Why the AIAA Should Advocate for GEO Space Solar Power

James Michael Snead*
Spacefaring Institute LLC, Beavercreek OH 45430, USA

This century, the United States faces two serious and related threats. The first is the abnormally high atmospheric carbon dioxide concentration due to anthropogenic causes. The second is an inadequate domestic fossil fuel supply that will lead to shortages, and likely warfare, later this century. This paper begins by defining these two threats to establish why America now needs to transition, this century, from fossil fuels to sustainable energy. The paper continues by evaluating the domestic options for sustainable energy. Each of the three primary terrestrial options—nuclear, wind, and solar—are quantitatively assessed and found to be impractical solutions at the scale needed to replace fossil fuels. The paper then examines what will be required to use GEO space solar power to replace fossil fuels. The paper concludes with a call for the AIAA to advocate that the United States establish a national GEO space solar power program and explains why the AIAA has a clear ethical obligation to undertake this advocacy.

Nomenclature

BOE	=	*Barrel of oil equivalent (1 BOE = 5.8 million Btu)*
CO_2	=	*Carbon dioxide*
endowment	=	*An estimate of the remaining quantity of technically recoverable domestic fossil fuels*
GEO	=	*Geostationary Earth orbit*
GHz	=	*Gigahertz*
GW	=	*Gigawatt of electrical power (1 billion watts)*
GWh	=	*Gigawatts of electrical power produced or used per hour*
GWy	=	*Gigawatts of electrical power produced or used per year (365 days)*
Insolation	=	*Sunlight that reaches the Earth's surface*
kW	=	*kilowatt of electrical power (1000 watts)*
kWh	=	*kilowatts of electrical power produced or used per hour*
LEO	=	*Low Earth orbit*
MW	=	*Megawatt (1 million watts)*
per capita	=	*The average quantity or rate of usage per person of an identified population*
PPM	=	*A gas's concentration in the atmosphere expressed in parts per million by volume*
psi	=	*pounds per square inch of pressure*
sq km	=	*Square kilometer*
sq m	=	*Square meter*
sq mi	=	*Square mile*
SSP	=	*Space solar power*

---

* President, Professional Engineer, AIAA Associate Fellow

Synopsis

A. National environmental and energy security (See Sections II and III)

As an industrialized nation, America's prosperity depends on its environmental and energy security. Both of these are now significantly threatened.

The world's environmental security is threatened by the abnormally high and rising atmospheric carbon dioxide (CO_2) concentration. This concentration is now about 40 percent greater than the natural maximum value measured over the last 800,000 years. The CO_2 concentration is believed to be abnormally high due to, as examples, the combustion of significant quantities of fossil fuels, land use changes due to agriculture, and large populations of domesticated ruminant animals. These anthropogenic causes have arisen due to the world's large human population and growing industrialized culture. **The environmental security threat is that there is no tested scientific hypothesis establishing, with reasonable certainty, that this high and rising CO_2 concentration will *not* bring unacceptable environmental harm.** For example, preliminary investigation finds that the nutritional quality of many domesticated plants is declining due to the higher CO_2 concentration. Essentially, the excess CO_2 is an anthropogenic pollutant that has not been shown to be benign. For this reason, **an end to the use of non-sustainable fossil fuels is inevitable.**

Fossil fuels provide about 80 percent of the energy Americans consume. As the energy per capita consumed in an industrialized culture is a primary indicator of prosperity, America's prosperity is substantially dependent on these non-sustainable fossil fuels. Partially due to the rising U.S. population, a projection of America's fossil fuel energy needs through 2100 indicates that **America's domestic endowment of technically recoverable oil, natural gas, and coal will be exhausted around the end of the century.** The resulting shortages of affordable energy supplies and a return to a growing reliance on imported oil and natural gas does not bode well for the prosperity and security of our children and grandchildren. For this reason, **America's orderly transition this century from fossil fuels to sustainable energy is needed.**

B. The avoidance of war (See Section IV)

The need to obtain or desire to control oil resources has been a primary cause for war since World War I. As long as America remains substantially dependent on fossil fuels, especially oil, this will exert substantial influence on the allocation of federal resources to ensure America's access to foreign fossil fuel sources.

Reasonable people understand the need to resolve the environmental and energy security threats due to the use of fossil fuels by an orderly transition to sustainable energy. For America, with its still significant remaining fossil fuel endowment, it is possible for the United States to become and remain energy independent through the transition to 100 percent sustainable energy by 2100. Plainly speaking, **the United States has sufficient oil, natural gas, and coal, to ensure that the domestic energy needs of a growing and prosperous economy can be met while the transition to sustainable energy is completed**. Undertaking this transition, as a national priority, will segregate America's energy security needs from its overseas national security and foreign policy obligations and considerations. **This will remove what many now see as an inevitable trigger for future foreign conflicts over energy in which the United States would otherwise become involved.** America's leadership in this peaceful transition to sustainable energy will provide a policy and technological path for America's friends and allies to emulate.

C. America's terrestrial sustainable energy options (See Section V)

To replace the energy liberated through the combustion of fossil fuels, electrical energy will become the primary energy source. By 2100, it is projected that each American will need a continuous electrical power supply of roughly 10 kilowatts—about the power needed to run 10 countertop microwave ovens. This electrical power supply would satisfy all of the energy needs used for daily living and working, as well as the energy needed to supply the goods and services consumed. **In 2100, with its projected population increasing by about 50 percent to 500 million, the United States would need a continuous electrical power supply in the ballpark of 5,000 gigawatts.** Today, primarily generated using fossil fuels, the United States has an equivalent continuous electrical power supply of roughly 475 gigawatts—about 10 percent of what will be needed by 2100.

While the United States has many terrestrial non-fossil fuel options to generate the needed additional electricity, most have little or no significant growth potential. These include: geothermal-electricity, hydroelectricity, tidal- and wave-electricity, and biomass. **The only three possible terrestrial electrical power options are nuclear fission, wind, and ground solar.**

- ***Nuclear fission***

To meet the nation's total 2100 energy needs, 5,155 1-gigawatt nuclear fission power plants will be required. (Each new plant is assumed to be operational 95 percent of the time.) The United States only has sufficient natural uranium, when speculative resources are included, to fuel about 100 such plants for their expected 120-year lives. Using plutonium and/or U^{233} will require that about 7,000 metric tonnes be bred each year. If the United States pursues this solution, other nations will follow. Hence, **a limited domestic natural uranium supply, nuclear weapon proliferation risks, safe nuclear waste disposal, plant siting, adequate cooling water, and plant security considerations all make a significant expansion of nuclear fission an impractical solution to replace fossil fuels.**

- ***Wind and ground solar***

Modern wind turbines now have hub heights of 110-140 meters. **Such a wind turbine will only have the ability to provide electrical energy to meet the total annual needs of about 50 Americans in 2100.** About 56 percent of the contiguous United States could be used for commercial wind farms. Fully populated with these newer turbines, this would only supply about 65 percent of the total U.S. 2100 electrical energy need. This would require erecting about 6.6 million turbines on almost all flat or near-flat land—essentially, where Americans live and work.

Using ground solar electricity, in 2100, the annual energy need of an American could be met by 1,650 square meters of solar farm in the sunny Southwest. To meet the total annual need for 500 million Americans in 2100 would require 825,000 square kilometers of solar farms. In the seven southwestern states of Arizona, California, Colorado, New Mexico, Nevada, Texas, and Utah, only about 225,000 square kilometers is suitable for commercial solar farms without extensive grading of the terrain. Such a buildout of solar farms would provide only about 27 percent of the total 2100 U.S. electricity need.

In combination with nuclear, hydroelectricity, geothermal-electricity, and biomass, a complete national buildout of wind farms along with the buildout of solar farms in the seven southwestern states could meet the projected total 2100 U.S. energy need. **This would require wind and ground solar farms covering almost 5 million square kilometers.** This is unlikely to be a politically-acceptable solution.

D. GEO space solar power (See Section VI)

First proposed in 1968, **large platforms placed in geostationary Earth orbit (GEO) would be able to capture sunlight, convert it into electrical power, and transmit this power to a ground receiving station—referred to as an astroelectric plant.** This GEO space solar power concept was studied extensively by the National Aeronautics and Space Administration (NASA), the Department of Energy, and U.S. aerospace companies in the 1970s and 1980s. **A baseline design emerged that would provide 5 gigawatts of astroelectricity per system, meeting the energy needs of 500,000 Americans in 2100.** By using sunlight in this manner, the 10 kilowatts of continuous electrical power needed per capita could be met by capturing about 38 square meters of sunlight. This is about the area of a two-car garage.

Replacing fossil fuels by 2100 would require building about 825 of these 5-gigawatt astroelectricity systems. Within the contiguous United States, this will require the use of about 135,000 square kilometers of land for the receiving antennas. From a 1979 study, this would use about 17 percent of the land then deemed suitable for such use. Overall, **this would use only about 1.5 percent of the land area in the contiguous United States compared with nearly 60 percent for the combined wind and ground solar solution. GEO space solar power is the reasonable alternative to the unwelcome transformation of America that wind and ground solar would require.**

E. America's coming spacefaring industrial revolution (See Section VII)

Undertaking GEO space solar power will require substantial new American space power, space mining, space manufacturing, and spacefaring logistics industries to build and operate the 825 GEO space solar power systems. (For the world, upwards of 10,000 GEO space solar power systems will be required.) Using the current cost per gigawatt of nuclear fission as a baseline, building the 825 U.S. astroelectricity systems would cost, in the ballpark, of $21 trillion. For the world, the cost would be, very roughly, $250 trillion.

Undertaking GEO space solar power requires a spacefaring industrial revolution comparable to the steam-powered industrial revolution of the 1800s. **Now substantially barren of a human presence, outer space will become the permanent home of tens of thousands of Americans working and living throughout the central solar system—in LEO and GEO, on the Moon, in lunar orbit, at the Earth-Moon LaGrange points, and at asteroids throughout the central solar system.** What an exciting time ahead for America's aerospace professionals.

F. The AIAA's ethical obligation to advocate for GEO space solar power

As a professional society, the primary ethical responsibility of the American Institute of Aeronautics and Astronautics (AIAA) is to "Hold paramount the safety, health, and welfare of the public in the performance of their duties." This responsibility supersedes everything else. America now faces two serious challenges to protect our children and grandchildren from the environmental and fossil fuel energy security threats described herein. The only reasonable action is to undertake an orderly transition from fossil fuels to sustainable energy. **For America, the only practical choice of a new sustainable energy source sufficient to replace fossil fuels, while maintaining our energy-dependent standard of living, is GEO space solar power.** Consequently, to faithfully adhere to the AIAA's paramount ethical priority while speaking from the position of being America's leading aerospace professional society, ***the AIAA should strongly and publicly advocate for the United States to undertake a national program to transition from fossil fuels to GEO space solar power.***

I. Introduction

> *We the People of the United States, in Order to form a more perfect Union, establish Justice, insure domestic Tranquility, provide for the common defence, promote the general Welfare, and secure the Blessings of Liberty to ourselves and our Posterity, do ordain and establish this Constitution for the United States of America.*

The U.S. Constitution was adopted to create a federal government to provide for the defense and general welfare of Americans, then and in perpetuity. Hence, per the Constitution, the Federal Government must act now, when needed, to secure the liberty and welfare of Americans in the foreseeable future against acknowledged threats.

Americans, this century, face two significant and related threats due to the use of fossil fuels to substantially energize our industrial culture. **To resolve these threats, while ensuring the defense, general welfare, and liberty of our children and grandchildren, the Federal Government must lead America's orderly transition from fossil fuels to sustainable energy this century.** Of the sustainable energy options available to the United States, **only GEO space solar power now offers the scalable potential to replace the non-sustainable fossil fuels** and provide the additional energy needed to remediate existing possible environmental harm that our past and continued use of fossil fuels created.

Undertaking this transition to space-based sustainable energy will require a national astronautical program—undertaking a spacefaring engineering and industrial revolution—of a scale unprecedented in America's peacetime history. By the end of this century, in large numbers, Americans will be working and living throughout the central solar system to provide America with the space-based sustainable energy it will need to remain prosperous, at peace, and free. (See Figure 1.)

Figure 1: Illustration of a future space colony. Mega space projects such as this will be common in the later 21st century. (Credit: NASA.)

II. The Anthropogenic CO_2 Environmental Threat

Over the last 800,000 years, the climate has experienced at least eight cycles of global cooling followed by interglacial warming. Using core drills, scientists have extracted samples of ancient Antarctic ice formed up to 800,000 years ago. As this ice formed, air was trapped within the ice in small bubbles enabling the atmospheric carbon dioxide (CO_2) concentration in these ancient air samples to be measured. The CO_2 concentration is expressed as parts per million (PPM) by volume. As shown in Figure 2, **across these 800,000 years, the pre-industrial CO_2 concentration has naturally varied from a low of about 185 PPM, during periods of global cooling, to a high of about 300 PPM during periods of interglacial warming.** (As a point of interest, the climate today is experiencing interglacial warming. Most of the time, the Earth is much colder that what we now believe to be "normal".)

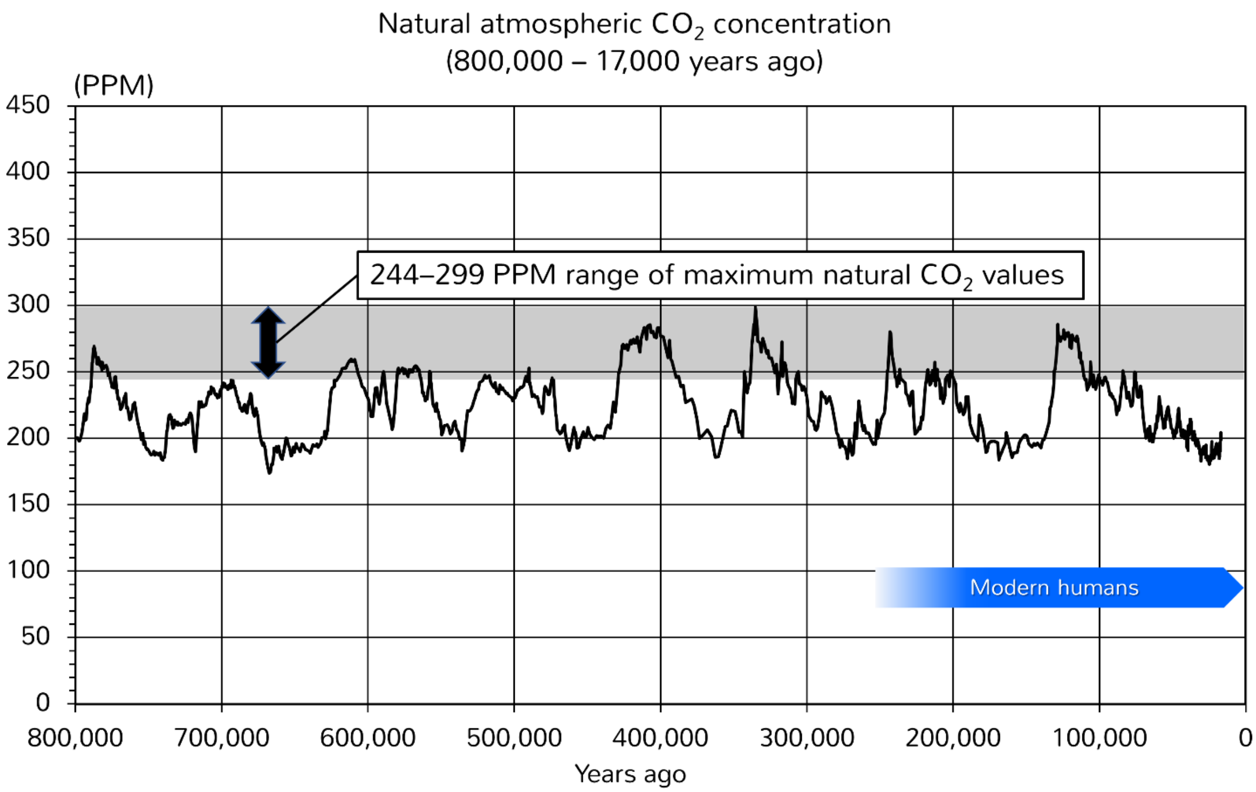

Figure 2: Atmospheric CO_2 concentration (parts per million by volume—PPM) from 800,000 years ago to about 20,000 years ago from ice core measurements. (Data source: World Data Center for Paleoclimatology, Boulder, and NOAA Paleoclimatology Program, retrieved 2016 and 2017. Credit: J.M. Snead.)

