fuels would, ideally, steadily decline to zero in 2100. To make this happen without supply disruptions, the U.S. fossil fuel industry would still need to produce about 673 billion BOE of fossil fuels or about 50% of the remaining U.S. fossil fuel endowment discussed above. This means that current private investment in fossil fuel production capabilities and privately-owned reserves would not be arbitrarily diminished in value. Instead, a robust U.S. fossil fuel industry would continue for most of the rest of the century.

With this new appreciation that the fossil fuel industry is not the enemy, but the underpinnings of maintaining America's energy security, what will replace fossil fuels? Conventional fission nuclear energy? Ground solar energy? Wind? Fusion nuclear energy? There can be no real transition plan for America to follow without identifying a suitable replacement energy supply capable of tens of billions of BOE annually. The first step is to analyze the magnitude of the non-fossil fuel energy supply needed by 2100, starting with an understanding of the units of energy used in this analysis. The unit "BOE", after all, is oriented towards fossil fuels. We need to switch to the unit made famous by the *Back to the Future* movie's Doc Brown—the gigawatt.

Section V – A Short Tutorial on the Power Unit of the 21st Century—The Gigawatt

As we move away from fossil fuels, the usefulness of using the BOE as the unit for measuring energy production and consumption diminishes. The reason is that the BOE relates to the thermal release of energy through combustion of some carbon fuel. Do we have any carbon fuels to replace fossil fuels? No, not really. Thus, what will replace fossil fuels will almost certainly be some form of electricity generation—nuclear-electric, geothermal, hydroelectric, solar, wind, etc. Characterizing the future power and energy needs, respectfully, in terms of the electricity generation units of gigawatts (GW) and gigawatt-hours (GWh) is, therefore, useful.

Power and Energy are Not the Same

It is important to recognize that "power" is not the same as "energy", although they are related. Energy reflects how much power is required over a period of time.

The watt is the international unit measuring the production or consumption of power.[15] Example: When a 100-watt light bulb is turned on, it consumes 100 watts of power

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[15] The unit "watt" is named after James Watt, the 18th century inventor of the improved steam engine that enabled the industrial revolution.

continuously. At the end of one second, the bulb has consumed 100 watt-seconds of electrical energy. At the end of one hour—3,600 seconds—the bulb will have consumed 0.36 million watt-seconds. Obviously, such numbers rapidly become quite large. Thus, the number of watt-seconds is divided by 3,600 to yield watt-hours. Then, this is further divided by 1000 to yield kilowatt-hours or kWh. A 100-watt bulb operating for one hour will consume 0.1 kWh of energy. Residential electricity consumption is usually measured in kWh. A typical 2,000 sq. ft. home will consume about 1,000 kWh per month of electrical energy.

Units of Power and Energy Step Up and Down by Increments of 1000

If we divide the number of watts by 1000, this yields the number of kilowatts (kW). A home emergency generator will usually be in the range of 4,000-5,000 watts or 4-5 kW of power.

1 kW = 1,000 watts

Dividing again by 1,000 yields the number of megawatts (MW). Many utility generators are rated in terms of the MW of power produced. These typically natural-gas-fueled generators will be in the range of 100-200 MW of power.

1 MW = 1,000,000 watts

The next step up is to divide the number of MW by 1000 to yield the number of gigawatts (GW). Large baseload utility generators, such as coal and nuclear power plants, are generally in the range of 1000 MW or 1 GW.

1 GW = 1,000,000,000 watts

The final step is to divide the number of GWs by 1000 to yield the number of terawatts (TW). This unit is usually used to describe power consumption at the national or planetary level.

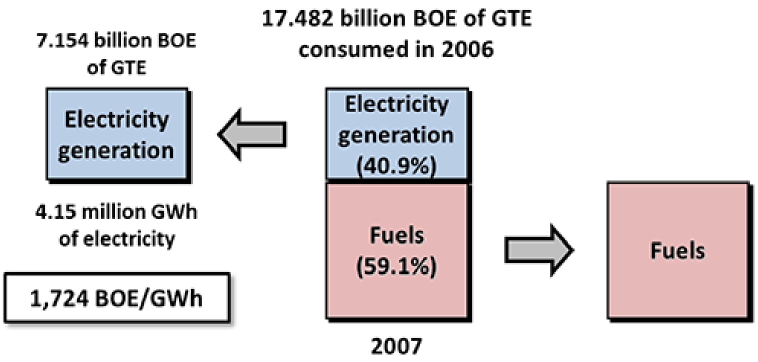
For this paper, U.S. national electrical power needs are described using the unit GW. In 2100, as the United States completes its transition from fossil fuels, the entire energy supply of the United States can be defined in terms of *XX* GW-years, rather than 31.25 billion BOE/yr. The number *XX* GW-years represents a continuous supply of *XX* GW of electrical power 24 hours a day, 365 days a year. The size of this number *XX* will surprise you.

Section VI – Assessing a Hypothetical All-Nuclear Energy Infrastructure for 2100

While currently the United States consumes around 18 billion BOE of gross thermal energy, in actuality, this energy is provided to the end consumer in two basic forms—dispatchable electricity and fuels used directly by the consumer for transportation, heating, industrial processing, etc. From 2007 data for the year prior to the start of the current recession, the distribution of gross thermal energy consumed as electricity and as fuels can be determined.

As shown in Fig. 14, in 2007, the United States consumed 17.482 billion BOE of gross thermal energy. That same year, 4.14 million GWh of electricity was generated. The EIA provides historical data on the thermal efficiency of the conversion of fossil fuels and nuclear energy into electricity, as well as the number of GWh generated by each.[16] In 2007, the average thermal conversion efficiency was 1,724 BOE per GWh of electricity generated. Using this conversion, 7.154 billion BOE of gross thermal energy was used to generate that year's 4.14 million GWh of electricity. The balance of 10.328 billion BOE was, thus, consumed as fuel by the end-consumer. That year, the split was 40.9% of the total BOE used for electricity and 59.1% for fuels. (The split each year, of course, varies somewhat due to weather, price, and other economic factors. In recent years, the split has been right around 40%/60%, so 2007 is a representative year.)

Fig. 14 - 2007 distribution of U.S. energy use



(Data source: U.S. Government)

Recall that the projection for 2100 is 31.25 billion BOE of gross thermal energy needed. Compared to 2007, this represents a growth of about 79%.

31.25 billion BOE in 2100 ÷ 17.482 billion BOE in 2007 = 1.788

Applying this to the 2007 electricity consumed yields a projected need for 7.42 million GWh in 2100.

4.15 million GWh in 2007 x 1.788 = 7.42 million GWh in 2100

In 2100, the estimated need for end-consumer fuels is about 18.5 billion BOE.

10.328 billion BOE of fuels in 2007 x 1.788 = 18.47 billion BOE in 2100

The balance of about 12.8 billion BOE would be used to generate the needed electricity.

31.25 billion BOE needed in 2100 – 18.47 billion BOE of fuels in 2100

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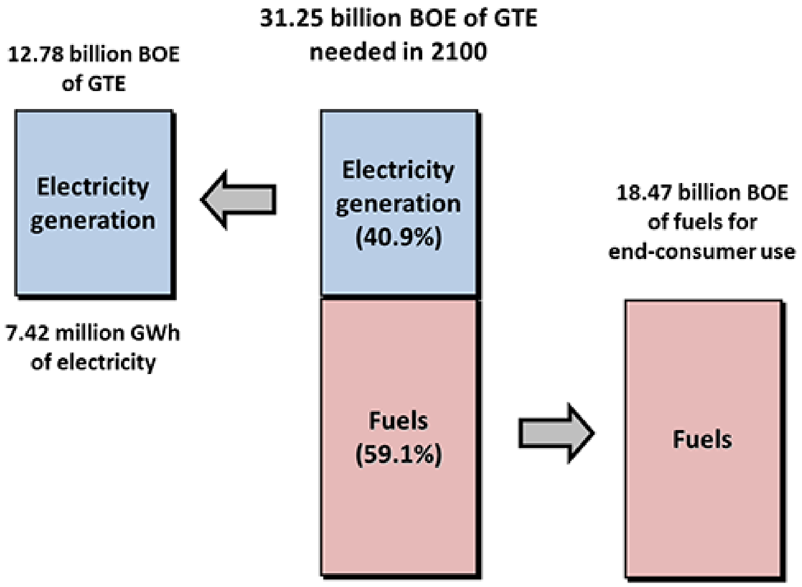
[16] In these calculations, the contribution of renewables was included with that of nuclear-electricity since a hypothetical all-nuclear energy infrastructure is being assessed.

= 12.78 billion BOE used to generate electricity in 2100

These results are shown in Fig. 15.

Fig. 15 - 2100 distribution of U.S. energy use



If Using Only Nuclear Energy, the United States Will Need 6,500 1-GW Plants Operating By 2100

For this hypothetical assessment of an all-nuclear energy infrastructure, it is assumed that in 2100 the United States is powered only by nuclear fission power plants. The nuclear electricity generated is used to supply electrical power to the end-consumers and to produce hydrogen fuel to be used as fuel by the end-consumers. This is depicted in Fig. 16.

