Analysis of US 2100 Energy Needs and Sustainable Energy Sources

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Version 2

Abstract

Environmental and energy security threats will bring an end to the general use of fossil fuels in the United States this century. To replace fossil fuels, the United States will need to build an immense sustainable energy capability. Nuclear fission energy, wind energy, and ground solar energy are the three primary terrestrial alternatives while space solar power is the primary space-based sustainable energy alternative. None of the three terrestrial energy alternatives provide a practical replacement for fossil fuels. Space-based sustainable energy, including space solar power, provides a practical alternative. US immigration policy will substantially influence the life of the remaining US fossil fuel endowment and the cost of building the replacement energy sources.

Key words: United States, fossil fuels, 2100, CO2, carbon dioxide, nuclear energy, nuclear power, solar energy, wind energy, space solar power, immigration, energy security threat, environmental security threat, hydrogen, electrolysis, immigration policy, zero net immigration

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Version 2 Notes

Version 2 incorporates a population projection update in 2014 by the US Census Bureau. This is added as a third case.

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1. Introduction

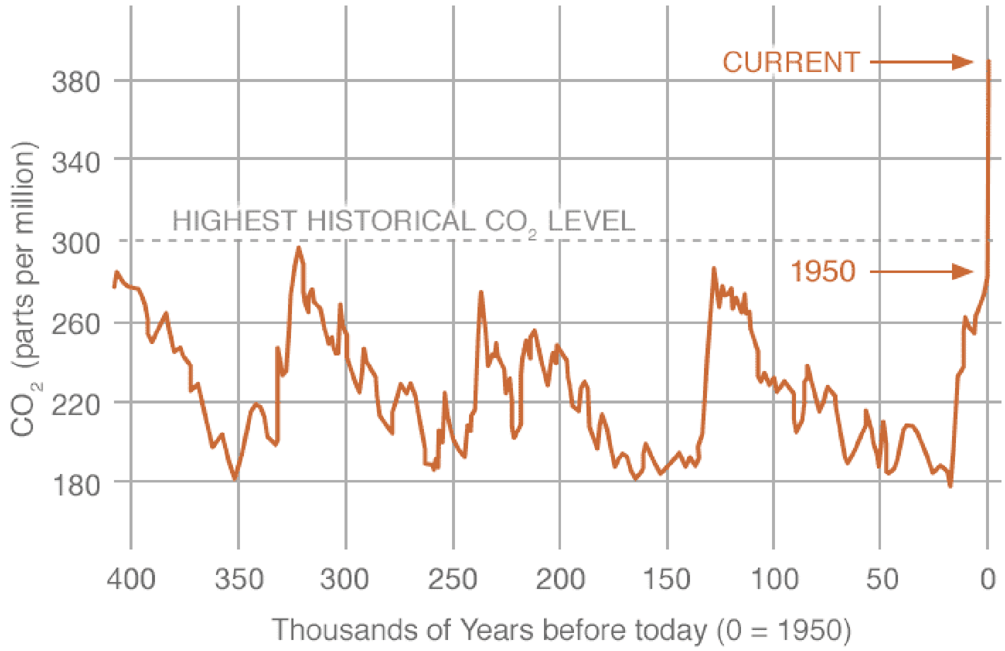
The modern world runs on electricity and fuels. Among large nations in population size, the United States has the highest per capita use of energy. Maintaining affordable supplies of energy is vital to American economic prosperity and national security.

1.1 The end of the era of affordable fossil fuels

1.1.1 The environmental security threat posed by fossil fuel carbon emissions

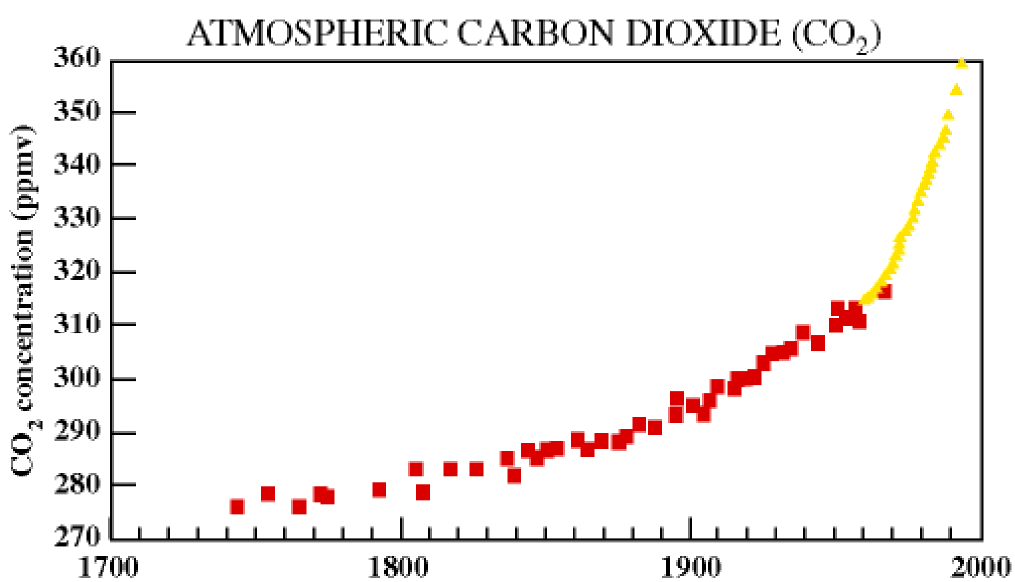
While the environmental impact of humans on the surrounding local environment has been understood for thousands of years, in the twentieth century the global impact of human civilization became apparent. It now appears that as the human population grew above about 1 billion in the mid-1700s, an accumulation of local environmental impacts became global.

Of particular interest to this discussion is the increase in the level of atmospheric carbon dioxide (CO2). CO2 is life's counterpart to oxygen in the atmosphere. Animals use various organic carbon compounds as fuel and release CO2 as an emission into the atmosphere. Plants take up this CO2 and, throughout photosynthesis, convert it into sugars and other carbon compounds releasing oxygen as an emission. Animals then consume this oxygen. This is the cycle of life of which CO2 is just as important as oxygen.