Beginning in the 1800s in America, the emerging industrial culture and the rapidly growing American population began to consume energy at non-sustainable rates. The remaining old growth forests began to be clear cut to meet the demands for timber, sawn lumber, and wood fuel in addition to clearing land for agriculture. Starting in the 1830s, coal began to be commercially mined to replace wood fuel where wood fuel shortages developed. By the 1880s, coal became the predominant energy source as the national wood fuel supply began to wane.

As a carbon-based fuel, the combustion of wood yields CO_2. All living creatures also release CO_2. Once released into the atmosphere, a CO_2 molecule is believed to have a resident time of up to a century before it is removed through plant growth or absorbed into the oceans, eventually ending up as rock. **Across at least eight cycles of global cooling and warming, for reasons that are not understood, the maximum natural CO_2 concentration always fell within the range of 244-299 PPM.** (See Figure 2.) Hence, up until the early decades of the Industrial Age, the total release of CO_2 and its removal through natural means remained in general balance, even as the climate naturally changed.

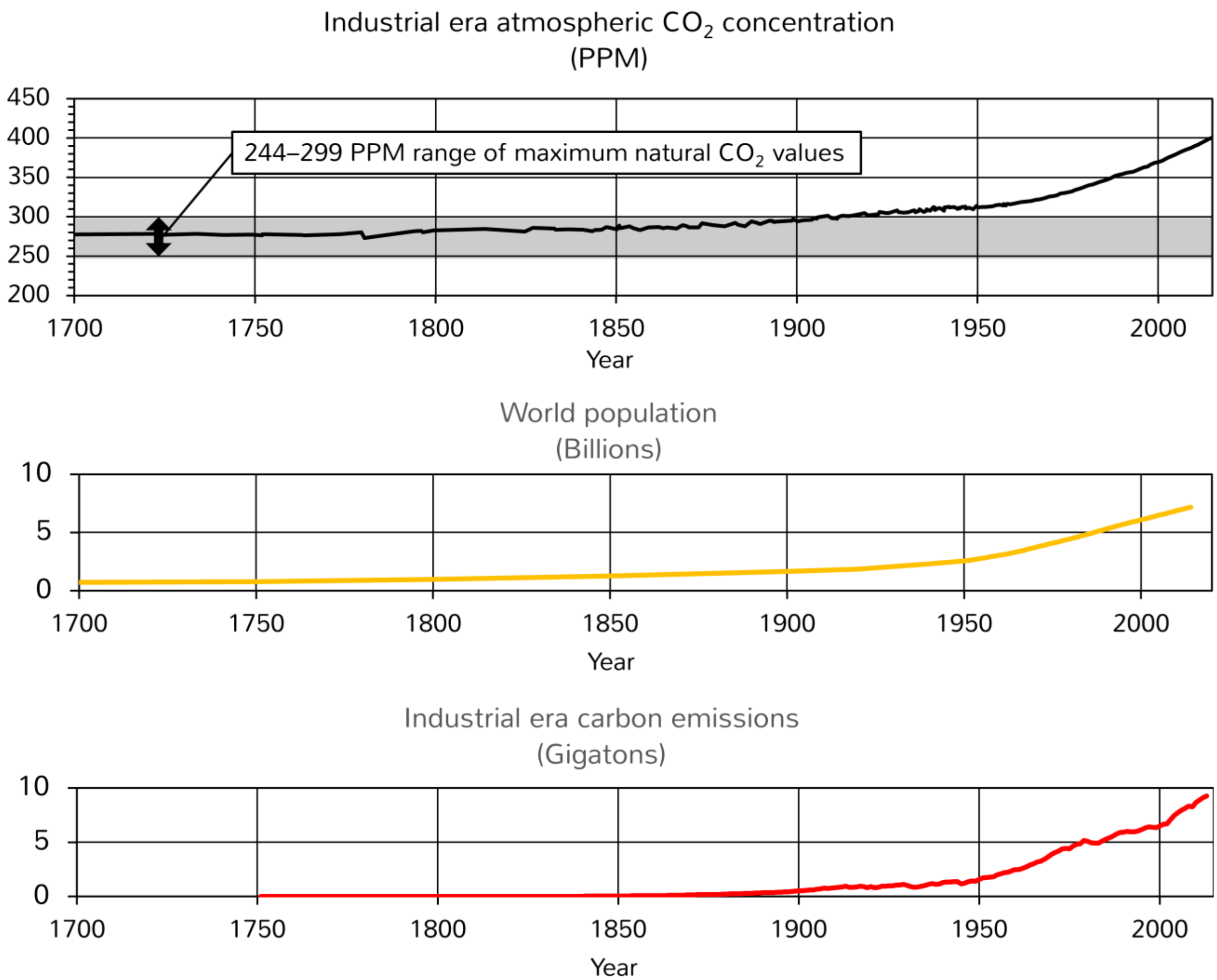

Figure 3: Industrial era atmospheric CO_2 concentration, 1700-2015. (Climate data source: World Data Center for Paleoclimatology, Boulder, and NOAA Paleoclimatology Program, 1700-1958, retrieved 2015 and 2016; NOAA/Mauna Loa, Hawaii, 1959-2015, retrieved 2016.) World population estimate. (Data source: U.S. Census Bureau.) Carbon emissions from fossil fuels. (Data source: U.S. Department of Energy's Carbon Dioxide Information Analysis Center and BP's Statistical Review of World Energy as compiled by the Earth Policy Institute. Credit: J.M. Snead.)

The growth of the human population has brought large-scale land use changes worldwide and an increasing demand for combustible fuels. These changes have increased the release of CO_2. **Around 1900, the atmospheric CO_2 concentration increased above the natural maximum of the preceding 800,000 years.** (See Figure 3.) Analysis of changes in the isotopic proportions of the carbon in the CO_2 indicates that this increase is primarily due to the combustion of plant-based fuels—wood and fossil fuels.* Today, the CO_2 concentration is above 400 PPM, climbing each year. **This roughly 33 percent increase above the natural maximum has occurred because anthropogenic CO_2 release has increased the total CO_2 release rate beyond what nature is capable of removing from the atmosphere.** Essentially, this excess CO_2 is a pollutant.

While once we ignored anthropogenic pollution, today we seek to eliminate it. For today's excess CO_2, there is no scientific certainty—no tested hypothesis—that the abnormally high CO_2 concentration will not harm the environment. In fact, **preliminary scientific investigation into possible changes has found that the nutritional quality of many of the plants on which our agriculture depends is being reduced by the increasing CO_2 concentration.**† [1] [2] Obviously, besides impacting our food supply, this will also likely impact the nutritional quality of the plants on which all living creatures depend. Hence, there is good reason for caution.

The lack of scientific certainty that the abnormally high CO_2 concentration is <u>not</u> causing harm constitutes an environmental security threat. Essentially, the excess anthropogenic CO_2 should be recognized as a pollutant that requires remediation because we do not have positive knowledge that the excess concentration is environmentally benign. **The first step to address this threat is to end the use of fossil fuels. The second step is to technologically remove the excess CO_2 from the environment to return the atmospheric concentration to, at least, 300 PPM.**

To undertake the first step, **the United States must develop sufficient non-fossil fuel energy sources to replace fossil fuels.** For the second step, additional non-fossil fuel energy sources must be built to provide the energy necessary to capture CO_2 from the atmosphere; to reform the captured carbon into synthetic coal, oil, and methane; and, to permanently geologically store these synthetic fossil fuels underground in empty coal mines and oil and gas reservoirs.‡

---

* While not settled science, changes in the atmospheric CO_2 proportions of C^{12}, C^{13}, and C^{14}, since the beginning of industrialization, are believed to be evidence that the combustion of fossil fuels is the primary source of the excess atmospheric CO_2. There may also be other significant sources due to other anthropogenic causes such as land use changes, agricultural plant selection, and large numbers of domesticated ruminants.

† Key elements, such as zinc and iron, are reduced, as is the production of protein. Plants affected include wheat, rice, corn, potatoes, and field peas. In wheat and rice, protein production declined about 7 percent when grown in CO_2 concentrations twice that of pre-industrial levels.

‡ Given sufficient time, once fossil fuel CO_2 emissions end, nature will remove the excess atmospheric CO_2 with this eventually ending up as rock or buried bogs. While we could simply wait for this to happen, the better choice is to extract the excess atmospheric CO_2 and use this CO_2 to create a synthetic fossil fuel reserve that would be available if needed in the future.

III. America's Fossil Fuel Energy Security Threat

At first glance, resolving the CO_2 environmental threat would appear to be a choice of whether to continue to use fossil fuels or not. It is not that simple. Because fossil fuels are non-sustainable, the supply of affordable fossil fuels will inevitably end. The three key national energy security questions addressed in this and the following sections are: (1) When will these supplies become unaffordable? (2) What will replace oil, natural gas, and coal? And, (3) When should the transition to replacement energy sources be completed to avoid serious economic disruptions and the threat of war?

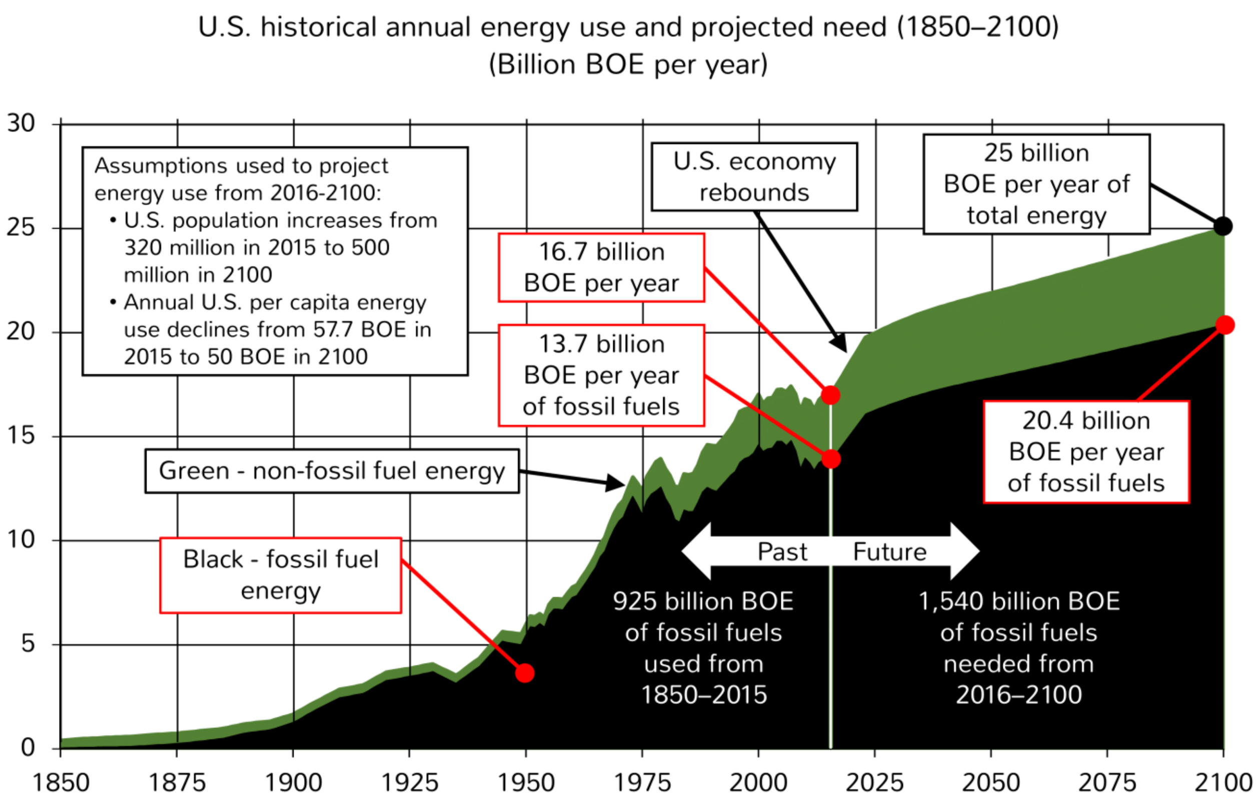

Figure 4: U.S. historical total energy use, 1850-2015, and projected energy need, 2016-2100, with breakouts for fossil fuel (black) and non-fossil fuel energy (green). (Historical data source: U.S. Energy Information Administration. Credit: J.M. Snead.)

Figure 4 shows America's fossil fuel (black) and non-fossil fuel energy (green) historic use from 1850-2015 and the author's projection of America's future energy need through 2100. The energy unit is the barrel of oil equivalent or BOE.*

* When crude oil was still shipped in wooden barrels in the late 1800s, a barrel containing 42 U.S. gallons was adopted as the standard for measuring oil. Since oil is primarily used as a fuel, recognizing that the energy content of crude oil varies, a barrel of oil was later defined in terms of the energy contained rather than the physical volume. A barrel of oil equivalent (BOE) is now set as equaling 5.8 million Btu of gross thermal energy. By using energy and not volume, all methods of producing or consuming energy can be expressed in terms of the equivalent BOE—even electrical sources such as nuclear power and hydroelectricity.

For the 2016-2100 projection, the total annual energy need is simply the product of the population size and the per capita energy need. To prepare this projection, the author assumes that the U.S. population will likely grow to 500 million by 2100 and, that over this period, new technologies will reduce the per capita energy need to 50 BOE per year in 2100.*†

In 2015, fossil fuels provided 82 percent of the total energy Americans consumed. Holding this percentage constant, Figure 4 shows that the United States will need 1,540 billion BOE of fossil fuels through 2100 (with, obviously, more in the 22nd century). **From this projection, the United States will require a total affordable fossil fuel supply through 2100 that is about 50 percent greater than the total fossil fuels Americans consumed since 1850.** Is this reasonable? We can address this question by looking at how much affordable domestic fossil fuels remain—what is referred to as the fossil fuel endowment.

During 2014-2016, the U.S. Geological Survey released (through the U.S. Energy Information Administration) an estimate of the remaining U.S. endowment of technically recoverable oil, natural gas, and coal. As seen in Table 1, **the remaining fossil fuel endowment is estimated to hold 1,592.1 billion BOE. Of this total, 17 percent is oil, 28 percent is natural gas, and 55 percent is coal.**

Table 1: United States remaining technically recoverable fossil fuel endowment.

Fuel	Endowment (Original units)	Endowment (Billion BOE)	Percentage
Oil	274.2 billion barrels[1]	274.2	17
Natural gas	2,474 trillion cubic feet[2]	438.5[4]	28
Coal	254.9 billion tons[3]	879.4[4]	55
Total		**1,592.1**	**100**

1. U.S. Energy Information Administration, Table 9.1, Technically recoverable U.S. Crude oil resources as of January 1, 2014, Chapter 9, Oil and Gas Supply Module, Assumptions to the Annual Energy Outlook 2016, page 132, January 2017.
2. U.S. Energy Information Administration, Table 9.2, Technically recoverable U.S. dry natural gas resources as of January 1, 2014, Chapter 9, Oil and Gas Supply Module, Assumptions to the Annual Energy Outlook 2016, page 133, January 2017.
3. U.S. Energy Information Administration, Table 15, Recoverable Coal Reserves at Producing Mines, Estimated Recoverable Reserves, and Demonstrated Reserve Base by Mining Method, Annual Coal Report 2015, November 2016.
4. 1 cu. ft. natural gas = 1,028 Btu; 1,000,000 cu. ft. = 177.2 BOE; 1 short ton of coal = 19.988 million Btu; 1 short ton = 3.45 BOE

* In 1999, the U.S. Census Bureau projected the likely U.S. population in 2100 at 571 million. Since then, various projections have indicated a likely lower value. The 500 million value used is representative of these later projections.

† The historic peak U.S. per capita energy use was 62.2 BOE per year in 1979, just prior to the oil supply crisis after the Iranian Revolution. During the subsequent 20 years, per capita demand declined only by 3.5 percent overall despite strong efforts encouraging energy conservation and improved energy efficiency. The author assumes a further decline to 50 BOE per year in 2100 due to continued improved energy efficiency, making a total decline of about 20 percent from 1979.

It is important to understand that this endowment estimate includes both proven reserves and unproven resources. **Only 14 percent of the oil and natural gas endowments are proven reserves—meaning high confidence production estimates.** The remaining 86 percent is based on expert judgement that one government report acknowledges as being "highly uncertain". Thus, the total endowment represents a ballpark estimate that is mostly a guestimate—an important point to keep in mind.