Using this model, how many 1-GW nuclear power plants would need to be operating in 2100 to provide:

- 7.42 million GWh of dispatched electricity.
- 18.47 billion BOE of hydrogen fuel compressed to 6,500 psi.[17]

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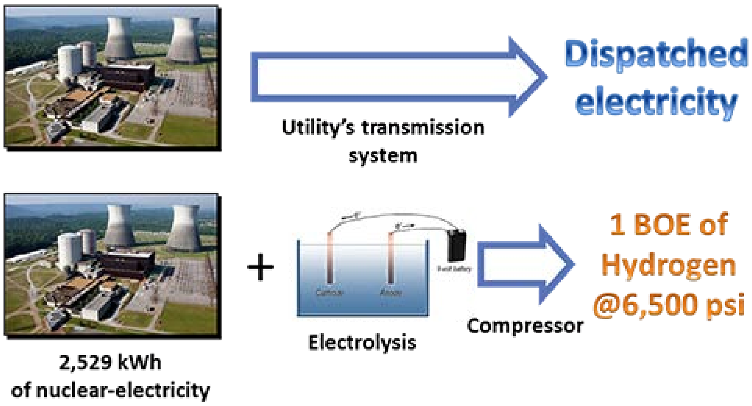
[17] Hydrogen, as a gas at normal pressure and temperature, has a density of only 0.006 lb/cu. ft. Thus, to store hydrogen in bulk, it must be compressed to high pressures. For comparison, natural gas storage is in the range of 2,000-4,000 psi when stored as a gas rather than a liquid. As it takes more energy to liquefy hydrogen, compared to pressurizing it to 6,500 psi, high pressure storage is the most likely method that would be used.

Fig. 16 - Nuclear energy production model



In this analysis, each of these nuclear power plants is assumed to generate 1 GW of power and to operate at full power for 95% of the year.[18] Each of these 1-GW plants would be capable of delivering 8,322 GWh of energy a year.

$$1 \text{ GW} \times 24 \text{ hours/day} \times 365 \text{ days/yr.} \times 0.95 = 8{,}322 \text{ GWh per plant}$$

In 2100, the projected electrical energy need for the United States is 7.42 million GWh. To produce this with 1-GW nuclear power plants would require 892 plants.

$$7.42 \text{ million GWh} \div 8{,}322 \text{ GWh/plant} = 892 \text{ 1-GW plants}$$

Obviously, conventional nuclear power plants do not produce hydrogen directly.[19] As seen in Fig. 16, hydrogen is produced through electrolysis where nuclear electricity is used to split the H_2O water molecule into its constituent hydrogen and oxygen atoms. The hydrogen is captured, compressed, and stored for end-consumer use as a fuel replacement for oil and natural gas.

The author estimates that—allowing for some technology improvement in the energy efficiency of the electrolyzers and compressors—producing and storing hydrogen for a lower heating value (LHV) use, such as home heating, will require 2,529 kWh of nuclear-electricity to produce one BOE of hydrogen fuel compressed to 6,500 psi.[20] As

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[18] The remaining 5% of the year—about 18 days—is used for refueling and plant maintenance. Modern plants operate up to 18 months between refueling.

[19] There are proposals for advanced fission nuclear power plants that use thermal energy to split water directly in the reactor to yield hydrogen. This is not, however, state-of-the-art for fission nuclear power.

[20] The condition under which any fuel is combusted controls how much useful thermal energy is produced. There are two standard sets of conditions for determining the useful thermal energy produced by gas and liquid fuels. These are referred to as the "lower heating value" or LHV and the "higher heating value" or HHV with the latter due to more efficient conditions of combustion such as ultra-high efficiency, combined-cycle gas turbines. Most other combustion conditions, such as home heating and transportation, fall in the LHV category. At the HHV conditions of hydrogen combustion, the author's estimate is that 2,137 kWh of electricity is required per BOE of hydrogen compressed to 6,500 psi. Because the combustion process is more efficient, about 15% less electricity is needed to yield 1 BOE of

seen in the following calculation, to produce 18.47 billion BOE of end-consumer hydrogen fuel used at LHV conditions, it requires 47 million GWh of electricity. This is ten times (10X) the amount of electricity consumed in the United States in 2006.

18.47 billion BOE of hydrogen fuel x 2,529 kWh/BOE of hydrogen @ 6,500 psi
÷ 1000 kW/MW ÷ 1000 MW/GW = 46,710,630 GWh for producing fuel

Recalling that each 1-GW plant will ideally yield 8,322 GWh per year, a total of 5,613 1-GW nuclear power plants would be required, in 2100, to provide U.S. consumers with needed end-consumer fuels.

46,710,630 GWh in 2100 ÷ 8,322 GWh/nuclear power plant/yr.
= 5,613 1-GW plants needed in 2100 for fuel

By combining these two estimates for the number of 1-GW nuclear power plants required to produce both dispatched electricity and hydrogen fuel, an estimate of the total *XX* GW of generation capacity needed in 2100 to provide 31.25 billion BOE can be determined. To replace fossil fuels by 2100, the United States would need about 6,500 GW of continuous generating capacity—or 6,500 1-GW nuclear power plants!

892 for electricity + 5,613 for fuels = 6,505 1-GW plants in 2100

Currently, the United States has about 1,100 GW of generating capacity. Further, the United States only has 104 GW of nuclear power generating capacity. The fact that the United States will need in the ballpark of 6,500 GW of non-fossil fuel generating capacity by 2100 illustrates the magnitude of the challenge America has to overcome to become energy secure by 2100.

Expanded Conventional Nuclear Fission is Not a Solution for 2100

The likely eventual non-fossil fuel energy source will be fusion nuclear energy. Developing this new type of nuclear energy has been underway for over half a century. While progress has been made in understanding the basic physics of non-explosive fusion energy, there is no current estimate for when commercialization of this technology will enable fusion plants to be built. Thus, with advanced nuclear fusion not being a current candidate for replacing fossil fuels, can conventional nuclear fission be used instead?

Fission nuclear energy, with sound plant siting and modern designs, offers a highly reliable and operationally safe baseload electrical power generation capacity. The challenges it faces, however, are not insignificant. These include physical security, damage containment in the event of extreme acts of nature (e.g., earthquakes) or

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net thermal energy. The LHV of hydrogen is 51,682 BTU/lb. Thus, 1 BOE equals 112.22 lb. of hydrogen or 50.9 kg. The author's estimate of 2,529 kWh/BOE, for both electrolysis and compression to 6,500 psi for storage, corresponds to 50 kWh/kg. According to Wikipedia, the typical range today is 50-79 kWh/kg for just electrolysis. The author's estimate anticipates some modest improvement in the efficiency of the electrolyzers and gas compressors.

terrorism, developing decades-long acceptable local waste storage at nuclear power plants, identifying acceptable millennia-long environmental radioactive waste disposal methods, denying uranium/plutonium production for weaponization by potentially hostile nations, and having sufficient fuel to power the plants for their expected 100+ year lives. Balancing these serious issues with the need to maintain a robust domestic nuclear power industry—anticipating the industry's eventual transition to fusion nuclear energy—leads the author to conclude that the use of uranium fission nuclear power will remain modest in the United States this century. Current plants totaling only about 104 GW—many with designs dating from the 1970s—will likely be modernized or replaced. A modest expansion of the total generation capacity to about 150 GW may also be undertaken, depending on the size of U.S. reserves of uranium fuel. However, any broad expansion of conventional uranium fission is unlikely.

Section VII – Assessing Ground-Based Solar Energy and Wind for Meeting U.S. 2100 Energy Needs

With conventional and advanced fusion nuclear energy being unlikely to replace fossil fuels this century, the only other practical terrestrial options are the renewable energy sources of wind, ground solar, hydroelectricity, geothermal-electricity, biomass, and tidal/wave-generated electricity. Can they provide the equivalent of 6,500 GW of dispatchable generation capacity?

The last four options fall into the category of either being impractical, e.g., tidal/wave-generated electricity, or not being capable of significant expansion.

- The United States has about 78 GW of installed hydroelectric generating capacity and the potential to add only about 30 GW of new generating capacity.[21]
- The United States has about 4 GW of geothermal-electricity generation. In 1978, the U.S. Geological Survey estimated the total identified and undiscovered geothermal electrical power generation potential in the United States at 95-150 GW. Yet, over the last 30 years, very little of this potential has been developed indicating the difficulty in commercializing this potential.[22]
- In 2005, the Departments of Energy and Agriculture evaluated the potential of land biomass as a fuel source.[23] This author estimated that the Government's projected potential could yield about 16.4 quadrillion BTU or 2.8 billion BOE of combustible fuels—alcohol, biodiesel, etc.[24] This required the substantial use of genetically-modified crops to increase residual biomass production and the use of nearly all recoverable agriculture, farm, and forestland waste from roughly one million sq. mi. of farmland and forestland. A key point of this 2005 study,

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[21] Feasibility Assessment of the Water Energy Resources of the United States for New Low Power and Small Hydro Classes of Hydroelectric Plants, DOE-ID-11263, January 2006, 1, http://hydropower.inl.gov/resourceassessment/pdfs/main_report_appendix_a_final.pdf.

