US Terrestrial Non-Fossil Fuel Energy vs. Space Solar Power

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The United States is facing two security threats that will force its use of fossil fuels to be abandoned this century and require it to build an immense new space-based sustainable energy industry. As discussed in the first article, a global environmental security threat exists due to the uncertainty of the potential harm the abnormally high atmospheric carbon dioxide level could cause to the environment and human existence (see "The Paris climate agreement and space solar power", The Space Review, February 29, 2016). As discussed in the second article, the energy security threat arises from the rapid depletion of America's remaining technically recoverable fossil fuel endowment and how this threatens our children's and grandchildren's standard of living (see "US fossil fuel energy insecurity and space solar power", The Space Review, March 7, 2016).

This final article shows why only space-based sustainable energy provides the United States with a practical replacement for fossil fuels.

The substantial US dependence on fossil fuels is at the heart of both of these threats. To resolve these threats, substantial new sustainable energy sources must be built. Many people incorrectly assume that these replacement energy sources will be terrestrial renewable and/or nuclear energy when, in fact, space-based sustainable energy—e.g., space solar power—is the only practical option. This final article quantitatively assesses the terrestrial nuclear and renewable energy options for the United States and shows why only space-based sustainable energy provides the United States with a practical replacement for fossil fuels. This article's focus is on defining what it necessary for the United States to transition completely to sustainable energy by 2100.

Evaluating US terrestrial energy alternatives to fossil fuels

Today, with fossil fuels still providing about 80 percent of the energy used in the United States, it is convenient to express the US per capita energy need using the barrel of oil equivalent (BOE) unit. A BOE is equal to the thermal energy of 42 US gallons of oil. All forms of energy can be expressed in terms of BOE enabling total energy production and consumption to be expressed using a common energy unit.

In 1979, the US historic peak per capita total energy use was 62.1 BOE/year. Nearly thirty years later in 2007, just prior to the start of the current economic recession, the US per capita total energy use had fallen slightly to 57.7 BOE/year. To estimate the energy needs in 2100, a further decline to 50 BOE/year per capita is assumed due to energy efficiency improvements and lifestyle changes. As discussed in the second article, the likely US population in 2100 will be 618 million. Hence, the total US energy need will climb from 17.4 billion BOE in 2007 to 30.9 billion BOE in 2100.[i]

The United States has three primary terrestrial alternatives: nuclear fission, wind, and ground solar. The other alternatives—biomass, geothermal-electricity, and hydroelectricity—cannot be scaled up to provide a substantial portion of the growing US energy needs. Thus, assessing the practicality of meeting the US 2100 energy needs with terrestrial non-fossil fuel alternatives starts with nuclear power.

Terrestrial fission nuclear power

For most forms of sustainable energy, the primary unit of power will be the watt, as electrical power will be the primary form of power production. The primary unit of energy then becomes the watt-hour. As the watt-hour is a small quantity of energy, the typical units used are kilowatt-hour, megawatt-hour, and gigawatt-hour.

Modern nuclear fission power plants are designed to operate continuously except for periods of scheduled maintenance and refueling. Let us assume that a new nuclear power plant will, optimistically, be online 95 percent of the time. Thus, a modern 1-gigawatt nuclear power plant would provide 1 gigawatt × 365 days × 24 hours/day × 0.95 = 8,322 gigawatt-hours of electrical energy per year. For convenience, the quantity of 8,322 gigawatt-hours is referred to as a gigawatt-year of electrical energy.

In 2007, the United States consumed 499 gigawatt-years of electrical energy and 10.9 billion BOE of fuels. As noted, total per capita energy consumption was equal to 57.7 BOE. In 2100, taking into account the assumed reduction in per capita energy use to 50 BOE/year, the United States would need 885 gigawatt-years of electrical energy and 19.3 billion BOE of hydrogen fuel to meet the needs of 618 million. For convenience, we will assume that all American energy in 2100 is provided by new nuclear power plants. Hence, in addition to the 885 gigawatt-years needed for dispatched electrical energy, producing the 19.3 billion BOE of hydrogen fuel would require an additional 5,481 gigawatt-years. Thus, a total of 6,367 gigawatt-years of nuclear power would be needed in 2100 to meet the total energy needs of 618 million. For the case of zero net immigration, also discussed in the second article, the total reduces to 3,537 gigawatt-years for 343 million in 2100.