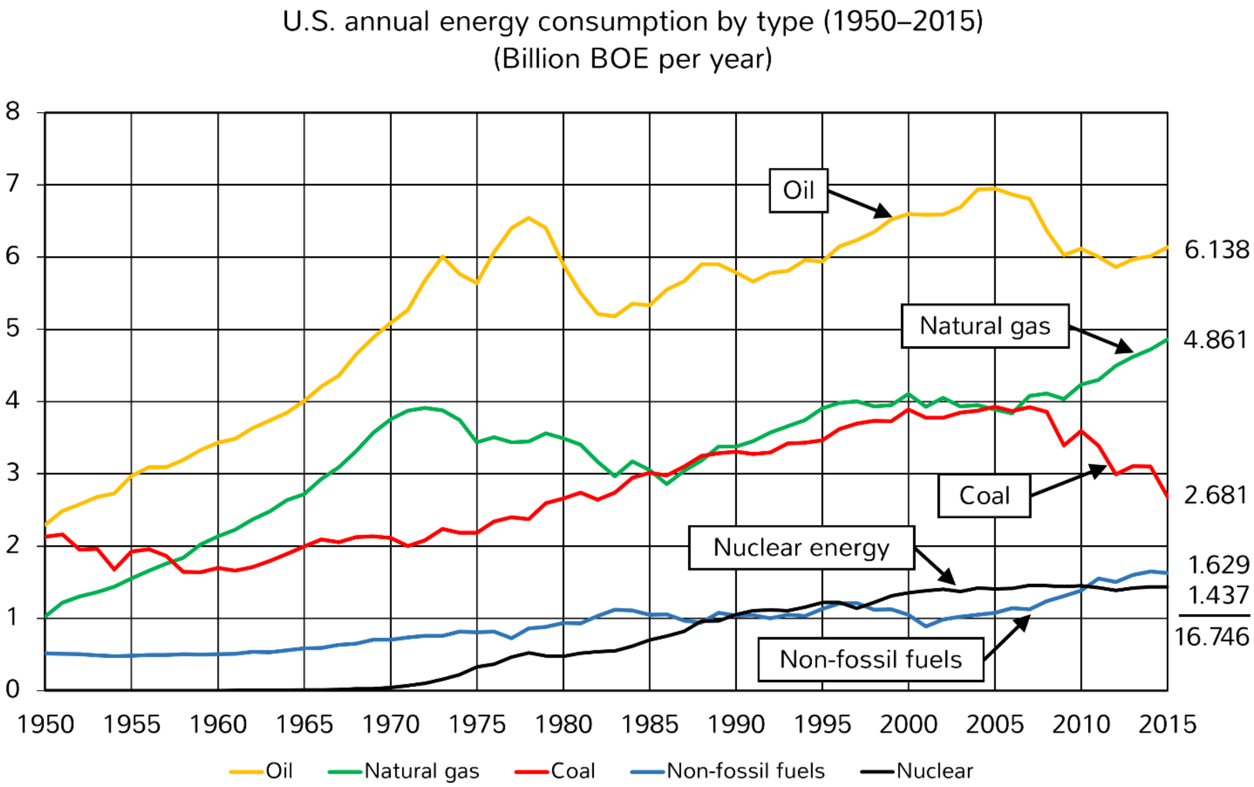

Figure 5: Annual energy consumption in the United States by type, 1950-2015. (Data source: U.S. Energy Information Administration. Credit: J.M. Snead.)

Figure 5 shows the historical consumption of energy in the United States from 1950-2015.* The numeric value of the consumption in 2015 for each type of energy is shown in the right column. These values are shown in billion BOE per year.

Using these 2015 oil, natural gas, and coal consumption rates, a rough estimate of the remaining life of the oil, natural gas, and coal endowments shown in Table 1 can be made. For each fuel, the endowment size is divided by the 2015 consumption rate to yield a rough estimate of how long the supply of that fuel would last. These calculations are summarized in Table 2. Assuming that only domestic sources are used—with no imports or exports—**the domestic oil and natural gas endowments will last, respectively, about 45 years and about 90 years.** Coal would last over 300 years primarily because, as shown in Figure 5, coal consumption has declined significantly since 2008 when fracking substantially increased the supply of natural gas.

---

* Since about 1970, the United States has imported significant quantities of oil and natural gas. Thus, the total energy consumed exceeds what was produced domestically. The United States has not been energy secure since about 1970.

Table 2: Estimate of the years of life of America's remaining fossil fuel endowment from 2016 using 2015 consumption rates. Quantities are expressed in billion BOE and rates are expressed in billion BOE per year. The 2015 consumption rates come from Figure 5. These estimates do not include the impact of the 50 percent increase in the total energy needed annually by 2100 due to expected population growth.

Fuel	Percentage of 2015 consumption	Remaining life computations				
		Endowment size		Consumption rate (2015)		Years of life from 2016
Oil	44.5	274.2	÷	6.1	=	45.0
Natural gas	35.8	438.5	÷	4.9	=	89.5
Coal	19.7	879.4	÷	2.7	=	325.7
Total	**100**	**1,592.1**	÷	**13.7**	=	

In 2015, the U.S. population was about 320 million. The expected increase to 500 million by 2100 represents a 56 percent increase. With this anticipated population growth and the associated increased total U.S. energy needs, the life estimates in Table 2 will be reduced. Thus, **Table 2 provides an optimistic estimate of the remaining life of domestic fossil fuels without imports.**

Reasonable people see that a continued U.S. substantial dependence on affordable fossil fuels represents a clear national energy security threat to America's future economic prosperity and national security. At some point, the United States will need to import substantial oil and natural gas just as it was doing from 1970-2008 prior to the "fracking" revolution. The national security implications of such a change are obvious, with the likelihood of the threat of war being significant. The United States is not alone among industrialized nations linking assured supplies of fossil fuels to their national security. (See Figure 6.)

Figure 6: One of many artificial islands China is building in the South China Sea to enable its land-based forces to expand their power projection abilities. (Credit: U.S. Navy.)

IV. The Rational Path Forward for the United States

The U.S. Constitution requires that the President and Congress address threats to domestic tranquility, national defense, and the general welfare of Americans. **America's continued substantial dependence on fossil fuels has created environmental and national security threats. The only rational path forward is for the United States to end its use of fossil fuels.** However, doing so must not be rash, as some appear to desire, but done in an orderly manner.

The starting point is to establish a target for when the transition from fossil fuels must be accomplished. The United States is a party to the international treaty, *The United Nations Framework Consensus on Climate Change (UNFCCC)*. One objective of this treaty is to mitigate possible environmental harm arising from anthropogenic greenhouse gas emissions, including CO_2. In 2015, the *Paris Climate Agreement*—the latest protocol intended to implement the treaty—was signed by the then President of the United States.* While it substantially fails to define an effective technological means of addressing CO_2, one important aspect was to establish 2100 as the goal for ending fossil fuel use.† Thus, setting 2100 as the target for ending America's use of fossil fuels would be consistent with an apparent primary goal of the Agreement. The impact of setting 2100 as the target for ending the use of fossil fuels is shown in Figure 7.

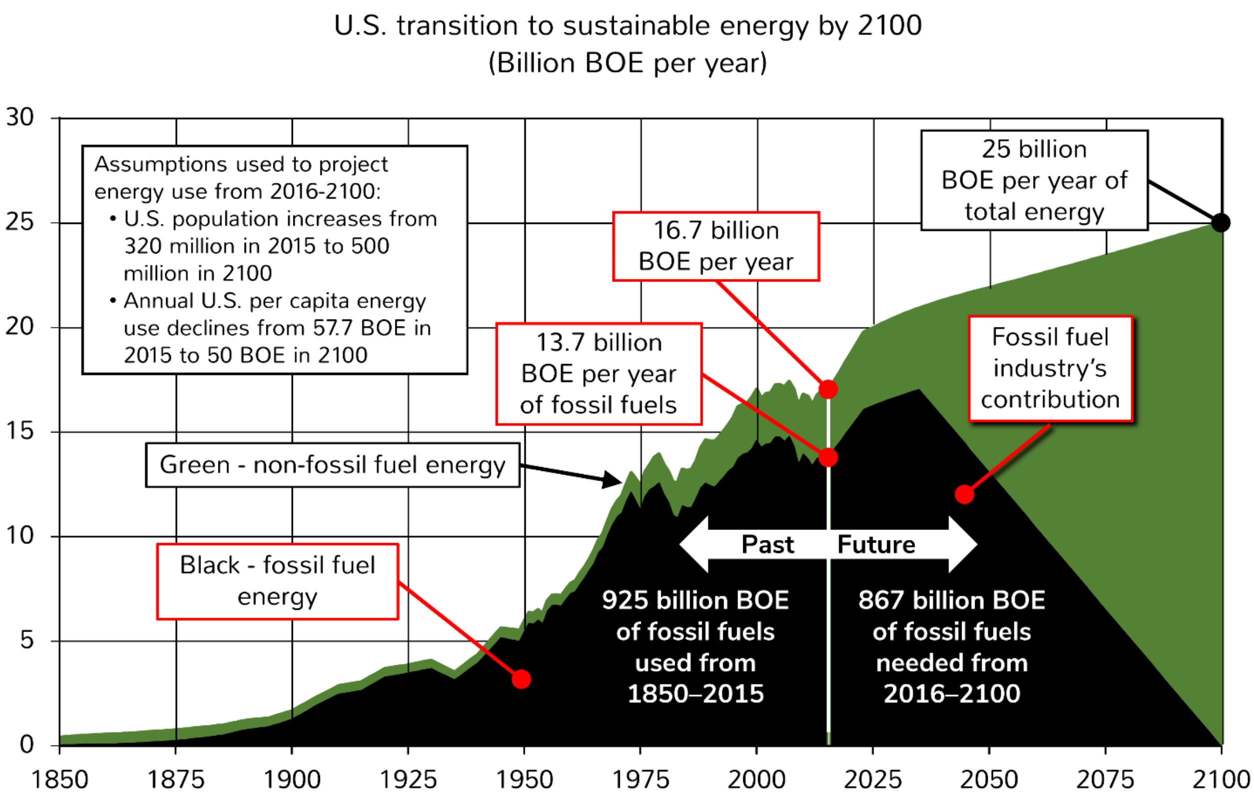

Figure 7: U.S. historical total energy use, 1850-2015, and transition to 100 percent sustainable energy by 2100. (Historical data source: U.S. Energy Information Administration. Credit: J.M. Snead.)

---

* The Paris Climate Agreement was not submitted to the U.S. Senate for advice and consent.

† The Paris Climate Agreement is often vague. For example, it does not mention carbon dioxide. Article 4 alludes to the completion of the Agreement's climate change mitigation efforts in the second half of the century, interpreted to mean by 2100.

In Figure 7, the U.S. consumption of fossil fuels is assumed to climb until 2035 when it peaks at about 17 billion BOE. From 2035-2100, fossil fuel use then declines as a national program to replace fossil fuels with sustainable energy is implemented. The period up until 2035 is used to define the replacement sustainable energy strategy, obtain political consensus, undertake needed studies and reviews, pass enabling legislation, define needed regulation, and build any necessary sustainable energy-enabling infrastructure.

As shown in Figure 7, with this transition approach, **the United States will need to consume in the ballpark of 867 billion BOE of fossil fuels through 2100. This will be about as much fossil fuels as the U.S. fossil fuel industry domestically produced since 1850.**

The 867 billion BOE can be broken down to estimate the amounts of oil, natural gas, and coal needed by using the 2015 consumption percentages for each of these fuels from Table 2. As shown in Table 3, the United States would need roughly 386 billion BOE of oil, 310 billion BOE of natural gas, and 171 billion BOE of coal through 2100.

Table 3: Estimates of how much oil, natural gas, and coal will be needed through 2100 taking into account a projected increase in the U.S. population to 500 million by 2100. The 2015 consumption percentages for each fuel type, from Table 2, are held constant. Quantities are expressed in billion BOE; consumption rates are expressed in billion BOE per year.

Fuel	Total needed through 2100		Percentage of 2015 consumption		Need through 2100 during the transition		2015 endowment size
Oil	867	×	44.5%	=	385.8		274.2
Natural gas		×	35.8%	=	310.4		438.5
Oil + natural gas combined		×	80.3%	=	696.2	<	712.7
Coal		×	19.7%	=	170.8	<	879.4
Total			**100%**		**867**		**1,592.1**

As shown in Table 3, the need for coal through 2100 is substantially less than the remaining coal endowment. Hence, having sufficient coal is not an issue.

As oil and natural gas are increasingly interchangeable when used as transportation fuels, their combined total of 696 billion BOE needed through 2100 is also shown in Table 3. From the last column of Table 3, the remaining estimated oil plus natural gas endowment totals 713 billion BOE. Thus, the need for oil and natural gas is about equal to the total estimated to remain in the endowment. Therefore, **by modestly increasing the use of natural gas as a transportation fuel to meet any shortfall in oil, while also increasing the use of electric-powered vehicles—using electricity generated by renewables, nuclear, natural gas, and coal—the United States could become completely energy independent forever provided it undertakes an orderly transition to sustainable energy this century.**

Figure 8: U.S. fighters flying over burning Kuwaiti oil wells at the end of the Gulf War. (Credit: U.S. Government work.)

With this orderly transition approach, four important political considerations are evident:

1. The United States will still need a robust domestic fossil fuel industry for most of the rest of this century to enable an orderly transition to sustainable energy while avoiding foreign entanglements through the need to import oil or natural gas. (See Figure 8.) One important consequence is that **the political war of fossil fuels versus sustainable energy vanishes,** thereby removing a contentious issue from the national political debate.

2. With the prudent management of America's remaining fossil fuel endowment, **the United States should be able to rapidly achieve and maintain domestic fossil fuel energy independence throughout this period of transition**. This would substantially change America's national security risks and provide significant domestic economic and foreign policy benefits.

3. The United States would be faithful in responding to the primary objective of the UNFCCC treaty, as well as the broad goal of the Paris Agreement, to end the use of fossil fuels by the end of the century. **This would eliminate the contentious CO_2 environmental issue from both domestic and international political discussions.**

4. **The United States would become a world leader in the movement to a sustainable culture by the 22nd century.** This will bring significant economic benefits to the United States.

V. America's Sustainable Energy Options

As seen in Figure 4, without any change in the percentage of fossil fuel use, the United States will need an annual supply of 20.4 billion BOE of fossil fuels in 2100 with an additional 4.6 billion BOE supplied by non-fossil fuel sources. Consequently, **to complete the transition from fossil fuels by 2100, new sustainable energy supplies providing the equivalent of nearly 21 billion BOE will be needed.** This would meet the energy needs of roughly 400 million Americans—about 80 percent of the expected U.S. 2100 population of 500 million. This defines the magnitude of the challenges facing American engineers: how to replace today's relatively easy-to-obtain fossil fuels with sufficient sustainable energy replacements.

America's terrestrial non-fossil fuel energy sources include: nuclear fission, wind, active ground solar, passive solar, hydroelectric, geothermal-electric, tidal- and wave-electric, and biomass. Of these options, **only the following three have the potential to be scaled up sufficiently to replace fossil fuels:**

- **Nuclear power**
- **Wind power**
- **Ground solar power**

Each of these three options will be evaluated to assess the practicality of using them to substantially replace fossil fuels. The starting point is to establish America's 2100 energy needs in terms of electrical energy rather than BOE.

A. Defining America's energy needs in 2100

With the transition from fossil fuels, electricity will become the fundamental energy source. Based on the above 2100 energy needs analysis, the assumed 2100 per capita energy need will be expressed in terms of the equivalent kilowatt-hours (kWh) of baseload electrical energy.

1. 2007 baseline per capita energy consumed

The selected baseline year is 2007—just prior to 2008 when per capita energy use started to decline due to the prolonged recession. In 2007, 37.4 percent of the gross thermal energy consumed was used to generate electricity. The remaining 62.6 percent—36.2 BOE—was consumed by the end user as fuels. In 2007, the gross thermal energy used to generate electricity produced 13,781 kWh of electrical energy per capita.

2. 2100 sustainable fuel

In the following analysis, all sustainable combustible fuel used by 2100 is assumed to be hydrogen produced by the electrolysis of water. For this analysis, hydrogen would replace oil, natural gas, and coal for industrial processes requiring a combustible fuel and for commercial and consumer uses such as transportation fuel. It is assumed that hydrogen would be distributed nationally through a hydrogen pipeline network much as natural gas and petroleum are distributed today.

While technology advancements are being made to enable the direct consumer use of hydrogen, primarily for fueling cars, the widescale adoption of this as a general consumer fuel is problematic. Hydrogen is extremely flammable, with hydrogen concentrations in air as low as 4 percent being ignitable. Further, with the required ignition energy being very low and a hydrogen flame being very hard to see, accidents of fires and burns are very likely.

Due to such safety considerations, by 2100, the likely general consumer fuel will be a synthetic methane—CH_4. The starting point in the production of this fuel will be the electrolysis of water to produce hydrogen using sustainable electricity. Carbon extracted from atmospheric carbon dioxide will be combined with hydrogen to yield the synthetic methane or, where needed, a synthetic liquid fuel. With this approach, the atmosphere becomes the conduit to return carbon for reuse so that the anthropogenic rise in atmospheric CO_2, due to the combustion of carbon fuels, ends. As mentioned previously, additional synthetic methane and liquid fuel can be produced and injected into geological storage in dry natural gas and oil wells to reduce the overall atmospheric CO_2 concentration.