[22] United States Geological Survey Circular 790, Assessment of Geothermal Resources of the United States, 1978, http://www.geo-energy.org/aboutGE/potentialUse.asp.

[23] Biomass as Feedstock for a Bioenergy and Bioproducts Industry: The Technical Feasibility of a Billion-Ton Annual Supply, April 2005, http://www1.eere.energy.gov/biomass/pdfs/final_billionton_vision_report2.pdf

[24] James Michael Snead, "The End of Easy Energy and What to Do About It," 2008, 82.

> however, was that it was based on meeting the food and feed needs of the U.S. at the present time and not in 2100 when the population will likely have doubled. All of these factors indicate that any significant expansion of biomass use for energy production is unlikely.

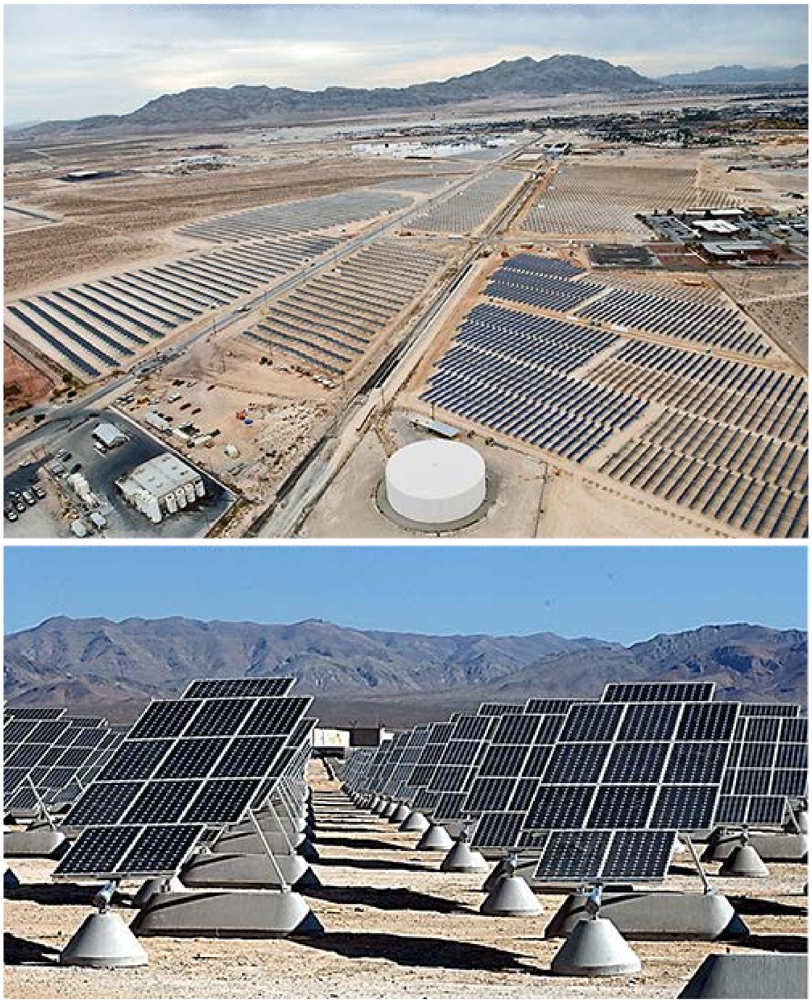
Consequently, of these remaining terrestrial renewable energy alternatives, only ground solar and wind have the potential to be scaled up to the necessary capacity. By using the information from the earlier all-nuclear energy assessment, the practicality of building ground solar and wind farms of sufficient scale to meet the 2100 energy needs can be readily evaluated.

The 14 MW Nellis Air Force Base Solar Farm is Used as a Baseline for Evaluating the Potential of Ground Solar Energy

In 2007, the U.S. Air Force installed a moderately-sized ground solar photovoltaic farm at the Nellis Air Force Base outside of Las Vegas, Nevada. Nellis Air Force Base is a primary flight training facility, indicating that clear blue skies are the norm and good solar insolation (watts of sunlight/sq. ft.), should be available most days. In fact, in terms of the level of solar insolation, this is one of the best locations in the continental United States. This makes this solar farm's performance a good baseline for evaluating the potential of ground solar energy.

The solar farm covers 140 acres (0.219 sq. mi.) and is comprised of solar photovoltaic panels mounted either on a translating stand, as seen in the bottom photograph in Fig. 17, or a standard fixed panel stand. The advantage of the translating stand is that it rotates the panels from east to west to track the movement of the sun across the sky to maximize solar-electricity output throughout the day. However, the disadvantage is the tracking system's added cost and maintenance needs.

Fig. 17 - Nellis Air Force Base 140-acre solar farm



(Source: U.S. Government)

The nameplate generation capacity of the 72,000 installed panels totals about 14 MW.[25] The monthly and annual performance of this solar farm over the years 2008-2012 is shown in Fig. 18a and 18b. The monthly output is shown in Fig. 18a while the year-to-year variation in total annual output is shown in Fig. 18b.

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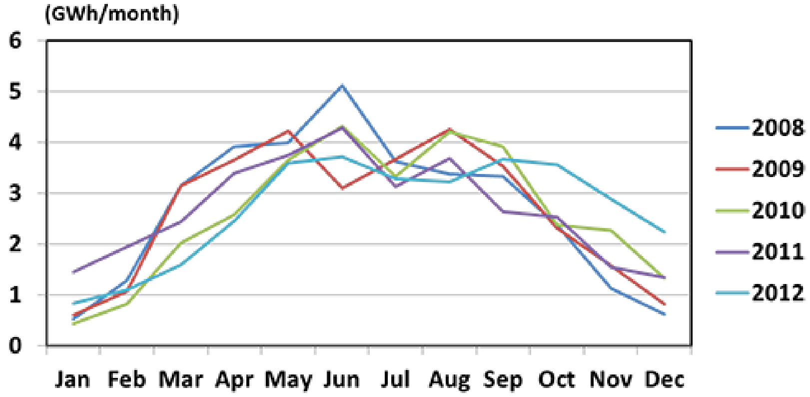
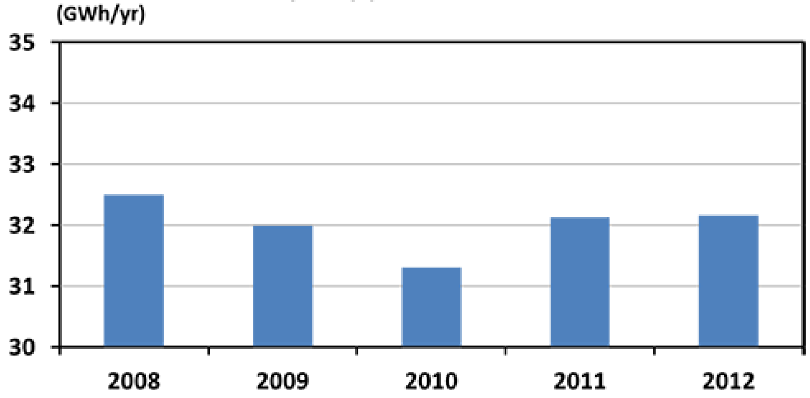
[25] The nameplate generation capacity of a panel is based on tests under simulated sunlight positioned directly over the panel. It is the maximum output of the panel under ideal conditions that rarely occur in practice.

Fig. 18a - Nellis Air Force Base solar farm monthly performance



(Data source: U.S. Government)

Fig. 18b - Nellis Air Force Base solar farm yearly performance



(Data source: U.S. Government)

During the first five years of operation, the 0.219 sq. mi. solar farm produced an average of 32.0 GWh/yr. of electrical energy. This equals 146.1 GWh per sq. mi. per year.

32.0 GWh ÷ 0.219 sq. mi. = 146.1 GWh/sq. mi.

To model a solar farm output using this Nellis data, the following adjustments are included:

- Increase the net output of the solar panels by 33% to account for more efficient photovoltaic cells, mounting, and positioning within the farm.
- Apply a 90% adjustment to account for lower average insolation values, primarily due to weather, as the area of the solar farms expands to cover most of the Southwestern United States.

- Apply a 73.9% adjustment to account for the use of lower-cost and easier-to-maintain fixed-panel mounting rather than the translating stand used primarily at Nellis.
- Assume 95% availability.

Applying these adjustments to the real-world Nellis data yields a model estimate of 122.8 GWh/sq. mi. for solar farms located across the American Southwest. This will be used in computing how many sq. mi. of solar farms are needed to yield the 31.25 billion BOE of gross thermal energy needed in 2100.

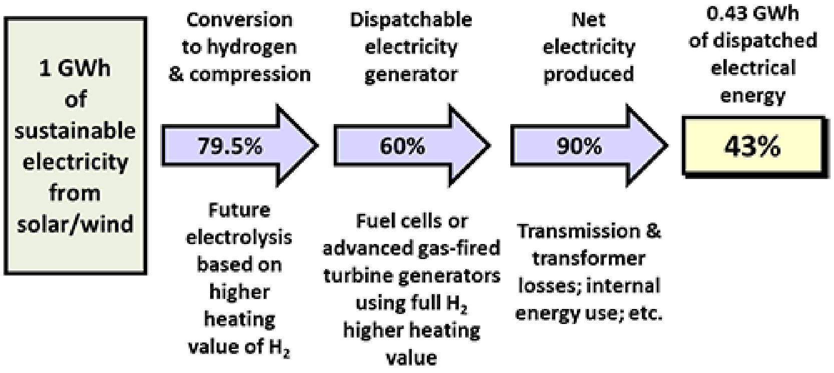
146.1 GWh/sq. mi. x 1.33 x 0.9 x 0.739 x 0.95 = 122.8 GWh/sq. mi.