Using government information, I have estimated the overnight capital cost of a new one-gigawatt nuclear power plant, with associated hydrogen production capability, at $6.5 billion. Using this ballpark value, the cost of building an all-nuclear energy infrastructure for 618 million would be roughly $42 trillion. The average annual cost would be $525 billion for 2020 through 2100. For the zero net immigration case, the rough cost would be $23 trillion, with an average annual cost of $288 billion. The 275 million increase in the size of the US population by 2100, due to likely net immigration, adds an additional $237 billion each year to the cost of building fossil fuel replacement nuclear power plants.

Concerns about disposing radioactive waste, siting a large number of additional plants, and the environmental impact of the waste heat of thousands of plants would likely make such an expansion unacceptable in the United States.

In 2014, the United States had 104.4 gigawatts of commercial nuclear power producing 96 gigawatt-years of electrical energy. This was only 1.5 percent of what will be needed in 2100. The United States would need to increase its nuclear power capacity by approximately a factor of 67.

While replacing older US nuclear power plants and building a modest number of additional plants to expand nuclear electricity generation will likely be beneficial, in order to diversify generation capability and improve safety, the large-scale expansion of fission nuclear power is unlikely. To achieve this, uranium-233 breeding or plutonium breeding will be necessary as there is insufficient technically recoverable natural uranium-235. As both uranium-233 and plutonium are capable of being used in nuclear weapons, this opens the door to international nuclear weapon proliferation should other countries follow America’s lead in going nuclear. Also, concerns about disposing radioactive waste, siting a large number of additional plants, and the environmental impact of the waste heat of thousands of plants would likely make such an expansion unacceptable in the United States.

Wind energy

Like ground solar energy, wind-generated electrical power is highly variable. To build a hypothetical all-wind energy infrastructure to meet the US 2100 energy needs means that this variability must be taken into account. The approach used in this analysis is to convert all wind-generated electrical power into hydrogen. This hydrogen will then be used by the utility to generate electrical power on demand and to supply hydrogen fuel to the end consumer. To meet the annual energy needs of the most likely immigration case of 618 million, the equivalent of 7,349 gigawatt-years of electrical energy would be needed. For the zero immigration case of 343 million in 2100, wind energy must provide the equivalent of 4,082 gigawatt-years.

The US National Renewable Energy Laboratory (NREL) has estimated the commercial wind energy potential of the contiguous United States. One best case example uses approximately 5.28 million 1.6-megawatt turbines. These stand 525 feet (160 meters) tall at the tip of the rotor blade and are spaced every half mile (0.8 kilometers). The total land area covered with turbines was about 1.3 million square miles (3.37 million square kilometers), or about 43 percent on the contiguous United States, primarily in the central United States from Texas to the Canadian border. The installed nameplate power would total 8,654 gigawatts. However, due to the variability of the wind, the total electrical energy produced in a typical year would be only 3,097 gigawatt-years. This would provide only 42 percent of the annual energy needed for 618 million in 2100 and only 76 percent of that needed in the zero net immigration case.

In 2014, the installed wind nameplate capacity in the United States was 66 gigawatts, or 0.8 percent of the total in the case cited above. Building wind farms in rural America is already generating opposition. Hence, constructing a forest of spinning wind turbines does not represent an environmentally-friendly or likely politically-acceptable means of providing sustainable energy to replace fossil fuels.

Ground solar energy

The NREL also provides information allowing the ground solar energy potential of the United States to be assessed. As with the wind-generated electrical power model, all ground solar electrical power is assumed to be converted to hydrogen. Thus, the gigawatt-years needed are the same. In terms of the size of the ground solar farms, meeting these energy needs requires:

- For the most likely immigration case of 618 million in 2100, 406,200 square miles (1,052,000 square kilometers) of solar farms, having 35,000 gigawatts of nameplate solar PV power, must be built. This would require 14 percent of the contiguous United States be converted to solar farms.
- For the zero immigration case of 343 million in 2100, roughly 225,600 square miles (584,300 square kilometers) of solar farms, having 19,000 gigawatts of nameplate solar PV power, must be built.

About 3.4 percent of the contiguous United States would be needed for the receiving stations and safety perimeter for space-based solar power systems.

The primary US location for ground solar is in the southwestern United States. In California, New Mexico, Arizona, Nevada, Utah, Colorado, and west Texas, only about 87,000 square miles (225,000 square kilometers) are suitable for commercial solar farms without the need for terracing and/or extensive grading. Thus, only about 21 percent of the energy needs for the most likely 2100 population of 618 million could be met without significant land environmental impact. For the zero immigration case, only about 39 percent of the 2100 energy needs could be met.