Significant research is underway to identify energy-efficient ways to produce synthetic carbon fuels from hydrogen and CO_2. Key advancements in catalysts are being made that could significantly reduce the additional energy required to prepare these synthetic fuels. Hence, due to the uncertainty of the additional energy that will be required, this additional energy is not included in this energy analysis. Given the uncertainty associated with other assumptions used—population size, future per capita energy use, electrolyzer efficiency, etc.—this is not believed to be a significant shortcoming—but a point to be aware of.

3. 2100 per capita energy needs

The per capita energy need for 2100 is assumed to be 50 BOE—86.6 percent of the 2007 rate. Applying this adjustment, while maintaining the 2007 percentages of energy used as fuels and electricity, **31.3 BOE of hydrogen fuel and 11,932 kWh of dispatched electrical energy will be needed per American in 2100.**

The author has estimated, using U.S. Energy Department projected future electrolyzer efficiencies, that 2,358.4 kWh of electrical energy will be required to produce one BOE of hydrogen fuel yielding the fuel's lower heating value.[*†] Thus, 73,817 kWh of electrical energy will be required to produce and deliver 31.3 BOE of hydrogen fuel. In total, **to provide the equivalent of 50 BOE of gross thermal energy in 2100, 85,759 kWh of continuous electrical energy will be needed per capita.**

4. Total American energy need in 2100

For the assumed American population of 500 million in 2100, a total of 5.996 million gigawatt-hours (GWh) of electrical energy for direct use and 15.66 billion BOE of hydrogen fuel will be needed. In terms of total electrical energy, America will need to generate 42.9 million GWh of continuous electrical energy in 2100. For perspective, this is roughly 10X the total electrical energy generated in America in 2007. **On a per capita basis, the needed continuous electrical power in 2100 is about 10 kilowatts (kW)—enough to operate 10 countertop microwave ovens.** Thus, 50 BOE is equivalent to the power used by 10 microwave ovens running continuously.

---

[*] The useful work produced by the combustion of a fuel depends on how efficiently the heat released by combustion is used. For general use, such as in an automobile, the lower heating value of the fuel is assumed. This means that some possibly useful heat is lost through the exhaust. In this analysis, the higher heating value is used only for advanced technology electrical generation where the primary waste heat is used as a secondary heat source to generate additional electricity. For hydrogen, the difference between these two heating values is sufficient to warrant incorporating this difference into these estimates. For carbon fuels, the difference is less and generally ignored.

[†] This estimate includes the additional electrical energy required to compress the hydrogen gas to 1200 pounds per square inch (psi) for injection into a hydrogen pipeline distribution system. An energy allowance is also included for a portion of the hydrogen to be further compressed for use as a transportation fuel.

B. Nuclear power

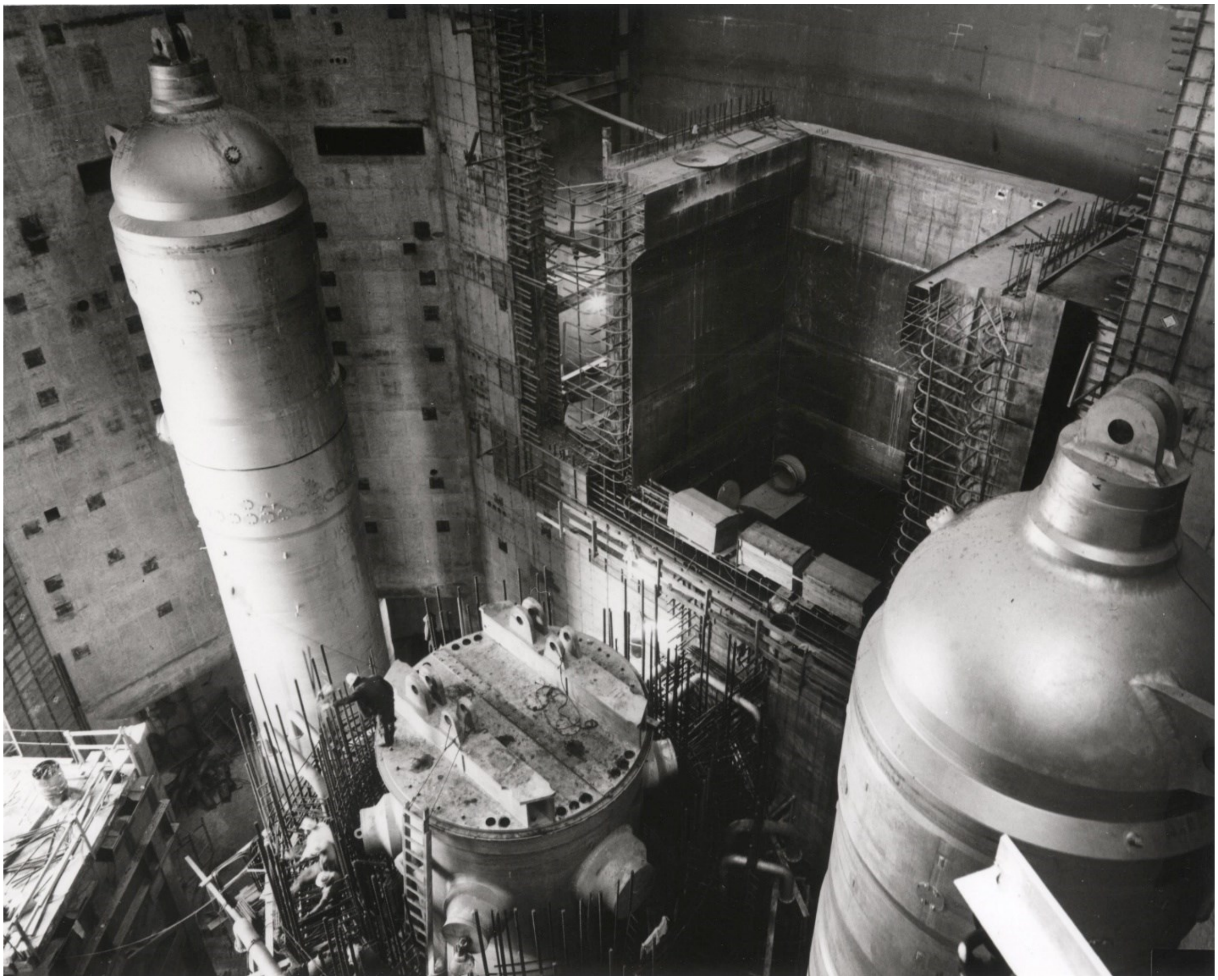

Figure 9: Nuclear power plant being built in the 1970s. The nuclear reactor is in the middle. The two tall cylinders are the heat exchangers to convert the nuclear heat into steam to power the turbines. (Credit: U.S. government work.)

1. Number of 1-GW nuclear power plants needed in 2100

A typical new nuclear power plant is sized to generate about 1 billion watts or 1 gigawatt (GW) of electrical power. (See Figure 9.) In this case, the "nameplate" power rating is 1 GW.

No nuclear or fossil fuel power plants operate continuously. In this analysis, the percentage of the total time that a new nuclear plant is operating each year—referred to as the plant's capacity factor—is assumed to be 95 percent. This means that the plant would be shut down about 3 weeks each year for refueling and scheduled maintenance.

A 1-GW nuclear plant operating with a 95 percent capacity factor will generate 1 GW × 365 × 24 × 0.95 = 8,322 GWh of electrical energy each year. Therefore, **to meet the 2100 U.S. need for 42.9 million GWh of sustainable electrical energy using only nuclear power, 5,155 1-GW nuclear power plants will be needed.** For comparison, the United States currently has only 99 operating commercial nuclear power plants with a total nameplate power of about 100 GW. Their average capacity factor is around 90 percent.

2. Nuclear fuel requirements

The primary fuel source for commercial nuclear power plants is natural uranium. Natural uranium contains the U^{235} isotope that can undergo fission yielding nuclear energy. In 2016, the World Nuclear Association estimated that a metric tonne (2,205 lb) of natural uranium will produce 44 million kWh in nuclear power plants. Thus, a plant-year of operation yielding 8,322 GWh requires 189 metric tonnes of natural uranium. To build up to the 5,155 1-GW nuclear power plants needed by 2100, the United States will need about 36.6 million metric tonnes of natural uranium through 2100 with more natural uranium needed after that.

The U.S. Energy Information Administration reports that the United States has only about 2.5 million metric tonnes of natural uranium even when speculative resources are included. This is far short of what would be needed. If fact, even with the speculative resources, **the United States natural uranium resources would meet the 120-year lifetime needs of only about 110 1-GW plants.** This would enable current aging plants to be replaced, but would be insufficient to enable any substantial expansion of nuclear power.

3. Fuel breeding and proliferation

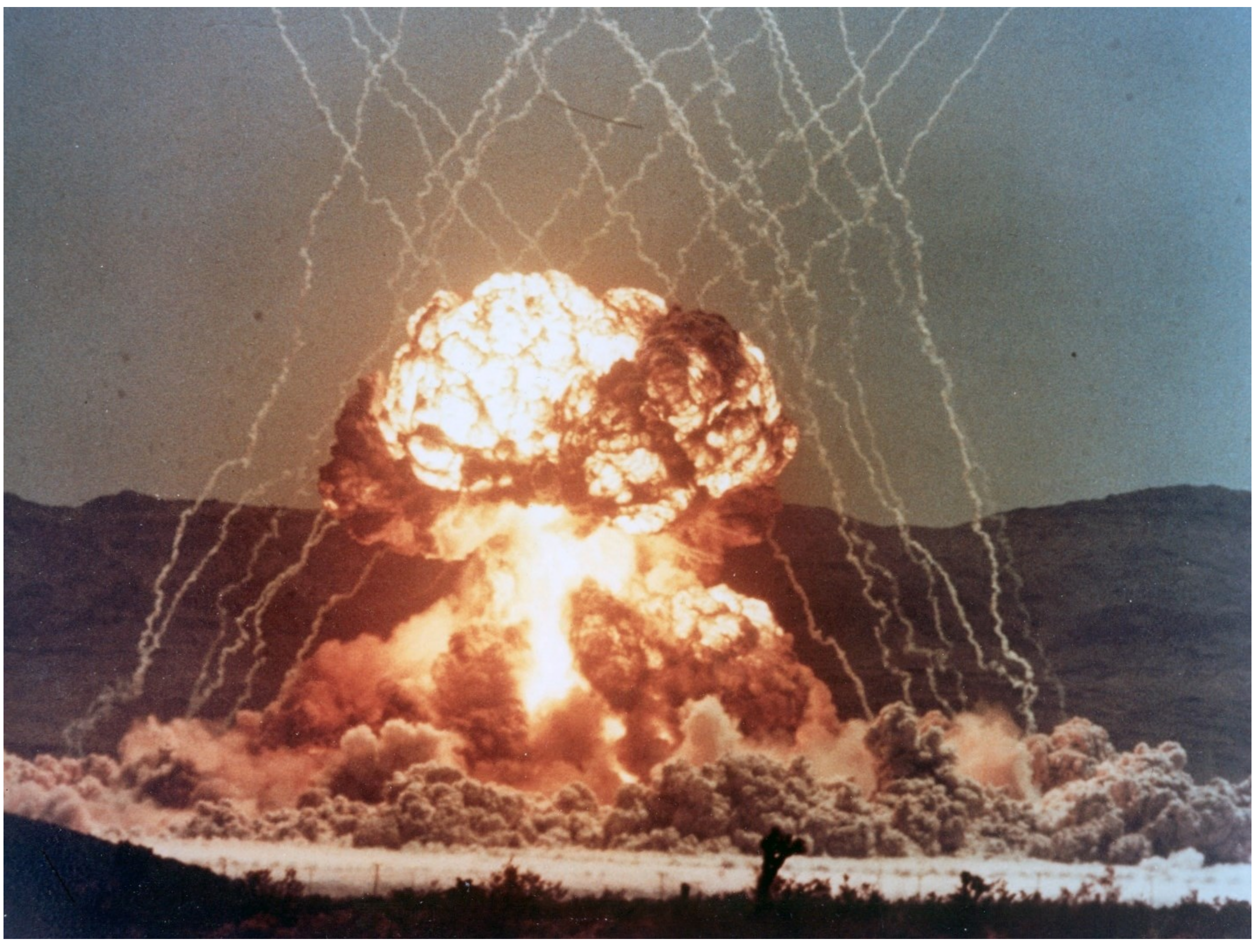

Figure 10: United States nuclear weapon test using a U^{233} core, April 15, 1955. (Credit: National Nuclear Security Administration, Nevada Site Office, Wikimedia Commons, public domain.)

Natural uranium contains only 0.72 percent of U^{235}. Thus, the 189 metric tonnes of natural uranium needed per plant-year contains 1.36 metric tonnes of U^{235}. Replacing this U^{235} with plutonium and/or U^{233} created using nuclear fuel breeding is an option. This would require breeding around 7,000 metric tonnes per year by 2100. Like U^{235}, plutonium and U^{233} can be used to build nuclear weapons. (See Figure 10.) * Thus, should the United States pursue nuclear fuel breeding, many other nations would likely follow. The option of breeding fuel to expand the use of nuclear power likely increases the threat of nuclear weapons proliferation.

4. Other considerations

In addition to the supply of fuel, long-term hazardous waste disposal, plant security, cooling water availability, and plant siting for thousands of nuclear power plants are additional considerations impacting the practicality of the large-scale use of terrestrial nuclear fission. **When combined with the limited supply of natural uranium and the proliferation risk inherent with fuel breeding, a large-scale expansion of fission nuclear power is not a desirable solution to provide sustainable energy to replace fossil fuels.**

The key takeaway point from this assessment of nuclear power is that, **by 2100, the United States will require on the order of 5,000 GW of continuous electrical power generation capacity to meet its sustainable energy needs.**

C. Wind power

Figure 11: School bus next to a wind turbine with a 79-m hub height. Most wind turbines would have hub heights of 110-140 m with 100+ m diameter rotors. (Credit: J.M. Snead.)

---

* Advocates for U^{233} breeding from thorium argue that proliferation-resistant reactors can be designed and that bred U^{233} is not practical to use in a nuclear weapon. On April 15, 1955, the United States exploded a nuclear weapon using a U^{233} core demonstrating that such assurances may be inadequate for preventing a rogue nation from obtaining nuclear weapons by secretively obtaining U^{233}. (See Figure 10.)

1. Contiguous United States wind power potential

Wind power is a generally favored form of renewable energy. Images of majestic wind turbines are often used, as in Figure 11, when discussing renewable energy.

Wind power has been thoroughly researched by the National Renewable Energy Laboratory (NREL) to establish the wind energy potential in the contiguous United States. This means how many GWh of electrical energy commercial wind farms could produce.

Across the contiguous United States, each 20 kilometer (km) by 20 km area had the wind power potential assessed for commercial wind farms using wind turbines with hub heights of 80, 110, and 140 meters (m) (459 ft). The map in Figure 12 shows the possible commercial wind farm locations when using turbines with a 140-m hub height. The results of the assessment are summarized in Table 4.