To Meet U.S. 2100 Energy Needs with Ground Solar Energy Would Require About 521,000 Sq. Mi. of Solar Farms

As mentioned, a primary issue with ground solar (and wind) is the variability of the electricity produced by a solar farm, as seen in Fig. 18b. The U.S. electrical power infrastructure is tightly regulated and controlled to ensure continuous, high-quality electrical power at all times. What the end-consumer receives from the utility is referred to as “dispatched electricity.” This electricity must be continuously generated because it only takes a fraction of a second for the generated electrical power to reach the end-consumer. (Electricity is not stored in the utility’s transmission and distribution system.)

As can be easily imagined, trying to deliver high-quality dispatched electricity from a variable input source, such as ground solar or wind, is very difficult, especially as the scale of production grows. The solution used in this model is to change the solar-electricity into hydrogen, store the hydrogen, and then use hydrogen-fueled gas-turbine generators at the local utilities to generate the needed dispatched electricity. The overall efficiency of this, using the same improved technology assumptions as were included in the previous nuclear model, is 43% (See Fig. 19). This means that 1 GWh of solar-electricity from a solar farm will yield 0.43 GWh of dispatched electricity from the utility to the customer.

Fig. 19 - Overall efficiency in producing dispatched electricity from a variable electrical power source



From Fig. 15, the U.S. will need 7.42 million GWh of dispatched electricity in 2100. To provide this from ground solar farms, the total area of the farms would need to be about 141,000 sq. mi.

7.42 million GWh needed in 2100
÷ (122.8 GWh/sq. mi. of solar farm x 0.43)
= 140,520 sq. mi.

A slightly different analysis is used to compute how many sq. mi. of solar farms are needed to provide the 18.47 billion BOE of hydrogen fuels needed in 2100. For this simple analysis, all of the solar-electricity generated for this purpose is assumed to be converted to hydrogen fuel. As in the all-nuclear case, the conversion rate is assumed to be 2,529 kWh per BOE of hydrogen stored at 6,500 psi. Repeating the calculation from the all-nuclear analysis, this requires around 46.7 million GWh. With each sq. mi. of solar farms yielding an estimated 122.8 GWh, the area needed to produce fuel in 2100 is about 380,000 sq. mi.

18.47 billion BOE of hydrogen fuel x 2,529 kWh/BOE of hydrogen @ 6,500 psi
÷ 1000 kW/MW ÷ 1000 MW/GW = 46,710,630 GWh

46,710,630 GWh ÷ 122.8 GWh/sq. mi. = 380,380 sq. mi. of solar farm

<u>By adding these two estimates, the total net area of advanced ground solar farms needed in 2100 is about 521,000 sq. mi</u>. The continental United States totals about 3 million sq. mi. Nearly 18% of the U.S. lower 48 states would need to be bulldozed flat and planted with solar arrays. Additional ground would be needed for access roads, transmission and distribution systems, substations, etc.

140,520 sq. mi. for dispatched electricity + 380,380 sq. mi. for fuels
= 520,900 sq. mi. of solar farms

An important point to recognize is that in the Southwestern United States, only a modest percentage of the ground is sufficiently flat to be used for solar farms. Hence, while the actual farms may require 520,900 sq. mi., this will be spread out over a much larger geographic area. For comparison, the entire land area of New Mexico and Arizona totals only about 236,000 sq. mi. Hence, virtually all of the flat ground in the southwestern states extending as far east as western Texas and as far north as northern Nevada would be needed for solar farms. Is this practical?

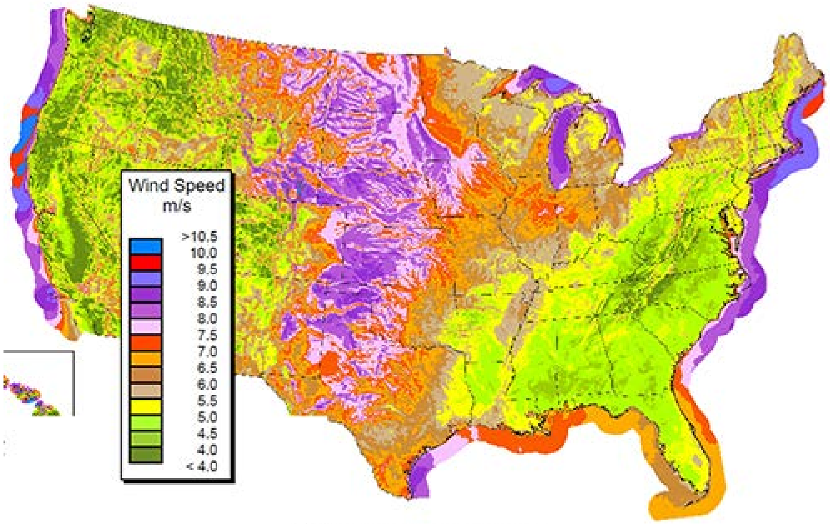
To Meet the U.S. 2100 Energy Needs with Wind-Electricity Would Require 1.4 Million Sq. Mi. of Wind Farms

Wind has been the fastest growing segment of the renewable energy portfolio. Wind, like ground solar, is a variable power source and must be treated in much the same way by producing hydrogen to generate both dispatched electricity and end-consumer fuel.

The Federal Government has mapped the wind energy potential across the United States. Figure 20 shows the distribution of average wind speed at 80 meters (262 ft.)

above the ground. This corresponds to the hub height of a typical 1.5-MW wind turbine. The purple-red areas in the map below have the greatest potential, with average wind speeds in the range of 8.5-9.5 meters/sec (19-21 mph). Most of the continental United States, however, has poor wind power potential. This means that wind farms must necessarily be located in the central United States—the primary food growing region of the country.

Fig. 20 - U.S. 80-meter wind power map



(Source: U.S. Government)

Figure 21 shows the variation in monthly output for four 1.8-MW wind turbines—7.2 MW total—located in northwestern Ohio. The "capacity factor" is the percentage of the total potential wind energy—expressed in GWh—that the wind turbine actually generates each month or year.[26] For the 12-month period of November 2003-October 2004, the average capacity factor was about 22%. To be clear, this means that over this 12-month period, the wind turbines produced only 22% of the energy that would have been produced had the turbines been generating their nameplate 7.2 MW continuously.

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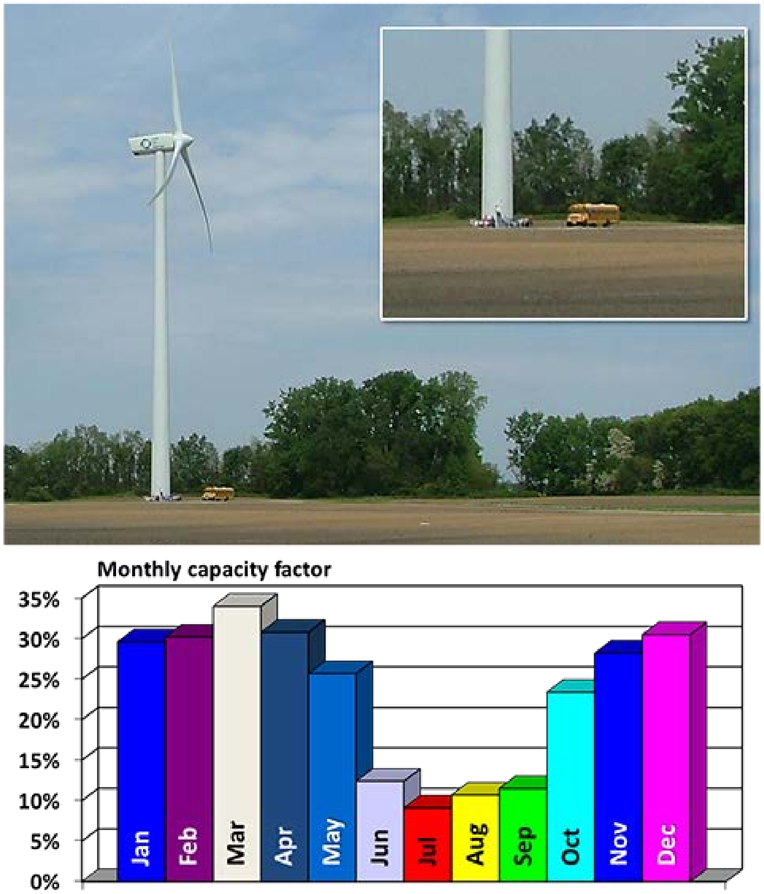
[26] The available wind power is a function of the wind's velocity raised to the third power. Hence, increasing the turbine's hub height generally raises the rotor into winds of higher speed, making more wind power available to be harnessed. Commercial wind turbines currently fall into two groups: 80 m hub heights, with a nameplate generation capacity of 1.5 MW, and 100 m hub heights with a 2.5 MW capacity. A wind turbine only produces its nameplate power when the wind speed is equal to or greater than the turbine's rated speed but less than the maximum permitted speed. For 2.5-MW turbines, this is usually in the range of 28-56 mph. Below the rated speed of 28 mph (12.5 meters/sec), the electrical power output is less than the nameplate power. Below about 7 mph, the turbine is stopped. Above 56 mph the turbine is also stopped to prevent structural damage. Most of the time, the wind speed is below the rated speed, which is why the capacity factor is less than 100%. In the best areas, the capacity factor is in the range of 35-40%.