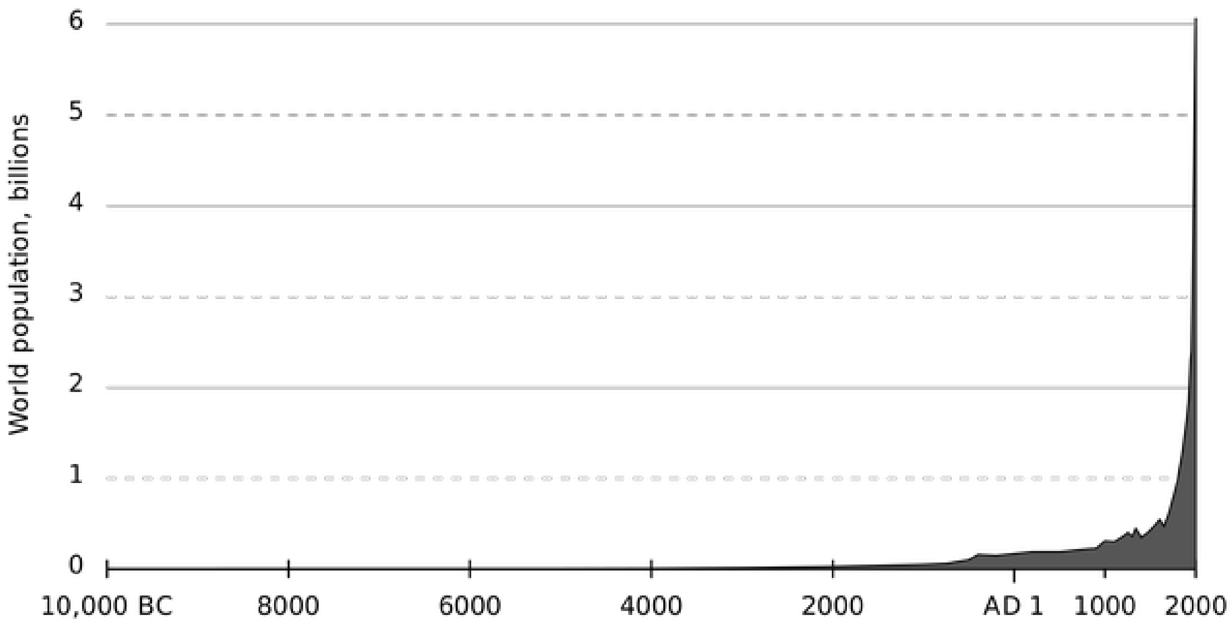
Atmospheric levels of CO2 over the past 400,000 years.
(Source: NASA.)

The above figure shows the variation in the atmosphere's CO2 level over the last 400,000 years through several periods of global cooling-induced glaciation alternating with shorter interglacial periods of global warming. The variation in CO2 is likely due to increased global animal activity during warmer and wetter interglacial periods. The normal range of CO2 was from about 280 parts per million (PPM) to 180 PPM.



Atmospheric CO2 levels from 1700–2000.
(Source: USGS.)

The current level of atmospheric CO2 is exceeding 400 PPM – abnormally high when compared to the variations over the past 400,000 years. With all other things presumed to be the same, the implication is that this has been caused by the growth in the population of modern humans. The atmospheric CO2 level began to climb in the mid- to late-1700s, about the time the total world population exceeded 1 billion.



World human population.
(Source: Wikimedia Commons, public domain image.)

The exact reason for this initial increase above normal interglacial levels is not known. It was likely a combination of human-caused factors potentially including land clearing for agriculture, increased numbers of domesticated animals, increased soil microbe activity due to farming, and the increased combustion of wood fuel. As the widespread use of fossil fuels did not begin until the 1800s, it appears that the initial abnormally high levels began before the "fossil fuel age" started. However, the use of fossil fuels has, since the mid-1800s, likely contributed to the high CO2 levels.

T**he high and increasing atmospheric CO2 level creates substantial uncertainty as to the environmental impact.** It is clearly not in the best interests of human civilization to cause change to the environmental conditions benefiting human civilization. This uncertainty constitutes an environmental security threat calling for actions to eliminate this threat. Ending the use of fossil fuels as the primary world source of affordable energy is a reasonable response to this threat. However, this must be done in a manner that enables developed countries to maintain their standard of living and enables developing nations to increase their standard of living. This means that substantial new sources of non-fossil fuels must be built.

1.1.2 The US energy security threat posed by a diminishing fossil fuel endowment

(Updated for Version 2)

U.S. Technically Recoverable Fossil Fuel Endowment

Fuel	***Native Units***	***BOE (Billion)***
Oil (2013)[1]	259.8 billion barrels	259.8
Natural Gas (2013)[1]	2,276.5 trillion cu. ft.[3]	403.4
Coal (2014)[2]	255.8 million short tons[4]	882.5
Total		1,545.7

1. U.S. Energy Information Administration, Assumptions to the Annual Energy Outlook 2015, Oil and Gas Supply Module, Reference case.
2. U.S. Energy Information Administration, Table 15 Recoverable Coal Reserves at Producing Mines, Estimated Recoverable Reserves, and Demonstrated Reserve Base by Mining Method, 2014.
3. 1 cu. ft. natural gas = 1,028 Btu; 1E6 cu. ft. = 177.2 BOE
4. 1 short ton of coal = 19.988 million Btu; 1 short ton = 3.45 BOE

The United States has immense remaining fossil fuel resources – among the most of any nation. However, like all natural resources, only a portion of these can be recovered safely and profitably brought to market. As of 2013/2014, the United States Geological Survey (USGS) estimated the US endowment of technically recoverable known and yet-to-be-discovered fossil fuel resources to be about 1,545.7 billion barrels of oil equivalent (BOE). The United States, with a population of 320 million in 2015, is now consuming about 13.7 billion BOE of fossil fuels each year. This value will increase as the population increases to an expected 500 million, at least, by 2100. Obviously, the United States has only about a century's supply of technically recoverable fossil fuels. This constitutes an energy security threat to the economic prosperity and national security of the United States.

1.2 What will replace fossil fuels?

The United States, like most other nations, will need to transition to non-fossil fuels this century. This will not be easy, quick, or inexpensive. The remainder of the paper evaluates the non-fossil fuel alternatives. What makes sense for the United States as the primary replacement for fossil fuels? Will it be nuclear energy? Terrestrial renewable energy? Or will the United States need to undertake building an immense new space-based sustainable energy industry? The following quantitative analyses make the suitable choice clear.

2. Units of energy and power

2.1 Barrel of oil equivalent (BOE)

As fossil fuels release thermal energy, an appropriate unit for measuring the thermal energy of fossil fuels is the barrel of oil equivalent or BOE. As an international standard, this was originally established based on the amount of energy contained in 42 US gallons of crude oil. Due to the variability of the thermal energy in oil from different locations, the BOE is now established to be equal to 5.8 million British thermal units or Btu.

When summarizing the total energy produced or consumed in a country, this is often expressed in terms of BOE or the total Btu. To calculate such a total, all other forms of energy, such as nuclear power and renewable energy sources, are expressed in terms of the amount of oil that would be needed to yield the same amount of energy.