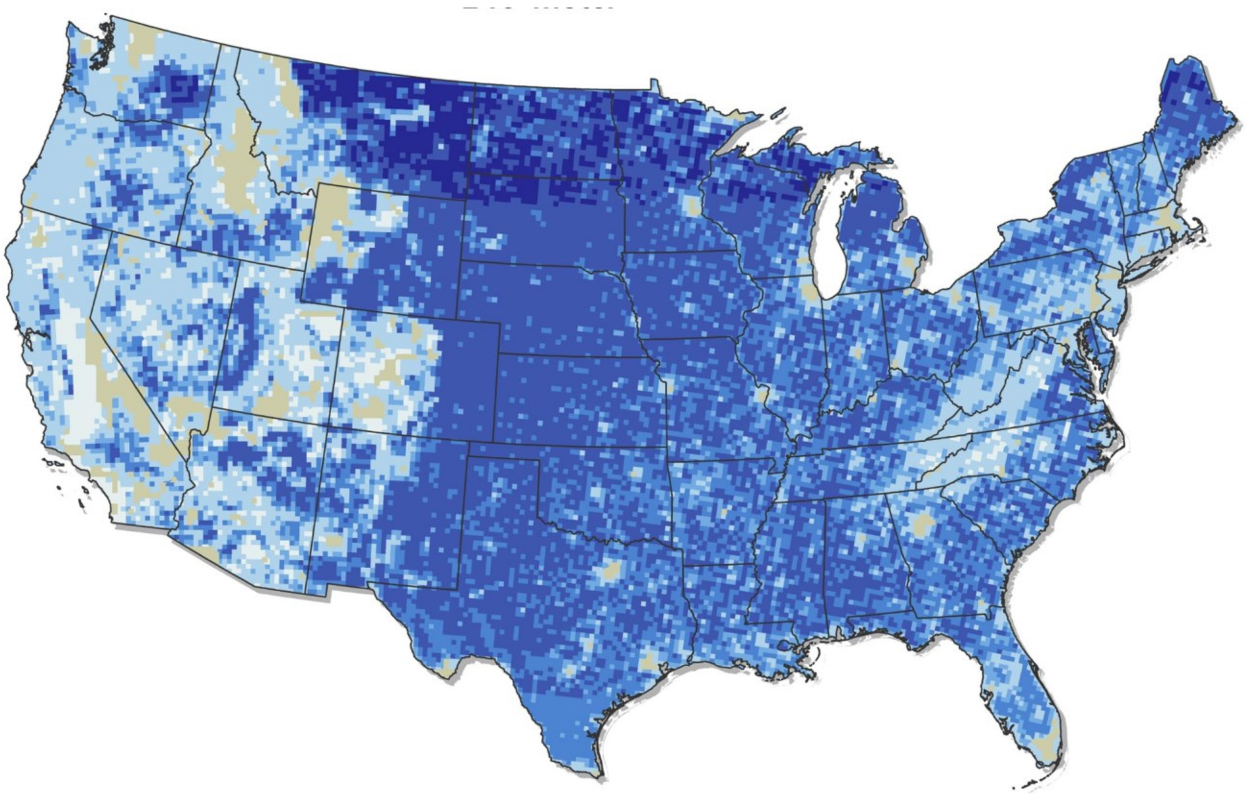

Figure 12: Commercial wind farm potential for a hub height of 140 m (459 ft) where the gross capacity factor is estimated to be 35 percent or greater—the minimum value with commercial potential. A blue color indicates some commercial wind farm locations may exist within each 20-km by 20-km square. The darker blue shades indicate a higher percentage of the land in each square has commercial potential. (Map source: National Renewable Energy Laboratory for the U.S. Department of Energy, no known restrictions.)

Table 4: Results of the National Renewable Energy Laboratory's analysis of the contiguous United States wind power potential with a gross capacity factor of 35 percent or greater for available land after exclusions. [3]

Hub height/Rotor diameter (m)	Contiguous US land area (sq km)	Installed nameplate power (GW)*	Nameplate power (MW per sq km)	8-rotor diameter turbine spacing (km)†
80/80	1,643,286	8,019	4.88	0.640
110/100	3,420,404	8,654	2.53	0.800
140/124	4,628,711	8,471	1.83	0.992
Hub height/Rotor diameter (m)	**Contiguous US Land area (sq mi)**	**Nameplate power (GW)***	**Nameplate power (MW per sq mi)**	**8-rotor diameter turbine spacing (mi)†**
80/80	634,476	8,019	12.64	0.398
110/100	1,320,625	8,654	6.55	0.497
140/124	1,787,155	8,471	4.74	0.616

* Nameplate power is the maximum electrical power output of the turbine's generator.
† Due to the wake turbulence created by the spinning rotor's blades, the turbines are assumed to be evenly spaced a set distance apart, based on the diameter of the rotors, when assessing the annual wind-electricity potential of large wind farms. Testing has shown that a spacing of 8 rotor diameters is about optimum. Thus, the wind power potential shown in the above table reflects this spacing.

As shown in Table 4, three turbine sizes were evaluated. These turbines are assumed to be located in a square grid. The amount of annual wind power available, per turbine, generally increases as the turbine height and the rotor diameter increase. However, with the increasing rotor diameter, the spacing between the turbines also increases, meaning that fewer turbines are installed per sq km. For this reason, the total installed nameplate power per sq km is different for each size turbine.

When using only a single size turbine, the maximum total nameplate power would be installed by using 1.6 megawatt (MW) turbines with 110-m hub heights and 100-m rotor diameters. These wind farms would cover 3.4 million sq km of the contiguous United States. The total installed nameplate power would be 8,654 GW (highlighted in yellow in Table 4).

From Table 4, the taller 140-m turbines could be installed on a larger total area of 4.6 million sq km. This is 1.2 million sq km more than using only the 110-m turbines. However, despite the larger area, the total installed nameplate power would be less, due to the increased turbine spacing. To maximize the wind power potential for the entire contiguous United States, 140-m turbines could be placed on this additional 1.2 million sq km. This addition would increase the total area of wind farms to 4.6 million sq km with an installed nameplate power of about 10,865 GW. The darker blue areas in the Figure 12 map illustrate roughly how much of the contiguous United States would be used to build 4.6 million sq km (1.8 million sq mi) of wind farms.

Using the Table 4 data, the total number of turbines needed can be estimated. **A combined total of about 6.6 million 110-m and 140-m turbines would be installed. Covering 56 percent**

of the contiguous United States, virtually all of the land on which people live would need to be used. To help visualize what much of the United States would look like, four of the 110-m turbines would be installed per square mile.

2. Wind power generation estimate

Today, most of the electricity generated comes from generators such as nuclear, coal, or gas turbines. These generators are turned on (dispatched) when the utility requires additional electricity to supply its customers. When turned on, these generators produce their nameplate power. If a generator operates continuously for the entire year, the capacity factor would be 100 percent. As mentioned earlier, a new 1-GW nuclear power plant is assumed to have a 95 percent capacity factor. It would be shut down for about three weeks a year for refueling and maintenance. At all other times, it would be generating its nameplate power (1 GW).

Wind turbines do not operate in this manner because the wind speed varies continuously. Even when the turbine is capable of generating power, it may be stopped because the wind speed is too low or too high. The rest of the time, even though the rotor is spinning, the actual power generated varies depending on the wind's speed.

For wind turbines, the capacity factor indicates the percentage of the ideal total annual electrical energy actually generated, on average, taking this variability into account. For example, wind turbines located at the best land locations have a gross capacity factor of about 50 percent. This means that they will generate, on average, about 50 percent of what would be produced if the turbines generated their nameplate power continuously.

For commercial wind farms using the 110- and 140-m turbines, an average gross capacity factor of 40 percent is assumed for this analysis. NREL assumes a 15 percent reduction for operational losses, yielding a net capacity factor of $40 \times 0.85 = 34$ percent. (This compares to the recent actual overall U.S. wind farm capacity factor of 32 percent.) Returning to the estimate using 6.6 million wind turbines, with an installed nameplate generation capacity of 10,865 GW, a 34 percent capacity factor yields an annual average electrical energy production of 32.3 million GWh. (Of course, this will vary from year-to-year.)

When using only dispatchable electrical power generation, such as nuclear power, the total 2100 U.S. electrical energy need would be met by generating 42.9 million GWh. When using only variable wind-generated electrical energy instead, the variability increases the needed total value to 49.5 million GWh.*

For 6.6 million turbines covering 56 percent of the contiguous United States, wind power could supply, on average, only 65 percent of the total energy needed in 2100. On average, each wind turbine would supply the annual energy needs of only about 50 people in 2100.

---

* The reliable functioning of America's power grid requires dispatchable electricity. A dispatchable power source is one that the utility can turn on when needed. The variability of wind-generated electricity generally prevents wind farms from serving as a dispatchable power source. Thus, for this analysis, all wind-electricity is assumed to be used to produce hydrogen. This hydrogen will then be distributed through a national pipeline network just as natural gas is today. Local utilities will use this hydrogen to power gas turbine generators to dispatch electricity to their customers as needed. Local utilities would also distribute the hydrogen to customers using it as a fuel. This approach for addressing the variability of wind-generated electricity increases the total wind-electricity needed from 42.9 to 49.5 million GWh to meet the U.S. total 2100 energy need.

3. Wind power impracticality

Figure 13: Damaged wind turbine. (Credit: National Oceanic and Atmospheric Administration, no known restrictions on publication.)

While individual wind turbines appear majestic, building a national wind turbine forest of nearly seven million wind turbines raises practicality issues such as the following:

- The turbine blade tips will reach over 200 m high (663 ft). As the rotors are turning much of the time, this will significantly impact aviation, particularly general aviation.
- The 6.6 million turbines will have nearly 20 million of the 50-m long blades. Based on a reported blade failure rate of 0.54 percent per year, perhaps on the order of 100,000 blade failures per year may be expected. [4] Blade failures can include broken pieces being thrown from the rotor. (See Figure 13.) In addition to blade failures, turbines also suffer from fires, lightning strikes, being blown over during extreme weather conditions, and throwing accumulated ice from the blades during cold weather conditions. Such considerations require a safe setback of the turbines from the public. Much of America would become hazardous due to the extensive land area required for wind farms.
- Each wind turbine requires installing a large concrete and steel structure underground to provide a foundation for the tower. (See Figure 14.) Modest size turbines require

bases using 24 tons of steel and several hundred cubic yards of concrete. The larger turbines used in this estimate will require correspondingly larger bases.

Figure 14: Construction of the base of a smaller wind turbine. Taller and larger turbines would require larger bases. Roughly 6.6 million bases would need to be built and periodically replaced. (Credit: Tradgen Farms, National Renewable Energy Laboratory for the U.S. Department of Energy, used as permitted.)

- Operating wind turbines have distinct moving shadows—called flicker—and sound signatures that are often disruptive to humans and animals, especially in rural areas. Operating turbines will also impact insects and birds, especially raptors.
- The installation and maintenance of the wind turbines impacts agricultural land fertility due to excavation, soil compaction, and evaporation.
- Wind turbines may impact the operation of radars used for air traffic control and national security.
- Offshore wind farms will impact shipping and, if visible from the shore, disrupt the visual harmony of the seashore that Americans value.

For reasons such as these, **the mass deployment of wind power to replace fossil fuels for the United States will likely be politically unacceptable in nearly all inhabited parts of the country.**

D. Ground solar power

The contiguous United States has substantial gross ground solar power potential. Unfortunately, the day-night solar cycle, weather-related insolation variability, existing land use especially for agriculture, and terrain are significant factors limiting the exploitation of this potential.

1. Ground solar farm land area required

Like wind farms, ground solar farms are a popular form of renewable energy production. Commercial solar farms have been built across the country, especially in the western states. (See Figure 15.)

Figure 15: Solar farm using 1-axis tilting photovoltaic panels. This farm is located at the Denver International Airport. Note that the ground is cleared and leveled. (Credit: National Renewable Energy Laboratory for the U.S. Department of Energy, used as permitted.)

The solar power potential of the contiguous United States has been extensively evaluated. Table 5 is taken from an NREL report summarizing data collected for existing solar farms. The total installed nameplate power generation capacity in the United States is about 12 GW. The average capacity factor for these solar farms was 20.77 percent. For the farms using fixed photovoltaic arrays, highlighted in Table 5, the average installed nameplate power was 33 MW (AC) per sq km or 85.5 MW (AC) per sq mi of the land area within the farm's perimeter fence.*

* Unlike wind turbines which generate alternating current (AC) electrical power, photovoltaic solar panels produce direct current (DC) electricity. To transmit this electricity from the farm, it must be converted into AC power. During this conversion, a portion of the total DC power produced is lost as waste heat. Thus, the proper output to discuss for photovoltaic solar is the final AC value.

Table 5: Summary of total land-use requirements for photovoltaic and concentrating solar farms. (Source: NREL/TP-6A20-56290, Table 9.) [5]

Technology	Total Area					
	Number of projects analyzed	Capacity for analyzed projects (MWac)	Capacity-weighted average land use (acres/MWac)	Capacity-weighted average land use ($MWac/km^2$)	Generation-weighted average land use (acres/GWh/yr)	Generation-weighted average land use ($GWh/yr/km^2$)
Small PV (>1 MW, <20 MW)	115	550	8.3	30	4.1	61
Fixed	52	231	7.6	32	4.4	56
1-axis	55	306	8.7	29	3.8	66
2-axis flat panel	4	5	13	19	5.5	45
2-axis CPV	4	7	9.1	27	3.1	80
Large PV (>20 MW)	32	3,551	7.9	31	3.4	72
Fixed	14	1,756	7.5	33	3.7	67
1-axis	16	1,637	8.3	30	3.3	76
2-axis CPV	2	158	8.1	31	2.8	89
CSP	25	3,747	10	25	3.5	71
Parabolic trough	8	1,380	9.5	26	3.9	63
Tower	14	2,358	10	24	3.2	77
Dish Stirling	1	2	10	25	5.3	46
Linear Fresnel	1	8	4.7	53	4.0	62

As with wind power, the variability of ground solar power increases the required electrical energy to meet the total U.S. 2100 need from 42.9 to 49.5 million GWh. With a 100 percent capacity factor, this would require 5,651 GW of nameplate power generation capacity. With only a 20.77 percent capacity factor, the required installed nameplate power is about 27,208 GW. The corresponding required solar farm land area to meet 100 percent of the 2100 energy need would be 824,000 sq km (318,000 sq mi). On average, each American in 2100 would need 1,650 sq m (17,700 sq ft) of solar farm to supply their total annual energy need.

2. *Solar farm placement*

As shown in the upper map in Figure 16, the American Southwest has the highest total ground solar insolation and is the best location in the contiguous United States for commercial solar farms. However, when this map is overlaid on a terrain map, as shown in the bottom map in Figure 16, terrain significantly limits the land area suitable for commercial ground solar farms. The reason for this is that generally for commercial solar farms only flat land at least a square kilometer in size with an overall grade of 1 percent or less is suitable.

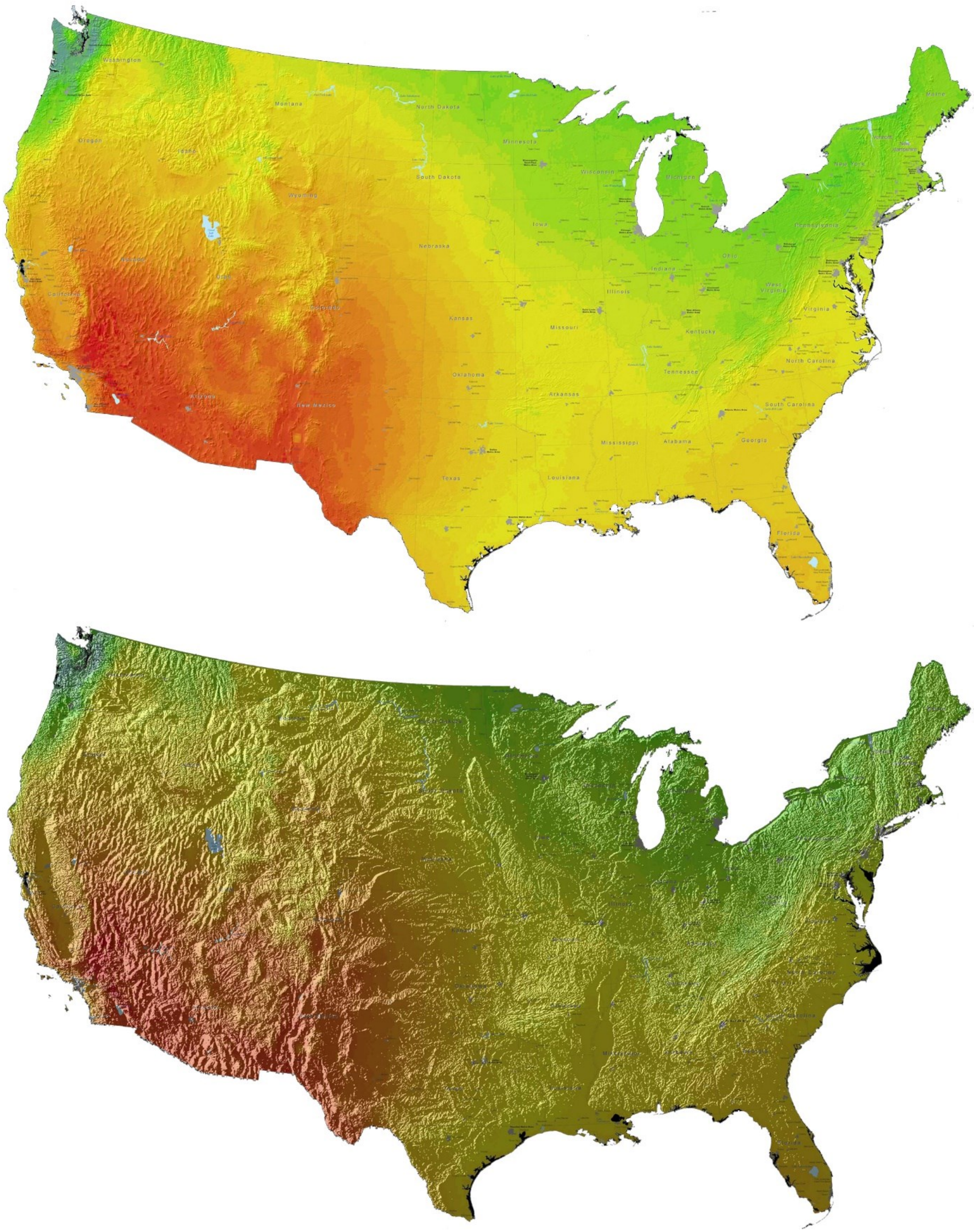

Figure 16: Top map shows the solar photovoltaic energy potential—annual average watts per square meter per day—for a flat solar array oriented south, tilted to the location's latitude from the vertical. The bottom map is the top image overlaid on a relief map of the terrain. (Solar map created by the National Renewable Energy Laboratory for the U.S. Department of Energy, used as permitted. Relief map credit: U.S. Geological Survey, no known restrictions. Credit: J.M. Snead.)