In 2014, the utility-scale solar PV systems totaled 8.7 gigawatts and provided the equivalent of 1.8 gigawatt-years of electrical energy. That was only 0.02 percent of the solar energy production needed in 2100 to meet the energy needs of the most likely US population size.

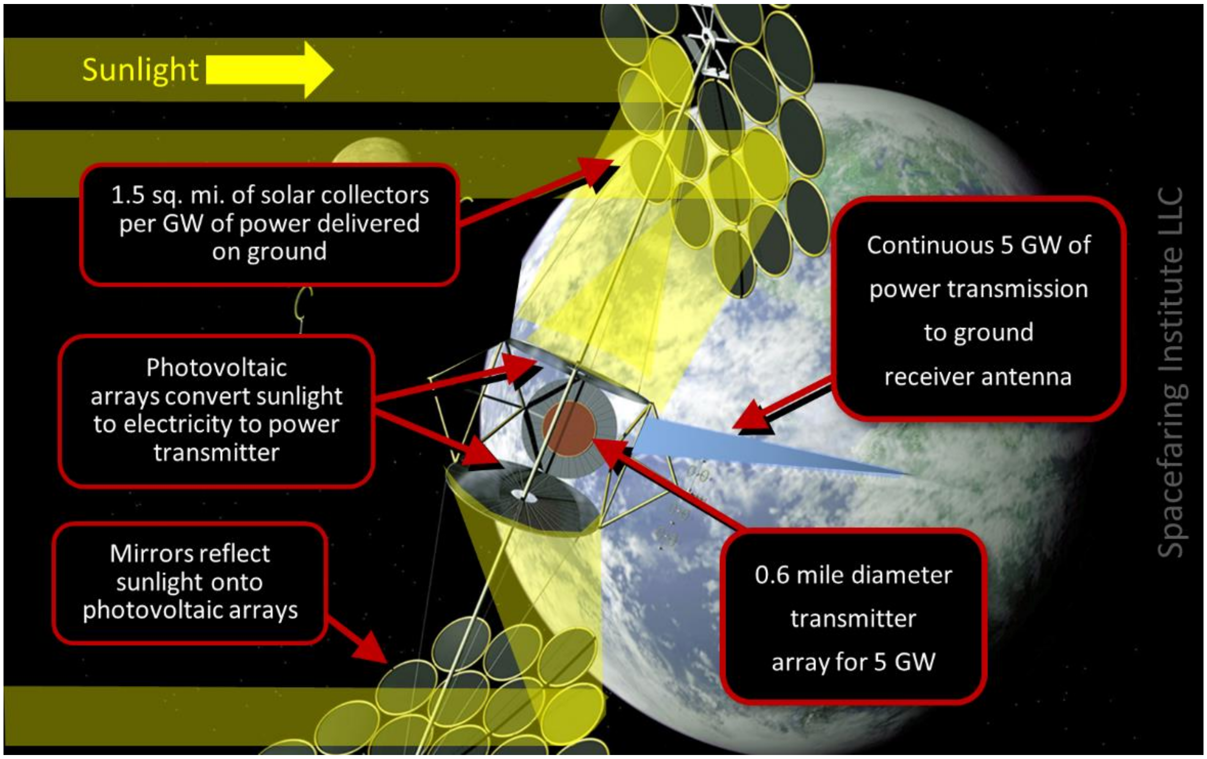
Other terrestrial renewable energy alternatives

These three examples indicate that other US terrestrial renewable energy alternatives have limited potential to meet US 2100 energy needs.

- The US Department of Energy determined that an additional 65 gigawatts of hydroelectric power generation could be added, primarily with small megawatt-class plants.
- The US Geological Survey has estimated that 9–40 gigawatts of additional geothermal electricity generation capacity could be added to the existing 3.8 gigawatts of generating capacity. A primary challenge is the general lack of the water, needed to extract the geothermal energy, at the geothermal plant locations.
- In 2014, biomass, e.g., corn and wood, produced only about four percent of the energy consumed in the United States. As the US population grows, food

demands will likely eliminate the use of corn for fuel. Wood fuel production is largely a byproduct of lumber production and is unlikely to significantly expand.

Space solar power alternative



Space solar power (SSP) places the solar power systems into Earth orbit, most likely in geostationary Earth orbit (GEO) where communication satellites are located. This enables the generated electrical power to be continuously transmitted to ground receiving stations located in the United States. The ground receiving stations would function as baseload power plants providing electrical power almost continuously throughout the year.