Defining the unit BOE: $BOE := 5.8 \cdot 10^6 \cdot Btu$

2.2 Electrical power and energy

“Electricity” is the general term applied to a current flowing through a conductor. Electricity is not, however, a unit of measure. The unit for measuring electrical power is the watt and the unit for measuring electrical energy is the watt-sec.

When turned on, a 100-watt electrical light bulb uses 100 watts of electrical power continuously. If the bulb is turned on for just one second, it would use 100 watt-sec of electrical energy. If it was used for one hour, it would use 100 watt-hours of electrical energy. A 25-watt light bulb turned on for four hours would also use 100 watt-hours of electrical energy. Multiplying the wattage times the duration yields the energy used.

As a watt is a very small amount of power, the convention is to represent this in multiples of 1000.

- 1000 watt = 1 kilowatt (kW)
- 1000 kW = 1 megawatt (MW)
- 1000 MW = 1 gigawatt (GW)

The unit of kW is typically used to measure the power consumption of a home or business. The units of MW and GW are typically used to measure the output of electrical generators. The Hoover Dam, for example, is capable of producing 2,080 MW or 2.08 GW.

3. United States' historical energy use in 2007

The United States pattern of energy use since 2008 has been atypical due to the influence of the severe and prolonged economic recession. Hence, 2007 is used as the most recent baseline for assessing typical US energy use under normal economic conditions.

3.1 US total gross thermal energy consumed in 2007

Ref: http://www.eia.gov/totalenergy/data/monthly/pdf/sec2_3.pdf

In 2007, the United States consumed 101,026.566 trillion Btu from all energy sources. This is referred to as the Gross Thermal Energy or GTE. Converting to BOE yields:

$$GTE\_consumed\_2007_{US} := 101026.566 \cdot 10^{12} \cdot Btu = \left(17.418 \cdot 10^{9}\right)\ BOE$$

3.1.1 Energy used in 2007 for generating electrical energy and as end-consumer fuels

The following table uses US Government data for the year 2007. The electrical energy generated using coal, oil, natural gas, nuclear, and renewable energy sources is shown. The actual or equivalent number of Btu required to generate 1 kWh is shown and then converted to the BOE required to generate 1 GWh. This value is then used to convert the actual total GWh provided by each energy source into the equivalent BOE used. These are totaled to yield the total equivalent Gross Thermal Energy (GTE) used to generate electrical energy.

US Electrical Energy Generated in 2007 and Gross Thermal Energy (BOE) Consumed

Thermal energy to electrical energy conversons

	Coal	*Oil*	*Nat. gas*	*Nuclear*	*Renewable*	*Total*
Btu/kWh	10,375	10,794	8,403	10,489	9,884	
BOE/GWh	1,789	1,861	1,449	1,808	1,704	
Production in 2007						
2007 GWh generated	2,016,456	65,739	910,043	806,425	358,083	4,156,746
BOE equivalent	3,607,022,586	122,342,546	1,318,464,022	1,458,377,901	610,222,823	6,506,207,055

Data sources:

http://www.eia.gov/electricity/annual/html/epa_08_01.html

http://www.eia.gov/electricity/monthly/xls/table_1_01.xlsx

Notes:

1. Petroleum is a sum of petroleum liquids and petroleum coke.
2. Natural gas includes other gases.

The percentage of the GTE cumsumed used to generate electrical energy is determined.

$$GTE\_consumed\_generating\_electrical\_energy\_2007_{US} := 6506207055 \cdot BOE$$

$$GTE\_percentage_{electrical} := \frac{GTE\_consumed\_generating\_electrical\_energy\_2007_{US}}{GTE\_consumed\_2007_{US}}$$

$$GTE\_percentage_{electrical} = 37.353\%$$

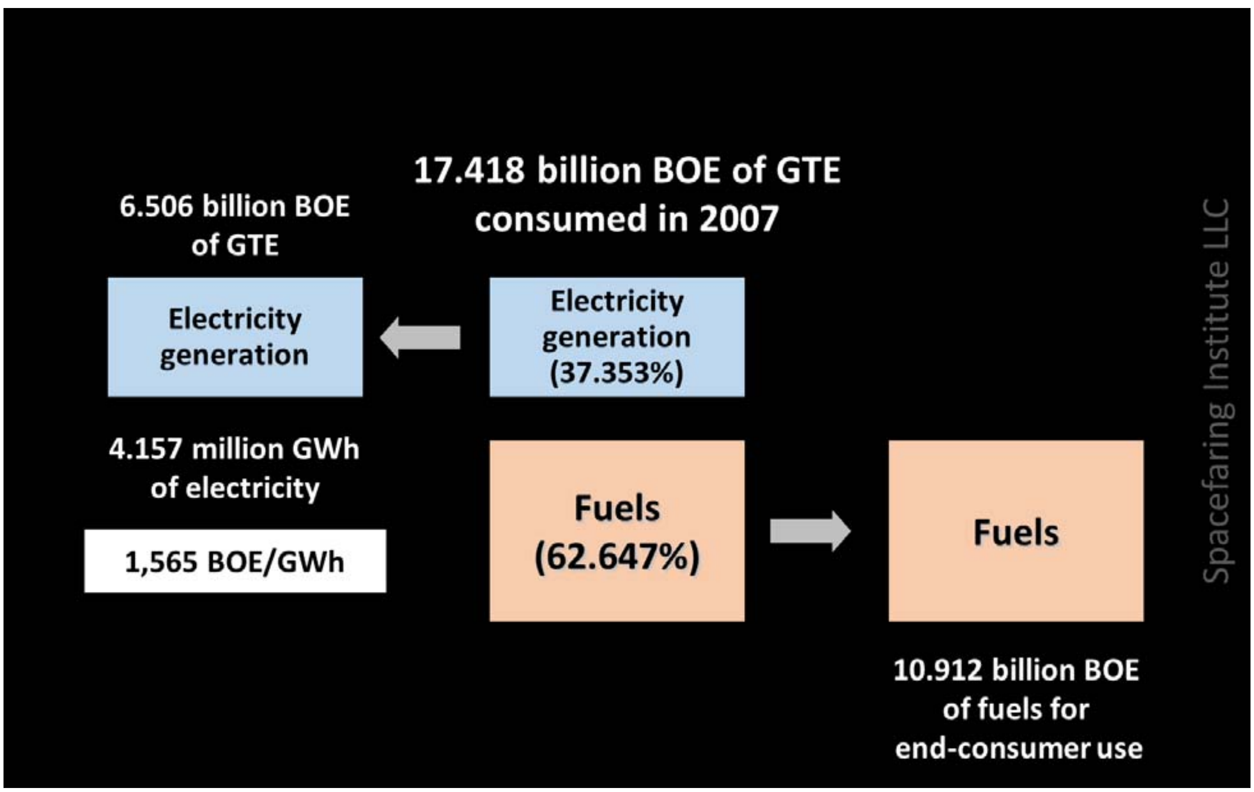
The quantity and percentage of the GTE consumed as fuels is determined.

$$GTE\_percentage_{fuels} := 1 - GTE\_percentage_{electrical} = 62.647\%$$

$$GTE\_consumed\_fuels\_2007_{US} := GTE\_percentage_{fuels} \cdot GTE\_consumed\_2007_{US}$$

$$GTE\_consumed\_fuels\_2007_{US} = \left(10.912 \cdot 10^{9}\right) BOE$$

This information is summarized in the following chart.