3. Ground solar power estimate

The seven southwestern states of Arizona, California, Colorado, Nevada, New Mexico, Texas, and Utah have the greatest ground solar potential. NREL assessed the land suitable and available for locating commercial solar photovoltaic farms in these states. The results are shown in Table 6.

Table 6: Results of an NREL study of the solar photovoltaic potential in the southwestern United States where the land slope is less than 1 percent. (Land area data source: National Renewable Energy Laboratory.) [6]

State	Land area (sq km)	Solar Nameplate Power [GW(AC)]	Electrical energy per year (GWh)
Arizona	35,258	1,164	2,120,740
California	16,260	537	978,036
Colorado	16,141	533	970,870
Nevada	28,723	948	1,727,687
New Mexico	52,722	1,740	3,171,217
Texas	16,509	545	992,992
Utah	60,316	1,991	3,627,987
Total	**225,929**	**7,458**	**13,589,529**
State	Land area (sq mi)	Solar Nameplate Power [GW(AC)]	Electrical energy per year (GWh)
Arizona	13,613	1,164	2,120,740
California	6,278	537	978,036
Colorado	6,232	533	970,870
Nevada	11,090	948	1,727,687
New Mexico	20,356	1,740	3,171,217
Texas	6,374	545	992,992
Utah	23,288	1,991	3,627,987
Total	**87,231**	**7,458**	**13,589,529**

If commercial ground solar farms are built on all suitable land in these seven states, this would provide, on average, 13.6 million GWh of variable electrical energy. This is only 27 percent of the total 2100 projected U.S. need. To increase the supply of solar-electricity, additional land could be graded flat in the Southwest and solar farms could be built on agricultural or undeveloped land in the Southern states. This is an impractical solution because the public is unlikely to accept such extensive solar farms, especially in the arid Southwest.

E. Combined terrestrial solution using primarily wind and ground solar

Figure 17: Wind farm in Washington. These wind turbines are closely spaced in rows to handle prevailing winds primarily from one direction. These turbines have a hub height of only about 60 m compared to turbines with hub heights up to 140 m used in this analysis. (Credit: Mike McPheeters, National Renewable Energy Laboratory for the U.S. Department of Energy, used as permitted.)

Combining wind and ground solar power could enable the United States to meet the projected 2100 energy needs using only terrestrial sustainable energy. The maximum buildout of wind power would provide 32.3 million GWh. (See Figure 17.) Solar farms in the seven southwestern states would provide an additional 13.6 million GWh. Together, wind and ground solar power would provide 45.6 million GWh or 93 percent of the needed total. Additional solar farms along with nuclear, geothermal-electricity, hydroelectricity, and biomass could make up the shortfall. **This solution would, however, entail building 4.6 million sq km of wind farms and about 225,000 sq km of solar farms covering nearly 60 percent of the contiguous United States.** (See Figure 18.)

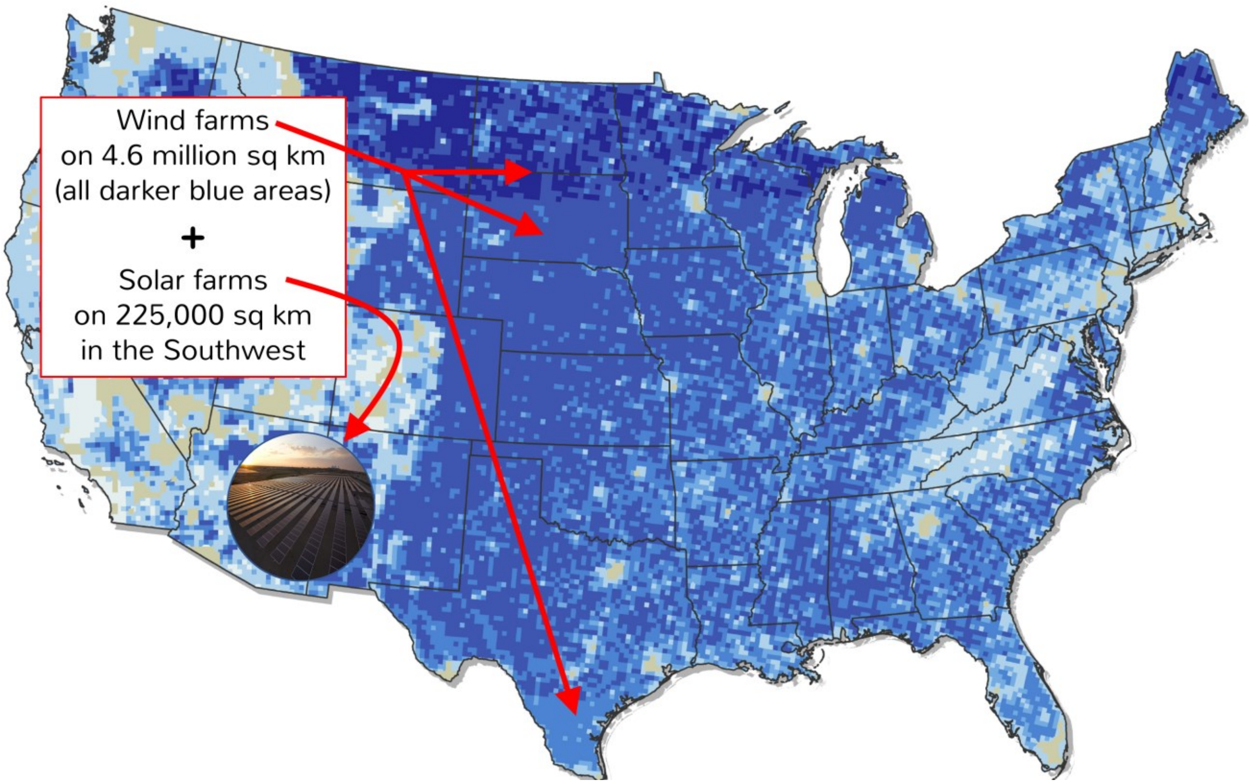

Figure 18: A combined wind and ground solar solution would require building about 4.6 million sq km of wind farms on all of the darker blue areas shown on the map *along with* about 225,000 sq km of ground solar farms in the Southwest. (Map source: National Renewable Energy Laboratory for the U.S. Department of Energy, no known restrictions. Credit: J.M. Snead.)

While the United States could adopt a wind and ground solar power solution for transitioning from fossil fuels, the extent of the needed wind and ground solar farms has not been properly delineated to the public. To pursue this solution, it is likely that the appearance of the Southwest—considered by many to be a national treasure—would be markedly altered with all suitable flat land needing to be cleared and leveled. The central United States, between the Rocky Mountains and the Alleghany Mountains, would be used to build horizon-to-horizon wind farms. About every one-half mile, a large 110-140 m hub height turbine would be installed, each requiring a substantial buried concrete base.

It is unlikely that blanketing the contiguous United States with nearly 5 million sq km (nearly 2 million sq mi) of these wind and solar farms will be acceptable. A different, less intrusive solution is needed. Therefore, with terrestrial renewable energy and nuclear solutions not providing the practical means to replace fossil fuels, we need to turn to space-based sustainable energy.

VI. GEO Space Solar Power

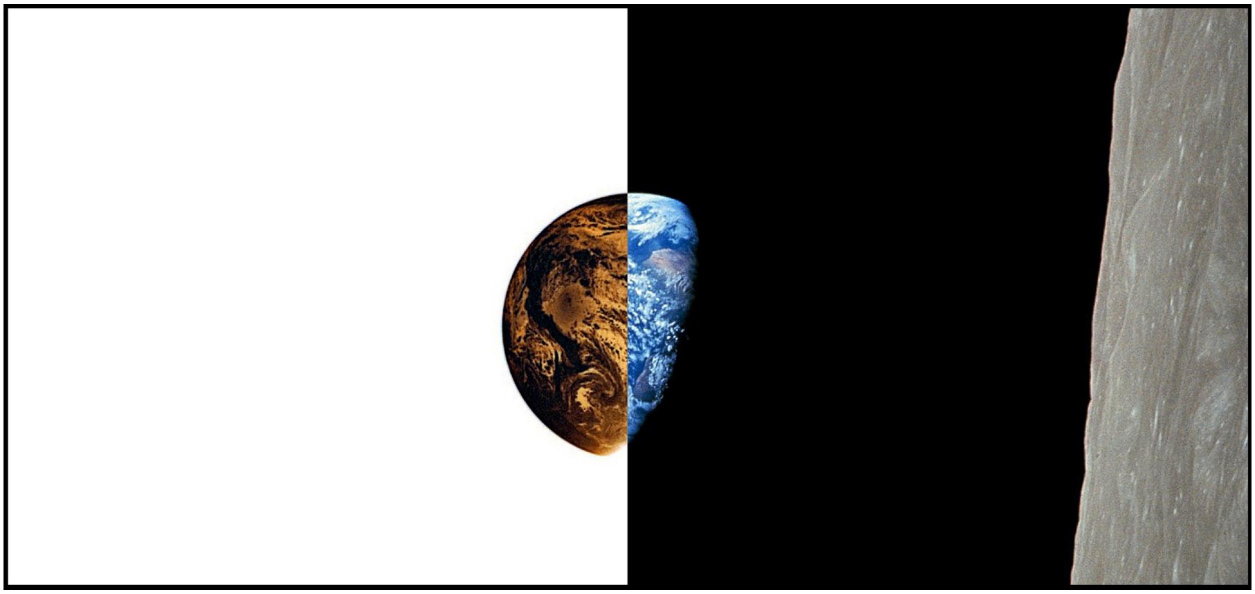

Figure 19: The right side of the split image is the famous Apollo 8 photograph of the Earth as seen from lunar orbit taken on December 24, 1968. The left side of the image is reversed in color to highlight that the space surrounding the Earth is filled with sunlight—renewable power—that is invisible to the human eye. (Credit: William Anders, NASA.)

With no practical terrestrial sustainable-energy solutions to replace fossil fuels, the United States must turn to the only remaining source of sufficient renewable energy—sunlight in outer space. As illustrated in Figure 19, while space appears to be empty, the space surrounding the Earth is actually filled with sunlight—space solar power freely available to be used.

Utilizing space solar power will be a macro-engineering project of immense scale. A century ago, American engineers faced comparable challenges with building large hydroelectric dams on a scale that had never been attempted. The Hoover Dam provides a useful historical example of what lies ahead to utilize space solar power.

A. Building the Hoover Dam

The United States is blessed with many large rivers that have been able to be tamed to control flooding, generate electricity, and enhance the economic prosperity of America. As settlement expanded in the western states in the late 1800s, building dams to control flooding and provide irrigation water in the arid parts of these states became a matter of national interest. The Colorado River was first used to supply irrigation water in the 1890s. In 1902, the growing city of Los Angeles investigated building a small 12-m hydroelectric dam. Finally, in 1922, the federal Bureau of Reclamation recommended building a dam in Black Canyon, several miles downriver of the original location of interest in Boulder Canyon. Congress finally approved a bill authorizing the Federal Government to undertake the construction of Boulder Dam—later renamed Hoover Dam—in 1928. The Bureau of Reclamation designed the dam, adding electricity generation only near the end of the design process. (See Figure 20.) Construction of the diversion tunnels began in 1931 with Lake Mead beginning to be filled on February 1, 1935. Electricity was first generated in March 1937.

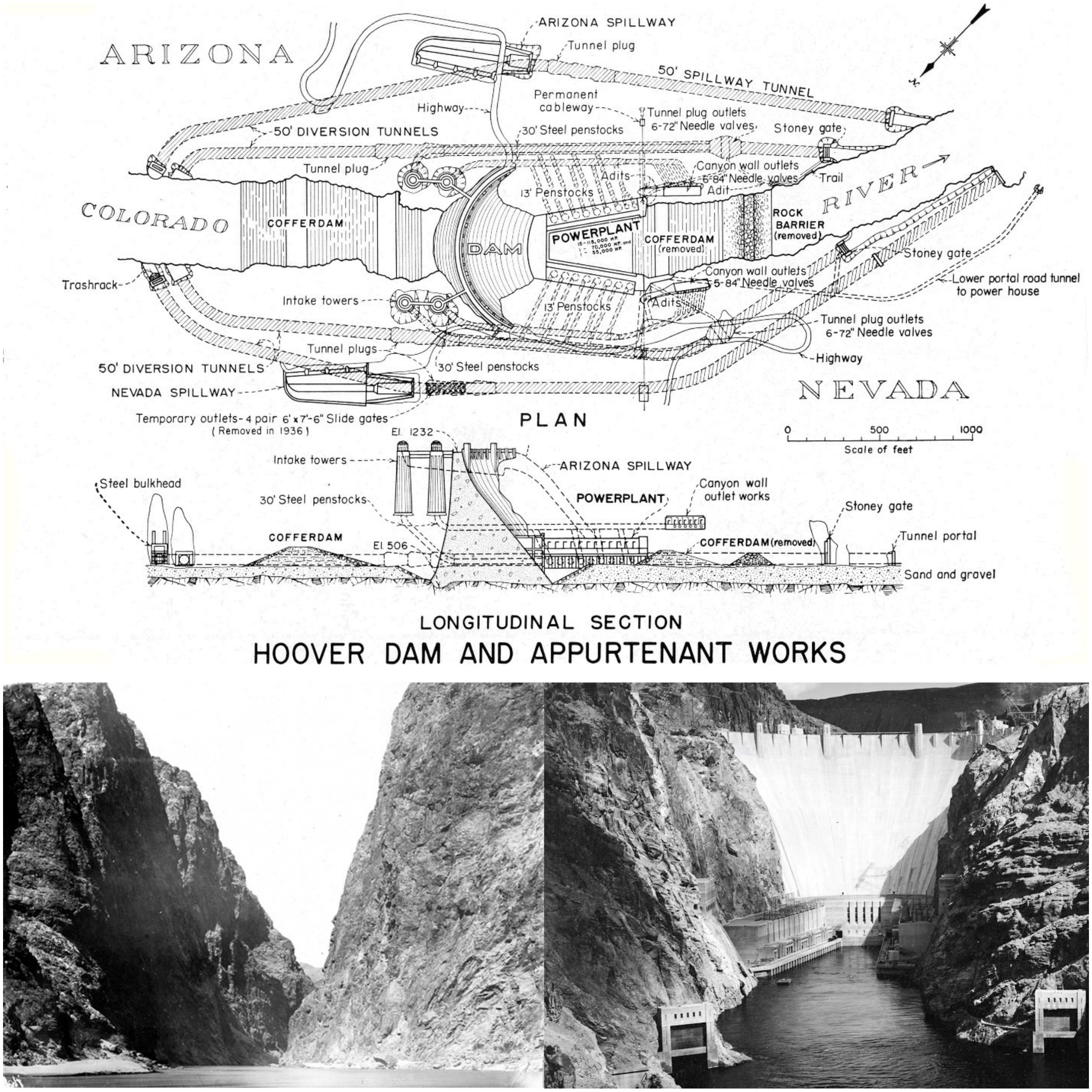

Figure 20: Engineering description of the Hoover Dam (top). Black Canyon before construction (lower left). Hoover Dam (lower right). (Drawing credits: U.S. Government, Wikimedia Commons, public domain. Black Canyon photograph credit: W. T. Lee, USGS, Wikimedia Commons, public domain. Hoover Dam photograph: Ansel Adams, National Archives.)

Black Canyon was a remote and extremely hostile location in the early 1900s. Summer temperatures in 1931 rose to 120 °F. Temperatures in the diversion tunnels hit 140 °F. There was no air conditioning. To house the engineering and construction workers, a model city was built near the construction site—today's Boulder City. Nearby Las Vegas had only 5,000 residents when the project began. Building the Hoover Dam was a major American engineering accomplishment of the 20th century. Today, the Hoover Dam can generate slightly more than 2 GW.