Fig. 21 - Actual monthly capacity factors at four Ohio 1.8 MW wind turbines for Nov 2003-Oct 2004



(Photograph: Author)

Early wind farms were concentrated on low mountain ridges in California because the ridge accelerated the wind's speed and, consequently, the available wind power. These wind farms positioned the turbines along the ridge because the wind direction was usually blowing in just one direction—across the ridge. Such ideal ridge locations are only a small percentage of the land area of the United States with good wind conditions. In more typical circumstances, the wind turbines are spaced in a grid to enable the wind to be harnessed regardless of the direction the wind is blowing. Wind turbines extract power by slowing down the wind. If the turbine spacing is too close, the wind speed does not have sufficient distance to recover and the wind farm loses generation potential.

For this reason, wind turbines are assumed to be optimally spaced in a grid such that the total installed nameplate power per sq. mi. of wind farm is about 12.9 MW.[27] If a

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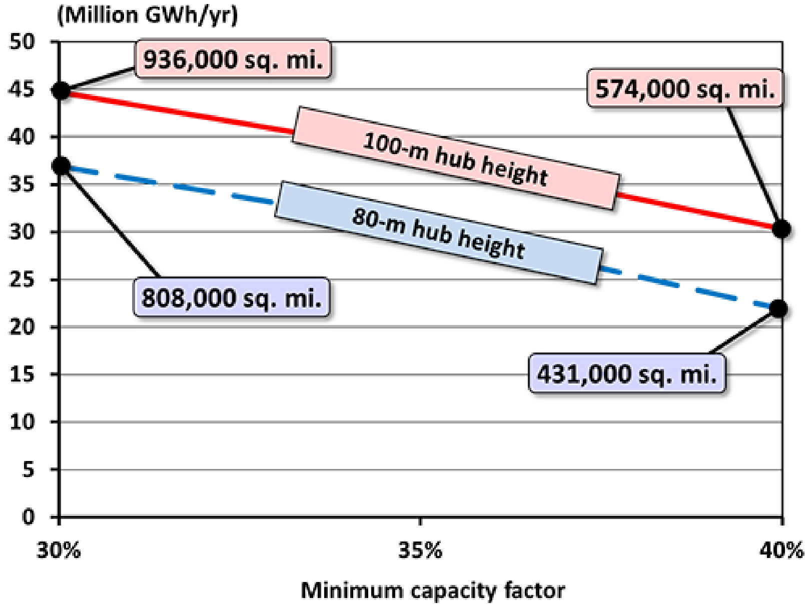
[27] 5 MW of installed nameplate power per sq. km—12.9 MW per sq. mi.—is the value used by the federal government to estimate the optimum spacing of wind turbines in wind farms. The actual value for a specific wind farm depends on a number of factors including average wind speeds, terrain, and hub heights.

wind farm uses 1.5-MW turbines, optimally 8.6 turbines would be installed per sq. mi. If a wind farm uses the 500 ft. tall 2.5-MW turbines, optimally 5.16 would be installed per sq. mi.

Using wind power surveys, the Federal Government has projected the wind energy potential of the United States. This is shown in Fig. 22 for a range of minimum capacity factors and hub heights. From this estimate, wind farms, with 100 m (328 ft.) hub heights and covering 936,000 sq. mi. of primarily the central United States, would be capable of generating about 45 million GWh of variable wind-electricity per year.[28] Assuming 95% availability, about 46 GWh of wind-electricity is generated per sq. mi. per year.

45 million GWh ÷ 936,000 sq. mi. x 0.95= 45.7 GWh/sq. mi.

Fig. 22 - Potential installed wind energy annual output (lower 48 states)



(Data source: U.S. Government)

Recall that the annual energy output of the ground solar farms was estimated to be 122.8 GWh/sq. mi. This required a total of 520,900 sq. mi. of advanced solar farms to meet the U.S. 2100 energy needs. Scaling this farm area up to account for the lower output from the wind farms, the required wind farm area in 2100 would be about 1.4 million sq. mi.—substantially greater than the suitable land in the United States for commercial onshore wind farms according to Fig. 22.

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[28] As seen in Fig. 22, the 936,000 sq. mi. value corresponds to a minimum capacity factor of 30%. While wind farms can be built in areas with a lower capacity factor, some argue that economically this does not make sense.

520,900 sq. mi. of solar farms x 122.8 GWh/sq. mi. of solar farms
÷ 45.7 GWh/sq. mi. of wind farms = 1,399,705 sq. mi. of wind farms

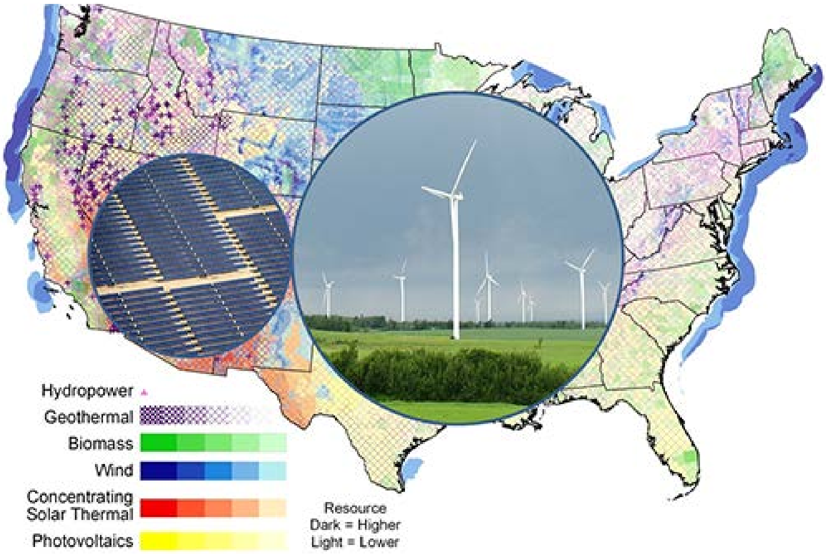
Other issues associated with large-scale wind farms include distribution of royalties to benefiting vs. impacted landowners; safe setback distances from inhabited buildings and roads; bird and insect kills; farm land compaction during construction and loss of productivity; interference with pivot irrigation systems and aerial spraying; impact on aviation, especially general aviation; impact on pollination; impact on soil moisture content; impact on crop moisture conditions; and a general change in the visual (shadow flicker) and acoustic conditions of the impacted and surrounding farmland. Given the obvious increasing demand for food as the nation’s population more than doubles by 2100, any measurable impact on agricultural output will be a significant issue. As seen in Fig. 20, the heart of the wind power zone is America’s breadbasket states in the central United States.

Offshore wind farms are now being installed around the world because the average wind speed is often greater. As shown in Fig. 20, the United States has belts along its coasts and on the Great Lakes that have substantial wind power potential. The challenge in installing substantial offshore farms is that they impede ship transport, often impact the view from the shore where tourism is important, are more difficult to connect to onshore utility grids, and can require elaborate anchorage systems in deeper waters, especially where hurricanes and/or ice are possible. Consequently, the potential for added wind-electricity generation from offshore farms is likely quite modest.

Neither Ground-Solar nor Wind Power Provide Practical Solutions for Meeting U.S. 2100 Energy Needs

The net land area required to meet the U.S. 2100 energy needs of a population of 625 million consuming 50 BOE/yr. using ground solar and wind farms is, respectively, 521,000 sq. mi. and 1.4 million sq. mi. This is what is required to equal the 6,500 GW of continuous nuclear-electricity sized to provide the same 2100 energy needs. To help appreciate the impact of the needed land areas, these are illustrated in Fig. 23.

Fig. 23 - Comparison of ground solar farm and wind farm net areas needed to meet U.S. 2100 energy needs



(Map and photograph source: U.S. Government)

An important point to reemphasize is that these are the net land areas, not the gross impacted land areas. The actual impacted land area in each case will be greater due to local terrain; set-asides for parks, roads, existing construction, etc.; local social/political opposition; aviation flight restrictions; availability of electrical power transmission lines, etc. With this understanding, it quickly becomes apparent that neither ground solar nor wind—or a combination of these—will be capable of providing a substantial percentage of the U.S. 2100 non-fossil fuel energy sources.