3.1.2 US per capita energy use in 2007

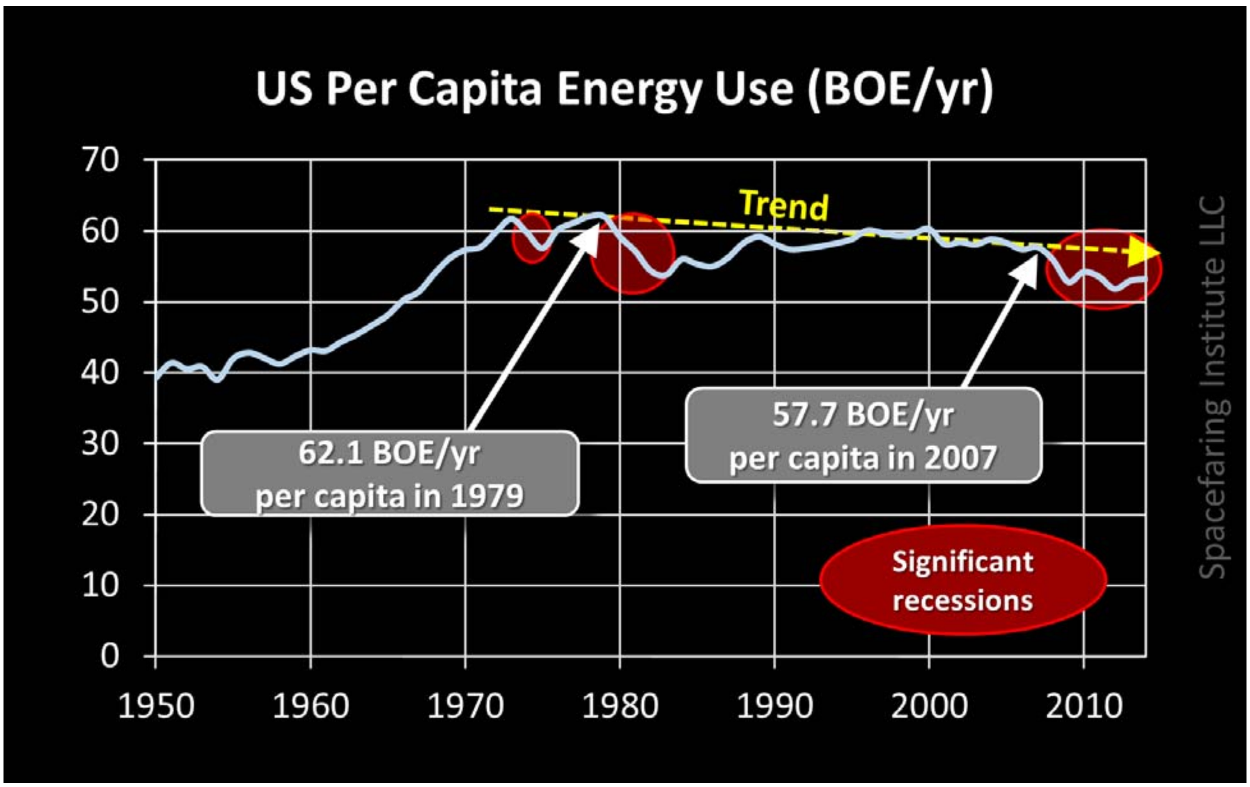
Ref: http://www.census.gov/popest/data/state/totals/2007/tables/NST-EST2007-01.xls

$$Population\_2007_{US} := 301621157$$

$$GTE\_per\_capita\_2007_{US} := \frac{GTE\_consumed\_2007_{US}}{Population\_2007_{US}} = 57.749\ BOE$$

3.2 US per capita GTE energy use 1950–2014

The chart below shows the US per capita GTE energy use from 1950–2014. The historic peak was in 1979 at 62.1 BOE/yr. The 2007 value was 57.7 BOE/yr. Periods of significant economic recession, when per capita energy use declines, as well as the long-term trend in declining per capita energy use are shown. Over the nearly thirty years from 1979–2007, the per capita energy use only declined by about 7 percent total or only about 0.25 per cent per year.



$GTE\_per\_capita\_1979_{US} := 62.1\ BOE$

$$\frac{GTE\_per\_capita\_1979_{US} - GTE\_per\_capita\_2007_{US}}{GTE\_per\_capita\_1979_{US}} = 7.006\%$$

$$\frac{GTE\_per\_capita\_1979_{US} - GTE\_per\_capita\_2007_{US}}{GTE\_per\_capita\_1979_{US} \cdot (2007 - 1979)} = 0.25\%$$

4. US energy needs in 2100

4.1 US per capita GTE use in 2100

For this analysis, the US per Capita GTE energy need is 2100 is assumed to be 50 BOE/yr. This would be a nearly twenty percent total reduction from the historic peak with an average annual decline of about 0.16 percent. While a further decline may be assumed, a rising standard of living, greater use of autonomous robotic systems, the need to build substantial new energy infrastructure and rebuild much of the nation's infrastructure, and the law of diminishing returns are assumed to moderate the total decline achieved by 2100.