B. United States' 2100 space solar power needs

As noted in the discussion of nuclear power, by 2100, the United States will need about 5,155 GW of continuous electrical generation capacity. Assuming that terrestrial sustainable energy sources—nuclear, wind, ground solar, etc.—will continue to provide about 20 percent of this need, GEO space solar power will need to provide the balance of about 4,124 GW. To put this starkly into perspective, **the United States will need to construct the generating capacity equivalent to about 2,000 Hoover Dams in geostationary Earth orbit by 2100.** To undertake this, America must pursue a spacefaring industrial revolution that will enable this vital, war-avoiding project to succeed.

C. GEO space solar power

While the idea of tapping space-based sustainable energy first arose from Konstantin Eduardovich Tsiolkovsky in 1926, the technical approach to accomplishing this was first defined by Peter Glaser in 1968, followed by his patent in 1973. Glaser proposed building large platforms in GEO that would convert sunlight into electrical power. This power would then be transmitted to the ground where it would be converted into AC electrical power, providing utilities with a nearly continuous supply of electricity. (See Figure 21.)

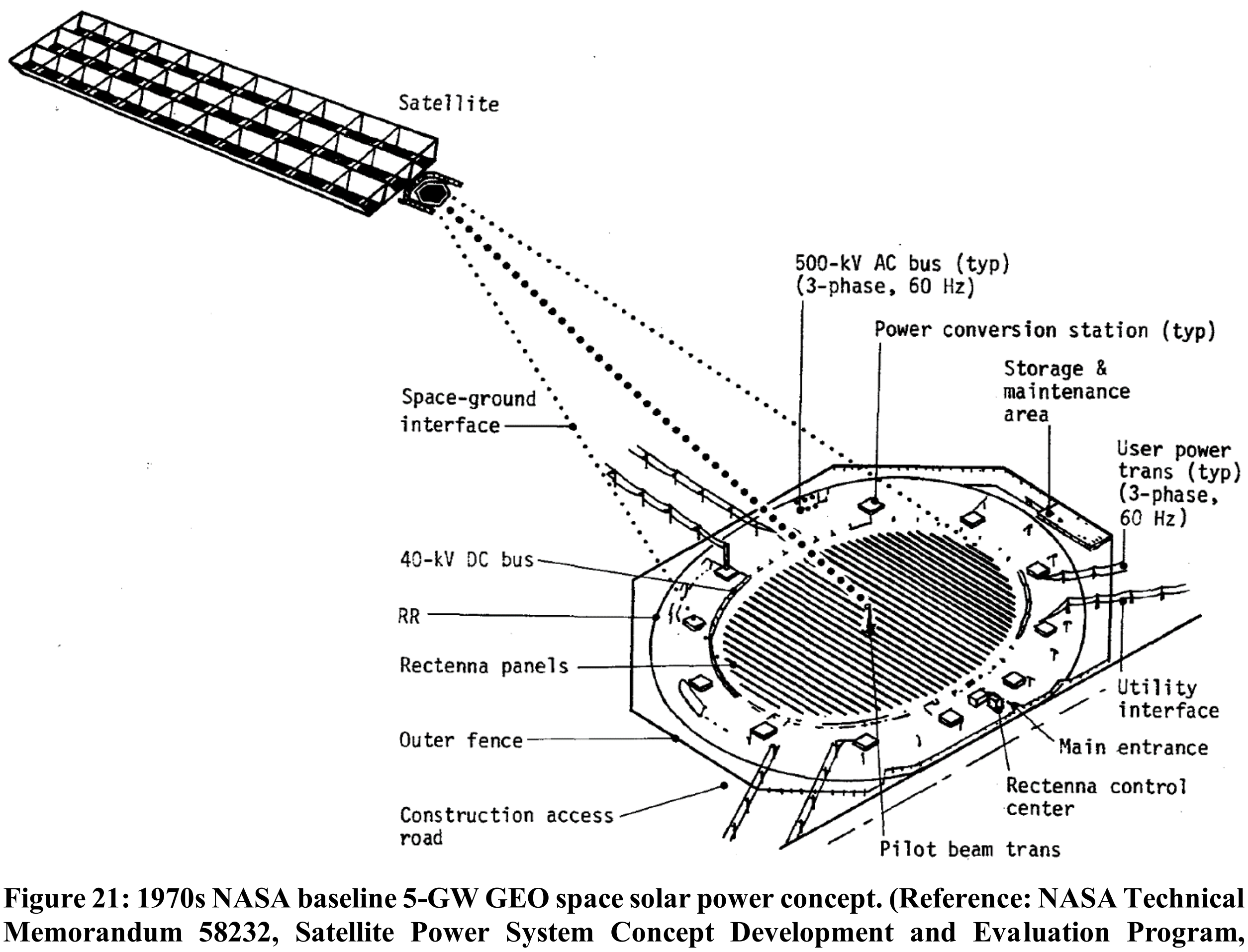

Figure 21: 1970s NASA baseline 5-GW GEO space solar power concept. (Reference: NASA Technical Memorandum 58232, Satellite Power System Concept Development and Evaluation Program, Volume I, Technical Assessment Summary Report, Fig. VII-4, November 1980.)

Beginning in the late 1970s, the National Aeronautics and Space Administration (NASA), the U.S. Department of Energy, and industry began a lengthy series of studies of GEO space solar power. A baseline design emerged that would deliver 5 GW—equal to 2.5 Hoover Dams—of nearly continuous electrical power from the ground receiving antenna array, referred to here as an astroelectric plant.*

Figure 22, using a later NASA GEO space solar power design, illustrates how such a platform would work. Sunlight is "captured" by mirrors that reflect the sunlight onto photovoltaic solar arrays. Converted into electrical power, the sunlight is then transmitted to the ground receiver. **Roughly 26 GW of sunlight yields 5 GW of baseload electrical power sent from the ground receiver to local utilities.** If the sunlight is not captured, it passes into the depths of space.

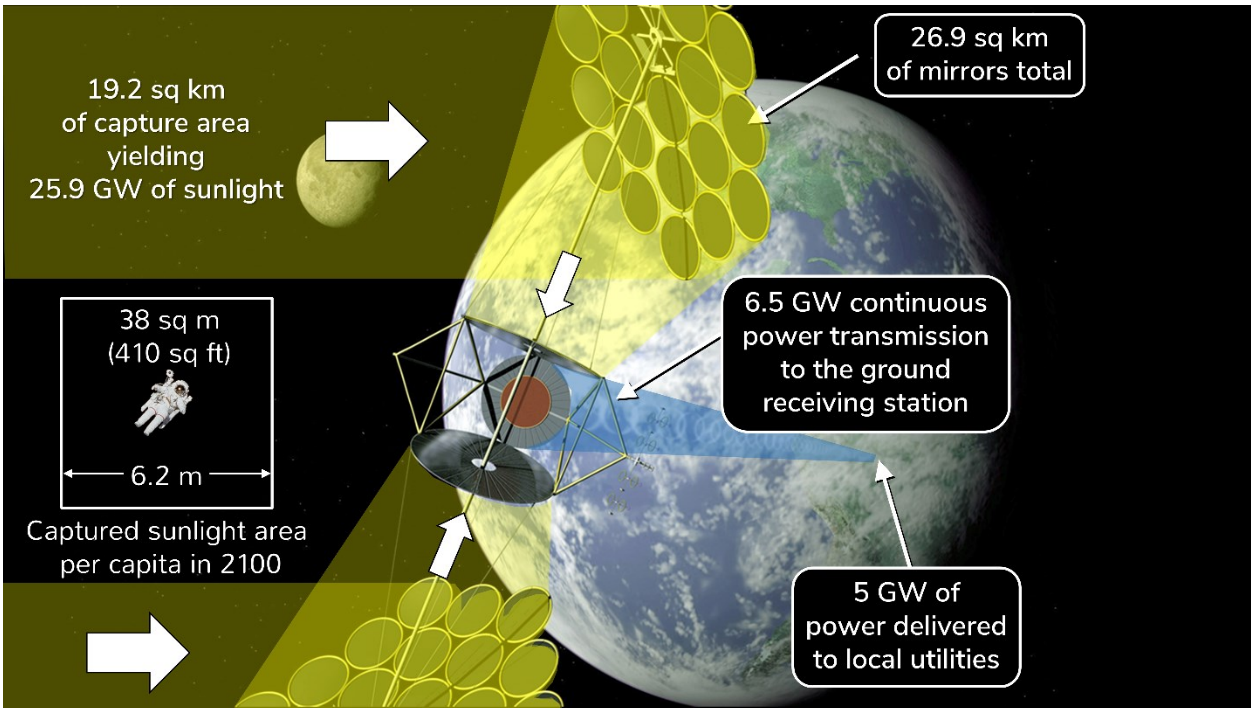

Figure 22: With an input of 25.9 GW of sunlight, the GEO space solar power system will deliver 5 GW of baseload electrical power to local utilities. (Original GEO space solar power illustration source: NASA. Credit: J.M. Snead.)

Recall that by 2100, the per capita need for baseload electrical power is about 10 kW. As shown in Figure 22, roughly 38 sq m of sunlight is all that would need to be captured to provide the 10 kW. This is about the floor area of a two-car garage.

D. Astroelectric plant land requirements

The baseline astroelectric plant size is shown in Figure 23. The receiving array is similar to a solar array except that the array panels contain small dipole antennas rather than photovoltaic cells. Each receiving array covers 104 sq km of land (40 sq mi). With the outer safety zone, each

* At local midnight near the spring and fall equinoxes, the GEO space solar power platforms will enter the Earth's shadow and temporarily stop collecting sunlight. This lasts for about one hour. Backup gas-turbine generators at the utilities will provide electricity during this period. The total period of outage will be about 5 percent of the year, yielding a capacity factor of about 95 percent compared to 21 percent for ground solar farms.

astroelectric plant will require about 164 sq km (63 sq mi). **To provide the energy required to replace fossil fuels in 2100, about 825 astroelectric plants will be required, covering about 135,000 sq km (52,000 sq mi). This compares very favorably with the nearly 5 million sq km (2 million sq mi) required for the combined wind and ground solar solution.**

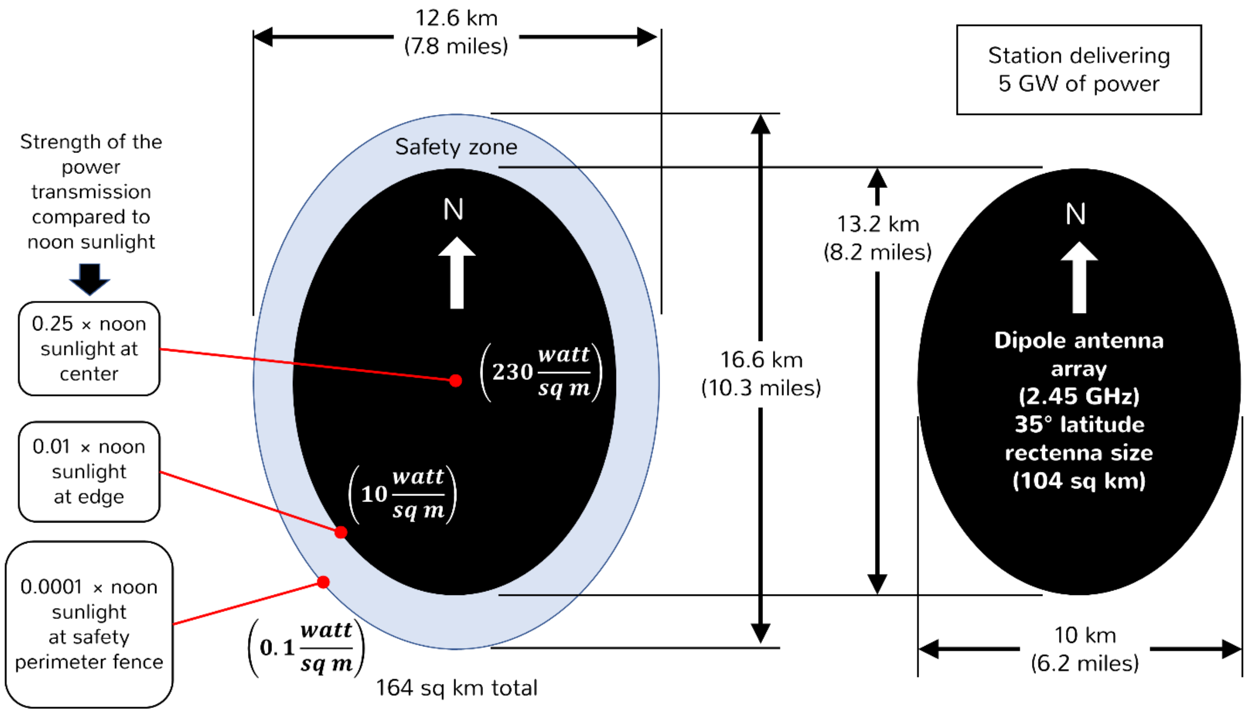

Figure 23: GEO space solar power ground receiving station—astroelectric plant— configured for a location at 35° latitude when using the 2.45 GHz transmission frequency and a 1-km transmitter diameter. (Credit: J.M. Snead.)

Also shown in Figure 23 is the power intensity of the transmission beam expressed in watts per sq m. By design, the peak power at the center of the beam is limited to about one-quarter of the noon insolation at the equator—about 230 watts per sq m. Noon insolation is about 1000 watts per sq m. For comparison, the power level in a countertop microwave oven is about 9000 watts per sq m. Therefore, the peak power level in the transmission is less than 3 percent of the power level in a kitchen microwave oven.

The power level in the beam falls off towards the edge of the receiving array. At the edge of the receiving array, the power is only 1 percent of the noon insolation. At the edge of the safety zone—the closest public access point—it is two orders of magnitude less. This is also two orders of magnitude less than the permitted exposure level per federal guidelines. The large size of the receiving antenna is used to keep the power levels low.

E. Astroelectric plant locations

To complete the transition from fossil fuels, 825 astroelectric plants must be built within the contiguous United States. As part of earlier studies, possible locations within the contiguous United States were examined. The contiguous United States has a land area of 7,663,942 sq km. This was divided into square cells measuring 26 km on a side, yielding 11,337 cells. Each cell has sufficient area for 1.5 astroelectric plants. Thus, about 550 cells would be needed. During the 1978 evaluation, cells were excluded due to unacceptable topography, navigable waterways, national recreation areas, population areas, marshlands, wetlands, national forests, Indian reservations, endangered species habitats, interstate highways, and land in cultivation. Of the total, 3,203 cells remained which should meet the needs of the 550 cells required to build 825 astroelectric plants. (See Figure 24.)