Section VIII - The Energy Security Dilemma Facing the United States is Serious

By now it should be clear that the United States has inadequate technically recoverable resources of ground solar and wind energy to replace fossil fuels. Hydroelectricity, geothermal-electricity, and biomass are not capable of significant increases in energy production. Finally, conventional nuclear fission energy cannot be scaled up by any significant amount and fusion nuclear energy is not yet available. Still, the need for a replacement for fossil fuels is readily apparent. Where must the United States now turn to find industrial-scale replacements for fossil fuels? This is the energy security dilemma the United States now faces; a dilemma that raises the very ugly “solution” of warfare—a solution that, surprisingly, the United States avoided in the 19th century while Japan did not in the 20th century.

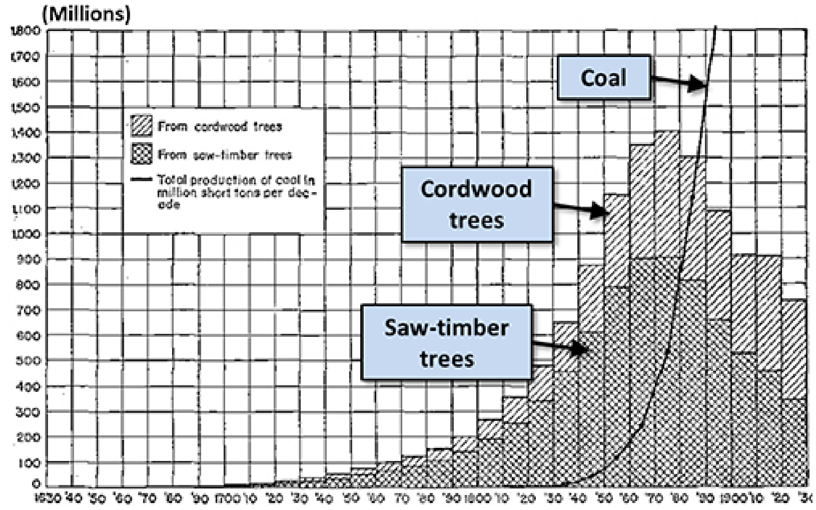
What Would Have Happened Had America Not Had Fossil Fuel Resources?

As we now consider the dilemma the United States faces in how to replace fossil fuels, we return our attention to the first energy support crisis the United States faced in the mid-1800s. Since our distant human ancestors learned to harness fire, biomass (primarily wood) has been human civilization’s energy source.

Over the time period that Leslie White examined in formulating what became known as White's Law linking energy and technology to cultural advancement, wood was the primary energy source for human civilization's advancement across some 600 generations. Eventually, the size of the human population grew to the point that the rate of the natural replenishment of wood—about one-half cord per acre per year—failed to meet the growing demand for energy. The United States, with the European-standard of living brought by immigrants beginning in the early 1600s, hit this point in the early 1800s. Consequently, sometime in the 1830s-1840s, wood fuel, along with wood being used for other purposes, was being consumed at a rate higher than natural replacement.[29]

Figure 24 plots the consumption of wood fuel from 1630-1930—across 300 years. This is an excellent example of the classic sinusoidal recovery pattern of over-harvested resources seen with fossil fuels, minerals, fish, etc. Imagine for a moment you are a government economist in the latter 1800s tracking wood fuel production. Further, for the purpose of this thought experiment, assume that fossil fuel recovery was still negligible. Perhaps, in this alternate history, anti-coal, anti-oil, and anti-natural gas commercial coalitions formed to protect the timber and whaling industries from competition.[30] As seen in Fig. 24, up through the 1870s, wood fuel production was still expanding with no evidence of decreasing production apparent.

Fig. 24 - Fuel wood and coal used in the U.S. (1630 – 1930)



(Source: U.S. Government)

As an economist, you note the first falloff in wood fuel consumption in the 1880s, indicating the lack of an adequate supply at affordable prices. Yet, the U.S. population is still rapidly growing and per capita energy use is also growing due to the technological

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[29] England had already passed this point when the first English settlers arrived in America in the 1600s. Endless old-growth forests stretching to the horizon were a fantastic sight to them.

[30] The first primary use of oil was to distill kerosene to replace whale oil for lighting. Natural gas then became a second source for lighting.

and societal changes brought by the industrial revolution. Your energy security forecast is bleak. The United States is consuming wood fuel at rates the forests cannot naturally replenish. Forests across the country are being clear cut. The U.S. industrial economy, approaching the point of inadequate energy supplies, will collapse back to an agrarian economy unless new replacement energy sources for domestic wood fuel are found. But there are none now available in the United States with the industrial scale capacity needed to keep the United States prosperous with a growing population and increasing per capita energy use. The fledgling fossil fuel industries could have done this had it not been for political opposition and Congressional naiveté preventing growth and technological development of these new energy sources.

The president, reading your report, notes the seriousness of your conclusion that it would take decades to develop the needed fossil fuel recovery technologies and build up this new industry to achieve the level of energy production needed to replace wood fuel. The rate of forest clearing is expanding to try to keep up with demand, but prices are inflating while production is declining. The report is forwarded to the Secretary of War for review. The War Department proposes, to prevent dramatic energy supply shortfalls and the accompanying severe economic decline, to invade Canada and seize sufficient Canadian forests to give the United States the time it needs to develop its fossil fuel industry. Canada, noting the devastation brought to America's forests, has declined to let American companies conduct the large-scale forest cutting needed to meet U.S. energy needs. Hence, instead of warfare with Spain, the Canadian-American War commences in the 1890s as escalating wood fuel prices and fuel scarcity forces American action to sustain its wood-fueled, steam-powered cultural evolution.

When Japan Faced This Choice, It Led to War

While you may find this alternate history incredible, a version of this played out in the early 20th century. Japan, adopting the Industrial Revolution in the late 1800s to transform its medieval society into a modern industrial society, lacked the fossil fuel and other industrial natural resources needed to thrive per White's Law. It began colonial expansion and military conquest to obtain these resources in northern China as early as the 1890s. A key part of this strategy was to build a modern military, becoming the preeminent military power in the Pacific from the 1920s until the early 1940s.

Fig. 25 - U.S. Navy under attack at Pearl Harbor on December 7, 1941

(Source: U.S. Government)

In particular, Japan needed oil and through the 1930s the United States was then its primary oil supplier—the United States being the OPEC of the early 20th century. When the United States cut off oil supplies to try to get Japan out of China, Japan decided to settle the issue by militarily seizing oil facilities in Southeast Asia belonging to European countries then at war with its ally Germany. However, to achieve this goal, Japan first had to neutralize the U.S. Navy's Pacific fleet then stationed at Pearl Harbor. When Japan attacked the United States, as seen in Fig. 25, it had, by some accounts, less than a year's worth of oil remaining—even less with substantial military warfare. Setting aside the cruelty with which Japan undertook many of its military campaigns, answer this important question: What really distinguishes Japan's energy security circumstance in the early 20th century from that of the United States in the early 21st century? White's Law applied then; it applies now.

The Development of America's Fossil Fuel Industry Shows That Substantial Change Can Occur, But This Takes Time

The primary focus of this paper on America's growing energy insecurity due to this century's pending exhaustion of technically-recoverable and affordable fossil fuels was first brought to the public's attention during the 1950s and again in the 1970s.[31] Further, the shortcomings of terrestrial renewable energy sources in becoming practical industrial-scale energy sources were also apparent in the late 1970s and 1980s. It was not a lack of renewable energy technology, but the scale needed to meet U.S. needs. The U.S. population and per capita energy needs were simply too large and still growing. Yet, White's Law tells us that either America solves the challenge of returning

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[31] See the work of American geophysicist M. King Hubbard with respect to his publications in the 1950s forecasting the peak in U.S. oil production around 1970.

to energy security by increasing E and T or human events will address the problem by forcing a dramatic decline in C.

Fig. 26a - Pennsylvania oil refinery in 1870

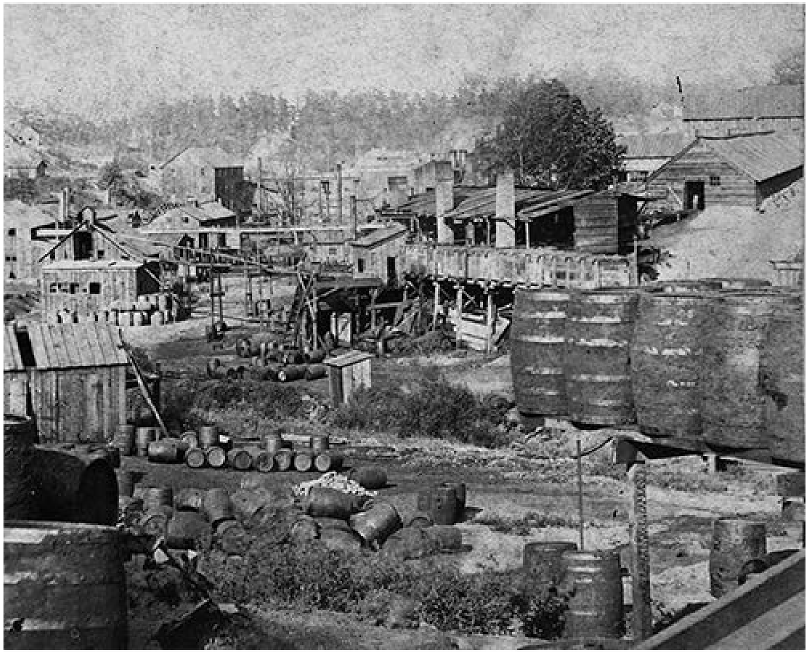


Fig. 26b - Standard Oil plant in 1905

(Source: U.S. Government)