$$GTE\_per\_capita\_2100_{US} := 50\ BOE$$

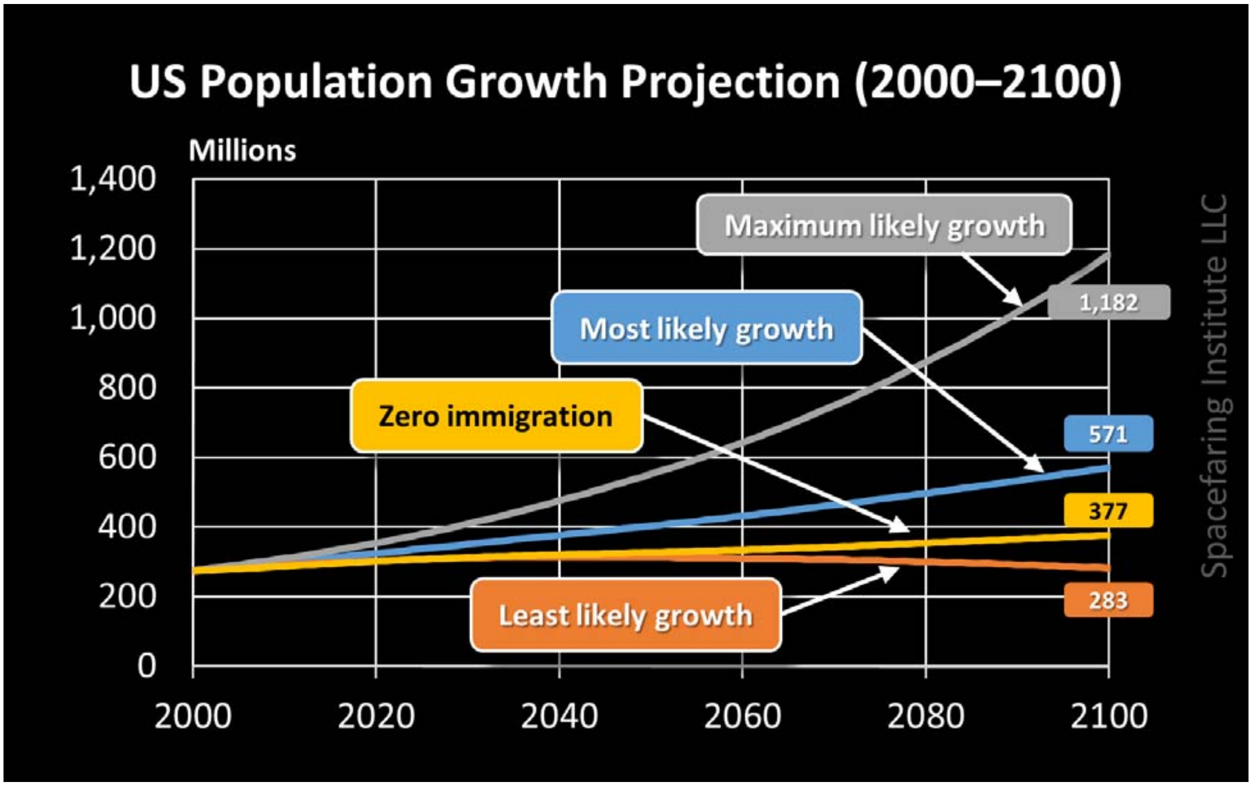
$$\frac{GTE\_per\_capita\_1979_{US} - GTE\_per\_capita\_2100_{US}}{GTE\_per\_capita\_1979_{US}} = 19.485\%$$

$$\frac{GTE\_per\_capita\_1979_{US} - GTE\_per\_capita\_2100_{US}}{GTE\_per\_capita\_1979_{US} \cdot (2100 - 1979)} = 0.161\%$$

4.2 US population in 2100

(Updated for Version 2)

In 1999, the US Census Bureau made projections of the US population to 2100. The fertility rate and death rate were varied to establish a least likely population, a maximum likely population, and a most likely population. In these three cases, international immigration was kept at the then current rates. A baseline projection for the case of zero international immigration was also done. These are shown in the following chart.



Ref: http://www.census.gov/population/projections/files/natproj/summary/np-t1.txt

In 2008, the US Census Bureau updated their projections through 2050 and a private company extended these to 2100. These values are relevant:

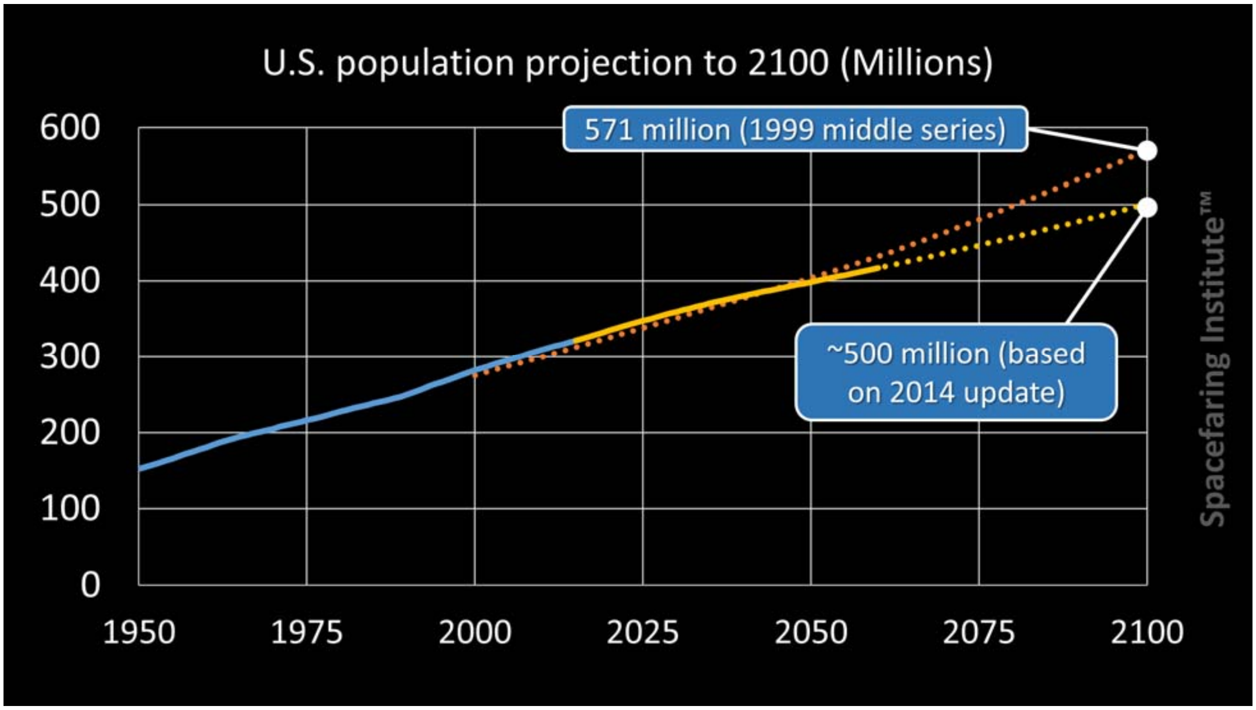
- With zero net immigration, the US population in 2100 will be about 343 million, up from 309 million in 2010. This is down from the 377 million in the 1999 projection.
- With the likely level of immigration, the US population in 2100 will be about 617.5 million, up from 309 million in 2010. This is up from the 571 million in the 1999 projection. This is highly influenced by immigration rates.