With sufficient land being available, at 825 locations across the country, the equivalent of 2.5 Hoover Dams providing space-based sustainable electrical power would be built enabling the United States to be energy secure with sustainable energy. **Each of these astroelectric plants would meet the annual energy needs of 500,000 Americans.**

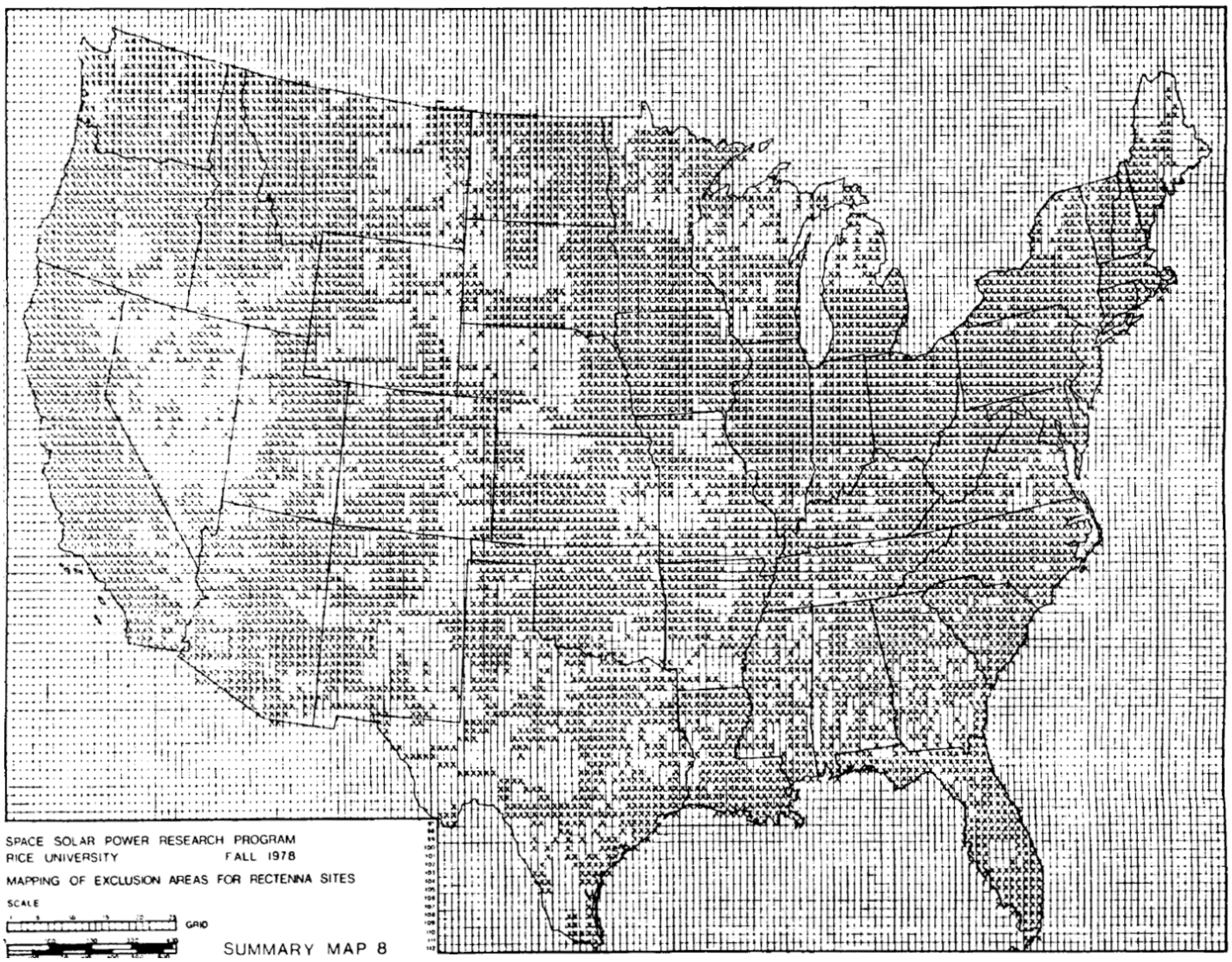

Figure 24: Summary Map 8 showing excluded cells (dark) and non-excluded cells (white). Excluded cells include: national recreation areas, population areas, unacceptable topography, navigable waterways, marshlands, wetlands, national forests, Indian reservations, endangered species habitats, interstate highways, and land in cultivation. (Reference: U.S. Department of Energy, Report: HCP/R-4024-10, Satellite Power System (SPS) Mapping of Exclusion Areas for Rectenna Sites, October 1978, Fig. 33.)

F. Comparison of GEO space solar power with wind and ground solar

Figure 25 compares the land area required for wind and ground solar power with the land area required for the astroelectricity plants needed to receive power from the 825 GEO space solar power platforms.

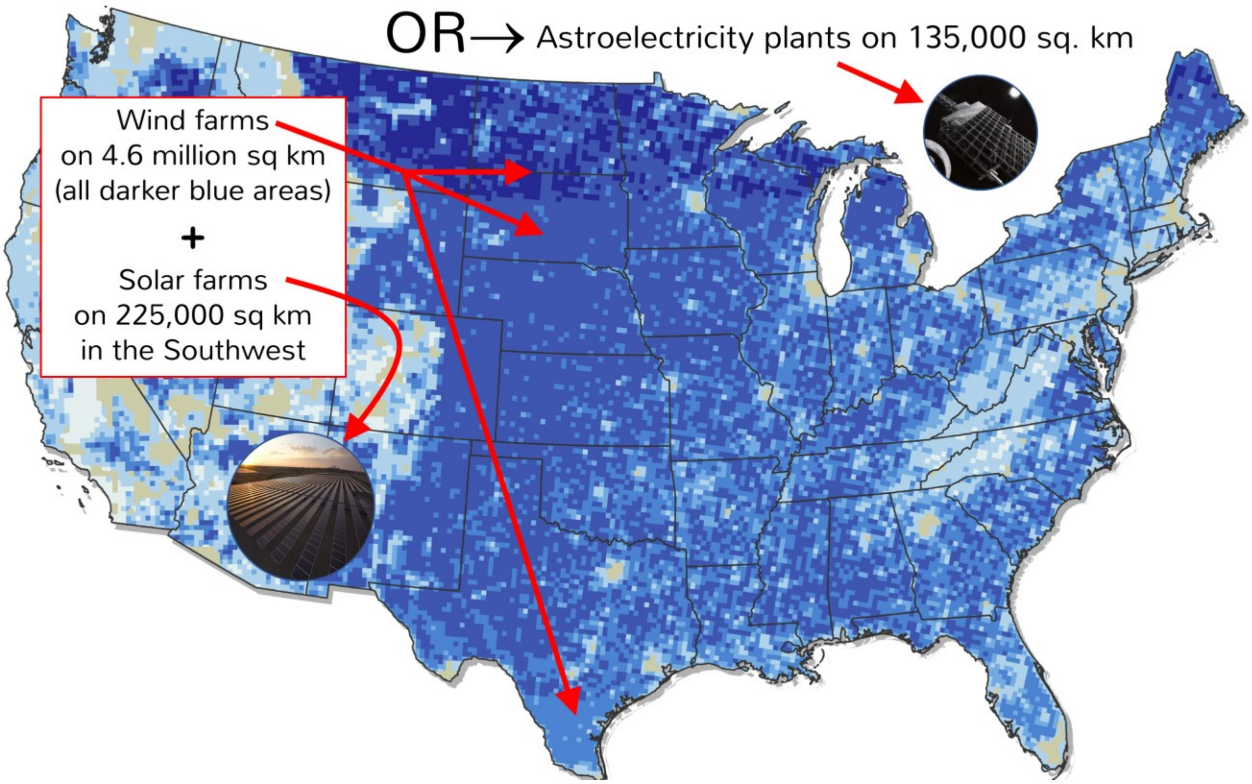

Figure 25: Comparison of the land areas needed to replace fossil fuels with wind and ground solar power and the land area required for the GEO space solar power (SSP) astroelectricity plants. (Map source: National Renewable Energy Laboratory for the U.S. Department of Energy, no known restrictions. Credit: J.M. Snead.)

G. The world's 2100 sustainable energy needs

The world must also transition from fossil fuels in an orderly manner. Historically, per capita energy use in the United States has been about twice that of Europe and Japan. **At this lower European/Japanese per capita energy consumption rate, each 5-GW astroelectric plant would meet the energy needs of about 1 million people. Using this as a planning benchmark, 10,000 5-GW astroelectric plants will be needed by 2100 to end energy impoverishment and enable sustainable development for the world's projected 10 billion people.** This is the scale of the sustainable energy engineering challenge that must be conquered if warfare is to be avoided and fossil fuel CO_2 emissions ended.

VII. America's Coming Spacefaring Industrial Revolution

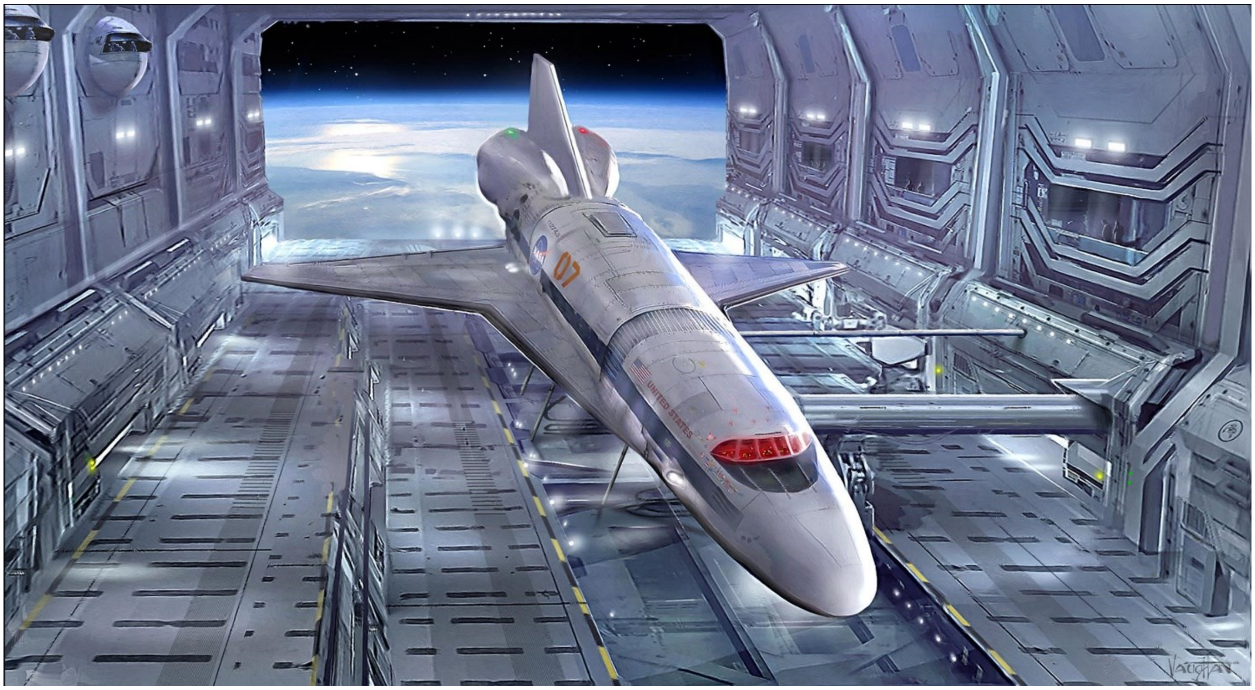

Figure 26: The next hundred years. Orbital space docks build and maintain growing space infrastructure. (Image and text credit: James Vaughan of James Vaughan Photography, used with permission.)

"To boldly go" has been an unofficial American spacefaring motto since the 1960s. Realized, so far, only in science fiction, America's pursuit of the now vital GEO space solar power will take Americans boldly throughout the central solar system. While space explorers will lead the way, a spacefaring industrial revolution will quickly follow, establishing a permanent American presence. **American aerospace professionals, this century, will turn America's long-held spacefaring dream into reality.** (See Figure 26.)

A. The scale of necessary human spacefaring operations this century

From what today is almost a standing start, America's human spacefaring operations will undergo a significant expansion throughout this century to undertake the unavoidable transition to space-based sustainable energy. **America will need to build, perhaps, as many as 825 5-GW GEO space solar power platforms by 2100.** Each of these platforms will mass on the order of 10,000-30,000 metric tonnes and will cover an area about the size of Manhattan Island. Obviously, **the existing approach of assembling a satellite on the Earth and remotely launching it into GEO will not work. Outer space will need to be industrialized—meaning Americans living and working in space.**

Low Earth orbit (LEO) will become the starting point for building the enabling spacefaring logistics infrastructure. Space bases, habitats, and space docks, as shown in Figure 26, will need to be built in LEO to provide a destination for Earth-to-orbit transports, logistics services such as housing and fueling, and a point of departure for transport beyond LEO. With strong federal leadership, the first generation of these LEO logistics capabilities can be made operational within 10-15 years.

As these permanent LEO facilities become operational, they will be used to expand the permanent logistics infrastructure to GEO, providing transport to and from GEO, and housing and work facilities in GEO. As the GEO capabilities become operational, the construction and evaluation of the prototype GEO space solar power platforms will be undertaken. This will be followed by the initial low-rate construction of operational GEO space solar power platforms along with their astroelectric plants within the United States. **Perhaps within a quarter century from today—around 2040—the first space power will be beamed to the Earth and fed into the U.S. electrical power grid.**

Figure 27: NASA Space Launch System (SLS) launching an Orion spacecraft on an exploration mission to the Moon. (Credit: James Vaughan, James Vaughan Photography, used with permission.)

While building the initial infrastructure, the search for and development of extraterrestrial resources will also be underway in parallel. As Gerard K. O'Neill identified in the 1970s, **it is not feasible to build a large number of GEO space solar power platforms using just terrestrial resources absent a dramatic breakthrough in space propulsion. Lunar and asteroid resources will be needed.** These resources must be located and the means to extract, refine, and produce the components needed to build the GEO space solar power platforms put in place. This will start with the extensive robotic and human exploration of the Moon and the asteroids. (See Figure 27.)

To undertake this routinely and safely will require expanding the spacefaring logistics infrastructure beyond GEO to lunar orbit, the lunar surface, and out into the asteroid belt. Orbiting space bases, surface bases on the Moon, lunar landers, space ferries, and spaceships capable of deep space operations will be needed. Eventually, large-scale industrial facilities will need to be built—probably at the Earth-Moon LaGrange points—to process these mined extraterrestrial resources into the products needed to build most of the GEO platforms.

Obviously, to build upwards of 10,000 platforms by 2100, the scale of these space industrial operations will rival large terrestrial industrial operations. **Toward the end of the century, one or two new GEO platforms and their astroelectric plants will need to be brought online daily.** This means that hundreds of platforms will be under construction at any time in the last quarter century. **This could easily involve 100,000 people living and working throughout the central solar system. With many of these future American spacers being today's children, we can only imagine what an exciting future awaits them!**

B. The scale of space solar power economic operations

A new 1-GW nuclear power plant now has a direct cost of about $5 billion. At this cost per GW, the United States may be expected to spend in the ballpark of, at least, $21 trillion to convert to GEO space solar power. The world will spend in the ballpark of $250 trillion.

Today, hydroelectricity has a cost of generation of about $0.01 per kWh or $10,000 per GWh. (For comparison, the cost of coal-generated electricity is about $0.04 per kWh.) Using this hydroelectric cost as a benchmark, in a year's time, a 5-GW GEO space solar power system would generate about $438 million worth of electricity. The 825 U.S. GEO space solar power systems would produce about $361 billion worth of electricity. Worldwide, the 10,000 systems would provide $4.4 trillion worth of electricity. Total annual commercial revenues would, of course, be some multiple of this amount.

C. America's spacefaring transformation

Clearly, **undertaking GEO space solar power will require an American aerospace enterprise involving government-only, joint government-private, and purely private operations** similar to what happened with the opening of the jet age beginning in the late 1940s. **By mid-century, immense new space power, space mining, space manufacturing, and spacefaring logistics industries will be created**. In short, America will be undertaking a spacefaring industrial revolution that will transform America into a true commercial human spacefaring nation.

This spacefaring industrial revolution will dwarf the Apollo program. Generations of Americans will be involved in GEO space solar power. Explorers will return to the Moon and venture to the asteroids to explore for critically-needed resources. Engineers and construction workers will build space facilities and habitats in LEO, GEO, the LaGrange Points, and on the Moon, and will build spaceships capable of traveling throughout the central solar system. Today's space capabilities will, in just a matter of decades, be considered antiquated. **What an exciting time to be an American aerospace professional!**

VIII. The Role of the AIAA

As a professional society, the primary ethical responsibility of the American Institute of Aeronautics and Astronautics is to "Hold paramount the safety, health, and welfare of the public in the performance of their duties." This responsibility supersedes everything else. America now faces two serious challenges to protect our children and grandchildren from the environmental and fossil fuel energy security threats described herein. The only reasonable action is to undertake an orderly transition from fossil fuels to sustainable energy. **For America, the only practical choice of a new sustainable energy source sufficient to replace fossil fuels, while maintaining our energy-dependent standard of living, is GEO space solar power.** Consequently, to faithfully adhere to the AIAA's paramount ethical priority while speaking from the position of being America's leading aerospace professional society, ***the AIAA should strongly and publicly advocate for the United States to undertake a national program to transition from fossil fuels to GEO space solar power.***

IX. Acknowledgement

The author expresses appreciation to Mr. James Vaughan for permission to use his illustrations.

X. References

[1] E. Kintisch, "High CO2 Makes Crops Less Nutritious," 9 May 2014. [Online]. Available: https://news.nationalgeographic.com/news/2014/05/140507-crops-nutrition-climate-change-carbon-dioxide-science/. [Accessed 2018].

[2] D. R. Taub, "Effects of Rising Atmospheric Concentrations of Carbon Dioxide on Plants," *Nature Education Knowledge,* vol. 1(8):21, 2010.

[3] National Renewable Energy Laboratory, "Estimates of land area and wind energy potential, by state, for areas >= 35% capacity factor at 80, 100, and 140m," February 2015. [Online]. Available: https://windexchange.energy.gov/files/docs/wind_potential_80m_110m_140m_35percent.xlsx.

[4] S. Campbell, "Annual blade failures estimated at around 3,800," 14 May 2015. [Online]. Available: www.windpowermonthly.com/article/1347145/annual-blade-failures-estimated-around-3800. [Accessed 12 May 2018].

[5] S. Ogg, "Land-Use Requirements for Solar Power Plants in the United States," 2013.

[6] N. Blair, "NREL Solar Data and Tools".