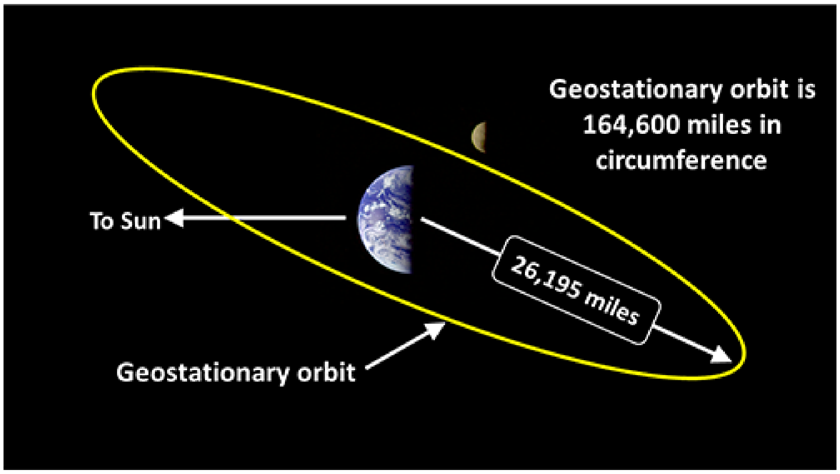
A second purpose of the earlier thought experiment was to make clear that the United States avoided its first serious energy supply crisis by a leap forward in technology to enable fossil fuels to be recovered and used on an industrial scale. Figure 24 shows how coal became king within about 50 years of when it first became commercially mined. Figures 26a and 26b show the advancement of oil refining from the crude refineries of 1870 to the fairly modern refineries in 1905—less than two generations later.

The cultural transformation America underwent in the last two generations of the 1800s was dramatic. By the turn of the century, the new fossil fuels had created modern America with automobiles, electricity, electric motors, electric lights, telephones, oil-fueled ships and trains, steel-framed buildings, steel-bridges over America's immense rivers, etc. The energy industry of America at the beginning of the 20th century was a far cry from America even at the time of the end of the Civil War. America's industrial history of the latter 19th century shows that, with determination, substantial change can be accomplished to prevent an energy security crisis from arising—but the United States needs time—several generations—for this to happen. It cannot happen overnight!

Section IX – Space Solar Power is America's Unavoidable Energy Future

Just as a leap forward in technology to fossil fuels prevented an energy supply crisis in the late 1800s, America must undertake a similar leap forward in technology to circumvent the upcoming end of the age of affordable fossil fuels. With no suitable terrestrial options available at this time, we must turn to the one truly sustainable energy source—our sun. However, with the impracticality of harvesting sufficient solar energy at ground level being apparent, the technological course of action to pursue is space-based solar power or, simply, space solar power. In space at Earth's geostationary orbit, sunshine is nearly continuous.

Fig. 27 - Geostationary orbit

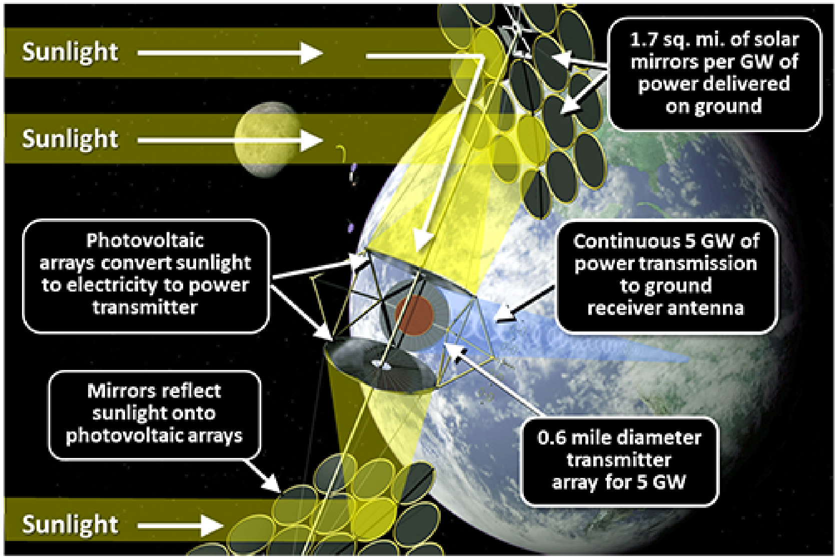


While there are several approaches to implementing space solar power, the baseline approach is to undertake this in geostationary orbit. Geostationary orbit or GEO is, as shown in Fig. 27, a circular Earth orbit about 26,000 miles above the Earth's equator. A satellite located in this specific orbit will circle the Earth once every day making it appear stationary in the sky. Thus, just as it is the ideal location for broadcasting television signals to Earth receivers, it is also a good location for a satellite that transmits electrical power to the surface to supply terrestrial power grids.

About 50,000 Sq. Mi. of Land Would Enable the United States to Use Space Solar Power

Invented in 1968 and studied extensively in the 1970s and 1980s—almost two generations ago—one concept for a space solar power satellite is shown in Fig. 28. In this illustration, sunlight (yellow) is reflected by arrays of circular mirrors onto two circular arrays of photovoltaic panels. These panels generate electricity that powers a transmitter to transmit the electrical power to the receiver site on the ground. With the exception of only a few short periods each year, the sunlight is continuous, meaning that the power transmitted to the ground is continuous and suitable for baseload power much as that supplied by nuclear and coal power plants.[32] Each solar power satellite (SPS) would transmit between 5 and 10 GW if it is based in GEO (5 GW is used in this example).

Fig. 28 - Space solar power satellite in GEO beaming power to Earth receiving sites



The author estimates that 1.7 sq. mi. of solar mirrors or direct collector area would be needed to yield 1 GW of power output from the ground receiver site.[33] Recall from the nuclear power example, the U.S. 2100 energy need would be met by 6,505 GW of continuous power. Hence, at 5 GW from each solar power satellite, the United States would need about 1,301 solar power satellites operating in 2100—the rest of the world perhaps 6X more. With each satellite requiring about 8.5 sq. mi. of solar mirrors or collectors, a total of 11,059 sq. mi. of mirrors or collectors would be needed in GEO. Is there enough room in GEO? Yes. The circumference of GEO is about 165,000 miles. Nature, once again it would seem, has given humanity the source of the energy it needs just as the T needed to harness this energy becomes available.

6,505 GW needed in 2100 ÷ 5 GW per satellite = 1,301 solar power satellites

6,505 GW needed in 2100 x 1.7 sq. mi. per GW
= 11,059 sq. mi. of collector in GEO

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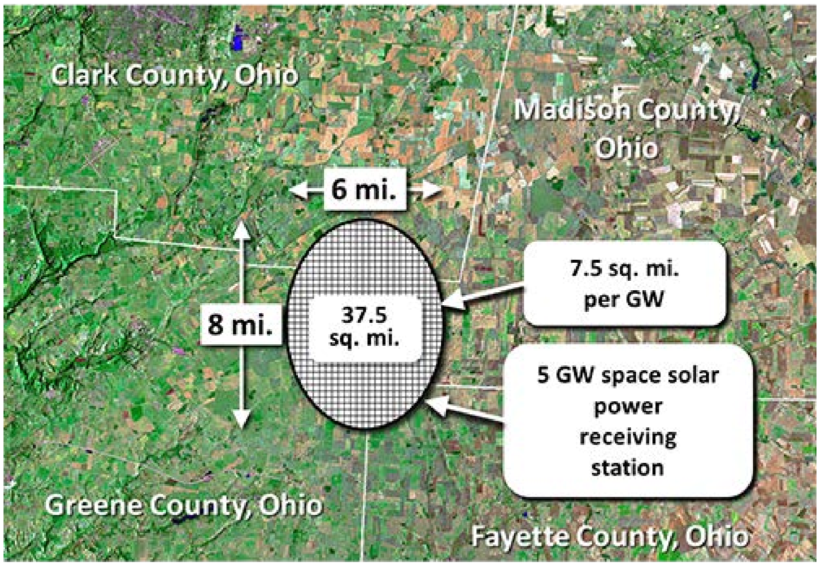
[32] A satellite in geostationary orbit will enter the Earth's shadow for up to several hours at local midnight on and near the spring and fall equinoxes. This corresponds to the period of typical minimum power demand due to the time of year and the time of day. Ground receiving stations would use secondary power, using stored hydrogen, to generate electricity during this period. All ground receiving stations would have secondary power generators for peak power and emergency generation needs.

[33] The gross solar insolation on 1.7 sq. mi. in geostationary orbit is about 6 GW. The conversion of this to electrical power, the transmission of the power to the ground receiving site, and the conversion back into electrical power fed to the local utility grid yields 1 GW. The end-to-end efficiency is about 17%.

In the baseline space solar power design studied in the 1970s and 1980s, the electrical power is transmitted to the ground receiving site as microwave energy. This means that the ground receiver is not photovoltaic arrays but radio antennas. The frequency of the microwaves is primarily governed by the transparency of the atmosphere to the microwave energy. With this fact, combined with the distance the power is transmitted and the peak power level to be permitted at the ground receiver, the size of the ground receiving antenna can be computed.