Ref: http://www.immigrationeis.org/eis-documents/us-demographic-projections-future

$$Population\_2100_{US\_zero\_immigration} := 343 \cdot 10^6$$

$$Population\_2100_{US\_likely\_immigration} := 617.5 \cdot 10^6$$

In 2014, the US Census Bureau updated their projections through 2060. Compared to the original 1999 projections, the near term population total was greater than the 1999 middle series projection, but fell below that earlier projection by 2060. This is shown in the chart below. (The solid yellow line shows the update 2014 projection. The dotted yellow line is a simple linear extension to 2100.)



By 2060, net immigration is projected, by the US Census Bureau to grow the US population at a rate 3.7 times that of natural population growth.

By 2100, the US population will be about 500 million. Additional calculations reflecting this updated value are added to the following analyses.

$$Population\_2100_{US\_2014\_update} := 500 \cdot 10^6$$

4.3 US GTE need in 2100

Using the population values above and the assumed per capita energy need in 2100, the total US GTE need in 2100 can be estimated.

$$GTE\_2100_{US\_zero\_immigration} := GTE\_per\_capita\_2100_{US} \cdot Population\_2100_{US\_zero\_immigration}$$

$$GTE\_2100_{US\_zero\_immigration} = \left(17.15 \cdot 10^{9}\right)\ BOE$$

$$GTE\_2100_{US\_likely\_immigration} := GTE\_per\_capita\_2100_{US} \cdot Population\_2100_{US\_likely\_immigration}$$

$$GTE\_2100_{US\_likely\_immigration} = \left(30.875 \cdot 10^{9}\right)\ BOE$$

$$GTE\_2100_{US\_2014\_update} := GTE\_per\_capita\_2100_{US} \cdot Population\_2100_{US\_2014\_update}$$

$$GTE\_2100_{US\_2014\_update} = \left(25.0000 \cdot 10^{9}\right)\ BOE$$

What is very interesting is that with zero net immigration, by 2100 the United States is likely to be consuming less energy than it did in 2007. However, with the likely level of immigration, the much larger US population will need about 77 percent more – with this increasing each year the population continues to grow.

$$\frac{GTE\_2100_{US\_likely\_immigration} - GTE\_consumed\_2007_{US}}{GTE\_consumed\_2007_{US}} = 77.255\%$$

4.4 US 2100 electrical energy and fuel needs

For this analysis, the electrical energy and fuel needs in 2100 will be scaled based on the ratio of the 2007 GTE consumed and 2100 GTE need.

Defining the unit GWh: $GWh := 1 \cdot 10^{9} \cdot W \cdot hr$

$$GWh_{2007} := 4156746 \cdot GWh$$

4.4.1 US zero net immigration case

$$GWh_{2100\_zero\_immigration} := GWh_{2007} \cdot \frac{GTE\_2100_{US\_zero\_immigration}}{GTE\_consumed\_2007_{US}} = 4092700.97\ GWh$$

$$Fuels_{2100\_zero\_immigration} := GTE\_consumed\_fuels\_2007_{US} \cdot \frac{GTE\_2100_{US\_zero\_immigration}}{GTE\_consumed\_2007_{US}}$$

$$Fuels_{2100\_zero\_immigration} = \left(10.744 \cdot 10^{9}\right)\ BOE$$

For the case of zero net immigration, the US sustainable energy needs in 2100 would be 4.1 million GWh of dispatched electrical energy and 10.7 billion BOE of hydrogen fuel. As noted, this is about the same as today and will be about constant with little population growth.

4.4.2 US most likely immigration case

$$GWh_{2100\_likely\_immigration} := GWh_{2007} \cdot \frac{GTE\_2100_{US\_likely\_immigration}}{GTE\_consumed\_2007_{US}} = 7368054.952\ GWh$$

$$Fuels_{2100\_likely\_immigration} := GTE\_consumed\_fuels\_2007_{US} \cdot \frac{GTE\_2100_{US\_likely\_immigration}}{GTE\_consumed\_2007_{US}}$$

$$Fuels_{2100\_likely\_immigration} = \left(19.342 \cdot 10^{9}\right)\ BOE$$

For the most likely net immigration case, the US sustainable energy needs in 2100 would be 7.4 million GWh and 19.3 billion BOE of hydrogen fuel. This value will still be increasing each year as the US population will continue to grow.

4.4.3 US 2100 population based on US Census Bureau 2014 update

$$GWh_{2100\_2014\_update} := GWh_{2007} \cdot \frac{GTE\_2100_{US\_2014\_update}}{GTE\_consumed\_2007_{US}} = 5966036.399\ GWh$$

$$Fuels_{2100\_2014\_update} := GTE\_consumed\_fuels\_2007_{US} \cdot \frac{GTE\_2100_{US\_2014\_update}}{GTE\_consumed\_2007_{US}}$$

$$Fuels_{2100\_2014\_update} = \left(15.662 \cdot 10^{9}\right)\ BOE$$

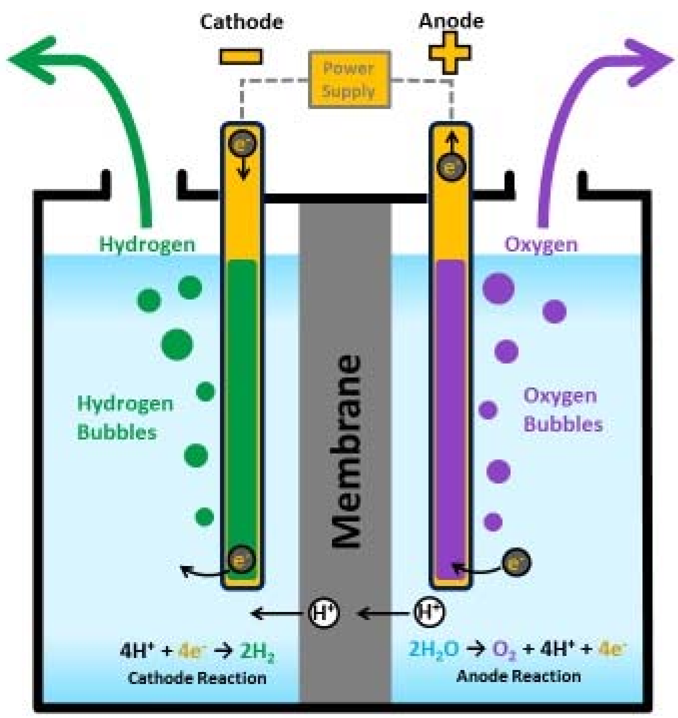
Using the 500 million likely US 2100 population, based on the 2014 US Census Bureau population projection to 2060, the US sustainable energy needs in 2100 would be 6.0 million GWh and 15.7 billion BOE of hydrogen fuel. This value will still be increasing each year as the US population will continue to grow.

5. Future hydrogen production energy requirements and costs

For the conversion to a sustainable energy infrastructure, the hydrogen will be produced via electrolysis using electrical power supplied by a sustainable source – either nuclear or renewable energy sources.