Using system parameters identified in John Mankins' 2014 book, *The Case for Space Solar Power*, the size of a hypothetical all-space solar power energy infrastructure would have these characteristics:

- Approximately 1.5 square miles (3.9 square kilometers) of sunlight capture would be needed to produce one gigawatt of electrical power from the ground receiving station. A five-gigawatt SSP platform would have nearly 7.5 square miles (19.5 square kilometers) of sunlight capture.

- The overall efficiency of sunlight-to-ground electrical power would be about 19 percent.
- About 8 square miles (20.8 square kilometers) of ground receiving station land area is needed for each gigawatt of electrical power delivered.
- For the most likely immigration case of 618 million in 2100, 1,273 five-gigawatt SSP platforms in GEO and 51,500 square miles (133,400 square kilometers) of land for the ground receiving stations would be needed. Adding the safety perimeter increases this to 101,100 square miles (261,600 square kilometers). About 3.4 percent of the contiguous United States would be needed for the receiving stations and safety perimeter.
- For the net zero immigration case of 343 million in 2100, 707 five-gigawatt SSP platforms and 28,600 square miles (74,100 square kilometers) of land for the ground receiving stations would be needed. Adding the safety perimeter increases this to 56,000 square miles (145,000 square kilometers). About 2 percent of the contiguous United States would be needed for the receiving stations and safety perimeter.

Space nuclear power alternative

In addition to SSP platforms located in geostationary orbit, it may be feasible and desirable to augment these with fission or, in the future, fusion nuclear power. Nuclear power plants are just another form of a thermal power plant. Several concepts for space solar power use thermal energy instead of photovoltaic arrays to generate electrical power so integrating a nuclear power plant into such a thermal SSP platform may be advantageous.

America must build an immense new space-based energy industry to remain energy secure and address its ethical obligation to protect the environment. This will require opening the Earth-Moon system to substantial commercial industrial operations.

One possible approach is to use thorium-cycle fission power plants. Thorium is a fertile isotope that can be bred to yield uranium-233. Designs for thorium-cycle plants have been proposed where the breeding and power generation all happen within the reactor. Initially, the reactor is “fueled” only with thorium, meaning that when launched it would not be radioactive. Once the reactor is positioned in geostationary orbit, a small “seed” of uranium-235 would be introduced into the reactor to provide the neutrons to breed the uranium-233. The uranium-235 seed would be transported separately using the same containment methods now used during launch for plutonium-fueled generators for deep space probes. Disposal of the reactor could involve sending it into an orbit ending with its impact in the sun. Such thorium-cycle reactors could also be used on the Moon and Mars and at other locations outside geostationary orbit.

Comparison of results

Comparison of US Non-Fossil Fuel Energy Sources for 2100

Energy Source	Most likely immigration (618 million)	Zero net immigration (343 million)
Nuclear	**6,367 GW-years**	**3,537 GW-years**
Wind (1.3 million sq. mi.)	**42% of 2100 need** (3,097 GW-years generated)	**76% of 2100 need** (3,097 GW-years generated)
Ground Solar	**406,200 sq. mi.**	**225,600 sq. mi.**
Max Wind + Balance from Ground Solar	**1,321,000 sq. mi. (wind) + 235,000 sq. mi. (solar)** (52% of contiguous US)	**1,321,000 sq. mi. (wind) + 54,000 sq. mi. (solar)** (46% of contiguous US)
Space Solar Power Ground Receiving Station	**51,500 sq. mi.** (101,000 sq. mi. with safety perimeter)	**28,600 sq. mi.** (56,000 sq. mi. with safety perimeter)

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Concluding remarks

This century the United States must successfully address the twin environmental and energy security threats created by its substantial dependency on fossil fuels. Much of its energy infrastructure must be rebuilt to replace fossil fuels with sustainable energy. The terrestrial nuclear and renewable energy options, generally presumed to be the replacements, cannot practically meet the US 2100 energy needs. This leaves space-based sustainable energy—solar and nuclear—as the only two viable options to replace fossil fuels. Hence, America must build an immense new space-based energy industry to remain energy secure and address its ethical obligation to protect the environment. This will require opening the Earth-Moon system to substantial commercial industrial operations. A truly exciting American human spacefaring future is now beginning!

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[i] Analysis of US 2100 Energy Needs and Sustainable Energy Sources, J. M. Snead, Spacefaring Institute, February 21, 2016, http://mikesnead.net/resources/spacefaring/sillc_us_2100_sustainable_energy_analysis_version_1%2020160221.pdf