Figure 29 illustrates the size of a ground receiving site producing 5 GW of baseload power. The immediate area occupied is 37.5 sq. mi. The site produces about 0.133 GW/sq. mi. The transmitted power is at its maximum at the center of the ellipse. There the power level is about one fourth of sunlight at noon on a clear summer day. The power level tapers off to near zero at the boundary of the site, consistent with federal regulations. As with other industrial facilities, the site would be fenced off out to a distance of a mile or so to keep the public from any potential harm. That land would be suitable for farming. In sparsely populated locations, such a fence may not be needed.

Fig. 29 - Space solar power 5 GW ground receiving site



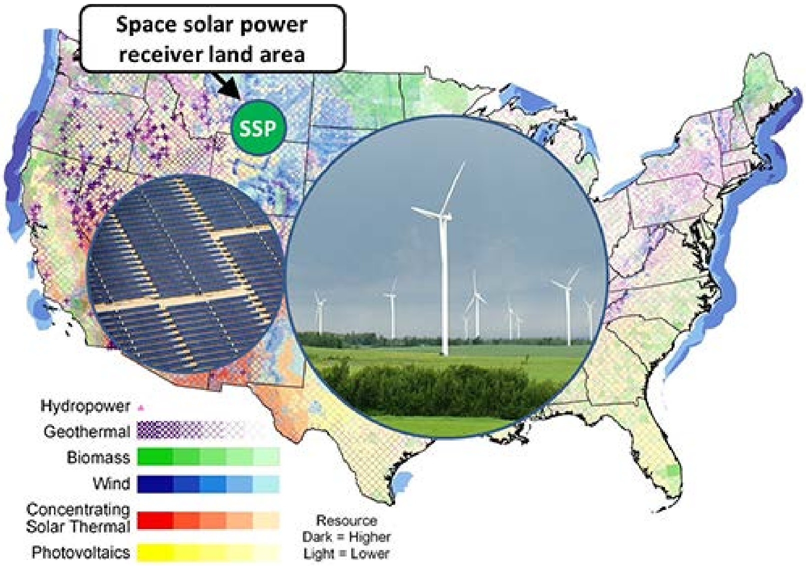
The 6,505 GW of baseload electrical power needed in 2100 would require about 50,000 sq. mi. of land for the space solar power receiver sites. This is illustrated in Fig. 30 compared to the net land area estimated to be needed for ground solar and wind. The difference is striking.

6,505 GW of electrical power in 2100 x 7.5 sq. mi. per GW
= 48,788 sq. mi. of SSP receiver sites

Recall that the advanced ground solar farms would likely yield in the ballpark of 123 GWh of variable solar electricity per sq. mi. per year. Wind farms will yield about 46 GWh of variable wind electricity per sq. mi. per year. Space solar power, immune to the variability of the day-night cycle and local weather, will yield an average of about 1,100 GWh of base load electricity per sq. mi. of ground receiver per year.

$$0.133\ \text{GW/sq. mi.} \times 365\ \text{days/yr.} \times 24\ \text{hours/day} \times 0.95$$
$$= 1{,}107\ \text{GWh/sq. mi. per year}$$

Fig. 30 - Comparison of total space solar power receiver land area to the ground solar farm and wind farm net areas needed to meet U.S. 2100 energy needs



Map and photograph source: U.S. Government)

When looking at Fig. 30, take note of the fact that these space solar power receiving sites would be spread out across most of the lower 48 states. The western states, in particular, have a great deal of open land suitable for their placement and would likely host most of the receiving sites. However, most states would be able to host some receiver sites to provide in-state baseload electrical power production.

A Spacefaring Industrial Revolution is Needed to Undertake Space-Based Solar Power

In 1976, Gerard K. O'Neill, a professor of physics at Princeton University, released the book *The High Frontier: Human Colonies in Space*. He introduced the new paradigm of transforming humanity into a true human spacefaring civilization focused primarily on the construction of space solar power platforms.[34] This book spurred tremendous public and professional interest in space solar power and the emergence of a spacefaring civilization. The key point of Dr. O'Neill's writing was that the magnitude of effort required—in terms of in-space industrial capacity and the use of extraterrestrial natural resources for fabrication—will invariably move humanity into the Earth-Moon system in large numbers and will do so permanently.

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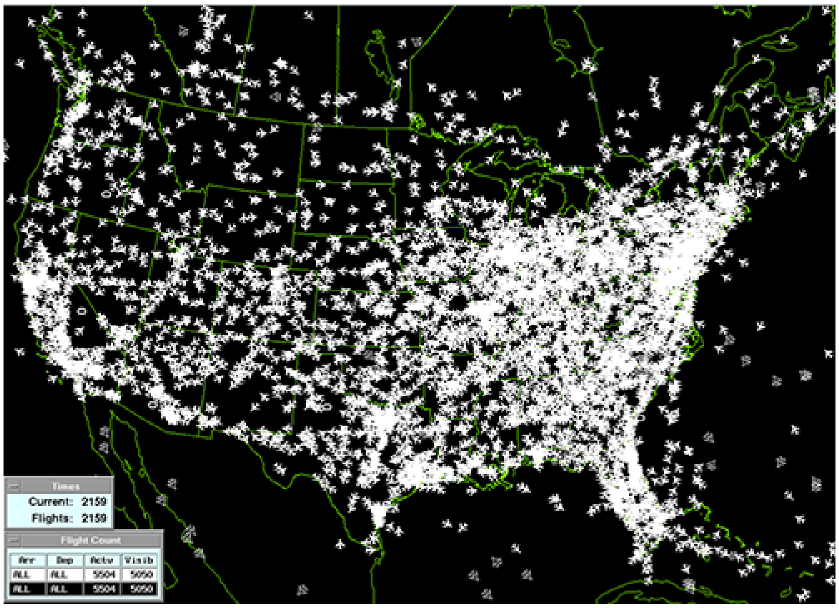
[34] Gerard K. O'Neill, *The High Frontier: Human Colonies in Space* (New York: Morrow, 1976).

Fig. 31 - Radar snapshot of commercial air traffic over the U.S.



Some will scoff at this as being unrealistic. Yet, consider the situation with aviation only a century ago and compare its technologies at the start of World War I, when aviation was barely a decade old, with where it progressed less than three generations later at the start of the jet age. Today, as you read this, there are likely several thousand commercial aircraft and a quarter million passengers in the skies above America and we don't give it a second thought. Unthinkable a century ago; ignored today due to its commonplace part of our culture.

The Earth-Moon system by the end of this century will witness a comparable cultural transformation as America undertakes its only real current engineering-ready replacement for fossil fuels—space solar power. Human space flight will expand beyond the current meager capabilities of infrequent access to low Earth orbit to achieve routine and safe operation throughout the Earth-Moon system. In leading this transformation, America will undergo a substantial spacefaring industrial revolution—rivaling the emergence of commercial aviation—as American industry develops the industrial mastery needed to meet the challenge of replacing fossil fuels with space solar power. It should not take a genius to understand the national potential of this coming spacefaring industrial revolution. Just as aviation defined the 20th century, the 21st century will be defined by America becoming a true commercial human spacefaring nation.

Section X – If Only the Titanic Had 30 Seconds More of Warning

America's need for a replacement for fossil fuels is undeniable. The age of affordable fossil fuels will end in America, likely within the lifetime of our children and grandchildren. Only through a decades-long concerted effort will America be able to build the new spacefaring industrial capabilities, infrastructure, and space solar power satellites needed to meet this clear energy security challenge successfully.

In terms of White's Law, America's energy future can now be expressed as:

$$E_{SSP} \bullet T_{spacefaring} \Rightarrow C_{United\ States\ in\ 2100}$$

Thus, for what reason do we dawdle? Imagine, for a moment, the thrill of sailing on the Titanic on its maiden voyage and of the awfulness that would have been avoided had there been only another 30 seconds of warning. Imagine now the thrill of setting America on a course of becoming a true human spacefaring nation, of being among the coming generations that will lift American culture permanently into space, that will develop the new T to allow us to exploit the new E from the solar power awaiting us in geostationary orbit and then exploiting all this new E and T to open the entire solar system to humanity. Imagine now the calamity of an America that waits too long, figuratively enjoying a peaceful but tragic cruise into the future, until one day there is no more affordable gas at the corner gas station, your home's natural gas supply ends, and rolling blackouts begin. Then, what will America's leaders say—"If only we had more time.…"

White's Law really is not an obituary of an unavoidable failure of civilization, but a roadmap of the path forward for America to follow to remain prosperous. Unmistakably, it now tells us it's time for America to climb a new mountain to achieve energy security—and to do so by becoming a true commercial human spacefaring nation. Again, with this new understanding, for what reason do we dawdle?

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Editors' Notes: Mike Snead is highly regarded within the Space Community for his extended dedicated research of all energy alternative systems. His conclusion that Space Based Solar energy is the major long-term solution for Earth's energy needs deserves the attention of decision makers worldwide. ***Bob Krone and Gordon Arthur***.