In this simple analysis, it is assumed that the hydrogen will be used directly. It is expected that most of this hydrogen will be converted into synthetic oil and methane by combining the hydrogen with carbon extracted from carbon dioxide (CO2) in the atmosphere. This will require additional sustainable electrical power. Combustion of the oil and methane will return the carbon to the atmosphere as CO2 enabling the carbon to be recycled continuously. While research for energy efficient methods to achieve this is underway, for this analysis all hydrogen is assumed to be used directly.

5.1 Hydrogen production by electrolysis



Water electrolysis illustration.
(Source: US Department of Energy, public domain image.

Unlike other thermal fuels, hydrogen fuel can be easily created by passing electricity through water causing the molecular bonds to break, liberating hydrogen and oxygen. This is called electrolysis. By capturing the hydrogen, electricity is converted into a useful thermal fuel to take the place of traditional fossil fuels. As long as sustainable electricity is available and water is available, hydrogen as a sustainable fuel can be produced.

5.2 Hydrogen fuel heating values

As hydrogen is a gas at room temperature, its quantity is normally measured in terms of its weight (lb) or mass (kg). (Note that whether the hydrogen is a gas or a cryogenic liquid, its energy content per lb or kg is the same.)

The U.S. Department of Energy's Hydrogen Analysis Resources Center provides these thermal heating values for hydrogen:

$$LHV_{hydrogen} := 51682 \cdot \frac{Btu}{lb} = \left(113.939 \cdot 10^{3}\right) \frac{Btu}{kg}$$

$$HHV_{hydrogen} := 61127 \cdot \frac{Btu}{lb} = \left(134.762 \cdot 10^{3}\right) \frac{Btu}{kg}$$

Recall that a BOE was previously defined as having 5.8 million Btu. The heating values of hydrogen can be used to calculate the number of lb or kg of hydrogen required to yield 1 BOE of thermal energy.

$$Weight\_BOE_{H2\_LHV} := \frac{BOE}{LHV_{hydrogen}} = 112.225\ lb \qquad Weight\_BOE_{H2\_LHV} = 50.904\ kg$$

$$Weight\_BOE_{H2\_HHV} := \frac{BOE}{HHV_{hydrogen}} = 94.884\ lb \qquad Weight\_BOE_{H2\_HHV} = 43.039\ kg$$

To understand subsequent discussions, it's important to address the difference between the Lower Heating Value (LHV) and the Higher Heating Value (HHV) shown above.

When combustion occurs, the maximum useful work that can be produced from the heat and pressure created by the combustion is when the final exhaust gas temperature and pressure falls to ambient conditions. Under these ideal conditions, the energy content of the fuel is its Higher Heating Value. Under typical combustion conditions, when the exhaust gas temperature is still somewhat hot—such as coming out of the car exhaust—the energy content of the fuel is its Lower Heating Value. For most carbon fuels, the difference between these two values is small and is ignored. For hydrogen, the difference is about 18 percent and must be taken into account when estimating how much electricity will be needed to produce the hydrogen. To produce 1 BOE of hydrogen fuel for a LHV use, such as transportation, requires about 18 percent more input electrical energy than producing 1 BOE of hydrogen fuel for a HHV use.

5.3 Electrolysis energy requirement

Ref: https://www.hydrogen.energy.gov/pdfs/progress13/ii_a_2_harrison_2013.pdf

The US Department of Energy has established, for 2020, a MW-class electrolyzer system goal of 44.7 kWh per kg of LHV hydrogen. At this value, the system would be 75 percent efficient meaning that 75 percent on the input electrical energy is converted to hydrogen chemical energy, when used at LHV conditions, while 25 percent is lost through waste heat. This target value will be used in this analysis.

Defining the unit kWh: $kWh := kW \cdot hr$

$$kWh_{electrolyzer} := 44.7 \cdot \frac{kWh}{kg} = 20.276\ \frac{kWh}{lb}$$

(Note: Current experimental electrolyzes are operating in the range of 54–65 kWh/kg. This provides an indication of the degree of improvement needed to achieve the target value.)

5.4 Hydrogen compressor energy requirement

Ref: https://hydrogendoedev.nrel.gov/pdfs/progress09/iii_5_dibella.pdf
Ref: http://www.nrel.gov/docs/fy14osti/58564.pdf

Hydrogen gas has a very low density at room temperature, thus, it's very inefficient to store it at room pressure. Hydrogen can be chilled to -423 °F where it will condense into a liquid. This requires an additional 11-15 kWh per kg of hydrogen and requires very well insulated storage tanks to keep it a liquid.

For a national hydrogen fuel infrastructure, the hydrogen will be compressed to 1200 psi and sent into a national hydrogen pipeline infrastructure. With advanced turbocompressors (80 percent efficient), 10,000 kg per hour can be compressed using 6,300 kWh or 0.63 kWh/kg.

Hydrogen fuel will be used for a variety of applications, one of which is a transportation fuel as a compressed gas. This requires compression to as high as 10,000 psia to achieve sufficient fuel storage to provide a reasonable vehicle range. The very preliminary estimate of the energy cost of this final compression ranges from 1.6 kWh/kg to 18 kWh/kg. In addition to the 0.63 kWh/kg to compress the hydrogen to about 1200 psi to enter the pipeline infrastructure, reflecting that only a portion of the hydrogen will be used for transportation, an additional 1 kWh/kg is assumed to compress the hydrogen to approximately 10,000 psi for transportation use.

(Note that only a portion of the hydrogen fuel will be used for transportation and will require this additional compression. Also note that the energy required to periodically repressurize the hydrogen in the pipeline is assumed to be already accounted for in the historical energy consumption data.

$$kWh_{H2\_compressor\_6000\_psi} := 1.63 \cdot \frac{kWh}{kg} = 0.739\ \frac{kWh}{lb}$$

5.5 Electrical energy required per BOE of hydrogen fuel (LHV)

$$kWh_{H2\_LHV} := \frac{Weight\_BOE_{H2\_LHV}}{BOE} \cdot \left(kWh_{electrolyzer} + kWh_{H2\_compressor\_6000\_psi}\right)$$

$$kWh_{H2\_LHV} = 2358.396\ \frac{kWh}{BOE}$$

5.6 Electrical energy required per BOE of hydrogen fuel (HHV)

While the general use of hydrogen as a fuel will yield its LHV per lb or kg, in some cases its use will yield the HHV per lb of kg. As discussed above, it takes fewer lb or kg of hydrogen, combusted under the HHV conditions, to yield 1 BOE of useful thermal energy. The electrolyzer and compressor don't know how the hydrogen will be used. Thus, to compute the input electrical energy required per BOE of hydrogen (HHV), only the weight of the hydrogen per BOE changes. The energy savings to produce the hydrogen is about 18 percent, as mentioned earlier.

$$kWh_{H2\_HHV} := \frac{Weight\_BOE_{H2\_HHV}}{BOE} \cdot \left(kWh_{electrolyzer} + kWh_{H2\_compressor\_6000\_psi}\right)$$

$$kWh_{H2\_HHV} = 1993.99\ \frac{kWh}{BOE}$$

Additional percentage of electrical energy needed to produce 1 BOE (LHV) vs. 1 BOE (HHV):

$$\frac{kWh_{H2\_LHV}}{kWh_{H2\_HHV}} - 1 = 18.275\%$$

5.7 Hydrogen electrolyzer costs

Ref: https://www.hydrogen.energy.gov/pdfs/14004_h2_production_cost_pem_electrolysis.pdf

The cited reference US DOE report predicts the future capital cost of electrolyzer plants, using 2012$, at $400/kW – down from about $900/kW currently. These plants are expected to have a useful life of 40 years.

Define the unit $: $\$:= ¤$

$$Cost_{electrolyzer} := 400\ \frac{\$}{kW}$$

5.8 Hydrogen compressor costs

Ref:

1. https://hydrogendoedev.nrel.gov/pdfs/progress09/iii_5_dibella.pdf
2. https://www.hydrogen.energy.gov/pdfs/progress14/iii_9_dibella_2014.pdf

The US DOE-developed hydrogen pipeline compressor project ended in 2014. The final report indicated that the expected cost for a 10,000 kg/hr unit was about $6 million. This unit consumed 6300 kW of electrical power for an installed cost of about $600 per kg per hour.

$$Cost_{compressor} := \frac{6000000}{10000} \frac{\$}{\frac{kg}{hr}}$$

6. Nuclear power

6.1 Advanced nuclear power plants

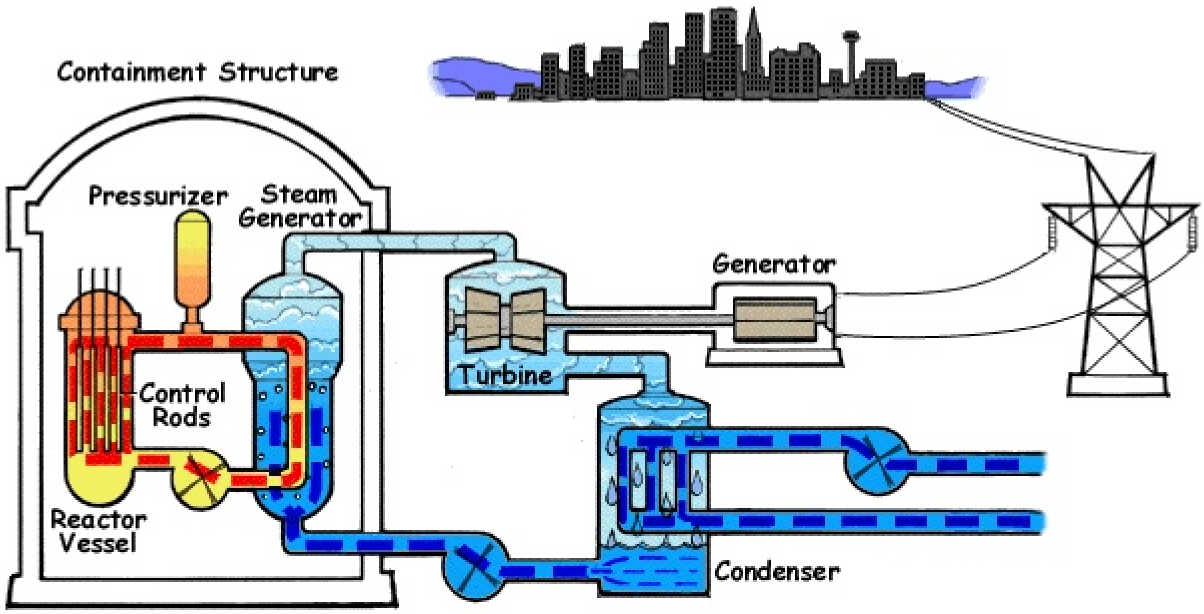


Diagram of a typical uranium fission nuclear power plant.
(Source: US Government, public domain image.)

Nuclear power is one possible replacement for fossil fuels. In this plant, the reactor vessel contains the uranium that undergoes fission. The released nuclear energy becomes thermal energy within the reactor vessel heating water. This hot water is pumped through a boiler where it heats a second flow of water to produce steam. (The original water flow returns to the reactor vessel.) The steam passes through a turbine to produce the mechanical power that drives the generator generating electrical power. This approach is about 30 percent efficient in converting the nuclear energy into electrical power. The remaining energy is waste heat.

6.1.1 GWh per plant year

Nuclear power plants are intended to operate at full power continuously. This is called baseload power. Older plants were online about 80 percent of the year. The downtime was to conduct periodic maintenance and to refuel the plant about every 18 months. For this analysis, the new generation of plants now being built are expected to be online about 95 percent of the time.

A modern 1-GW nuclear power plant, typical for the size being built, will produce 8,322 GWh of electrical energy per year.

Define the unit GW: $GW := 1000000 \cdot kW$

$$Plant\_year_{1\_GW} := 365 \cdot day \cdot 24 \cdot \frac{hr}{day} \cdot 0.95 \cdot 1 \cdot GW = 8322\ GWh$$

6.1.2 Nuclear plant overnight capital cost estimate

The US Department of Energy provides estimates of the capital and operating costs for power plants. The capital costs reflect the nameplate generation capacity.

Ref:

1. http://www.eia.gov/forecasts/capitalcost/
2. http://www.eia.gov/forecasts/capitalcost/xls/table1.xls

	Plant Characteristics		Plant Costs (2012$)		
	Nominal Capacity (MW)	Heat Rate (Btu/kWh)	Overnight Capital Cost ($/kW)	Fixed O&M Cost ($/kW-yr)	Variable O&M Cost ($/MWh)
Coal					
Single Unit Advanced PC	650	8,800	$3,246	$37.80	$4.47
Dual Unit Advanced PC	1,300	8,800	$2,934	$31.18	$4.47
Single Unit Advanced PC with CCS	650	12,000	$5,227	$80.53	$9.51
Dual Unit Advanced PC with CCS	1,300	12,000	$4,724	$66.43	$9.51
Single Unit IGCC	600	8,700	$4,400	$62.25	$7.22
Dual Unit IGCC	1,200	8,700	$3,784	$51.39	$7.22
Single Unit IGCC with CCS	520	10,700	$6,599	$72.83	$8.45
Natural Gas					
Conventional CC	620	7,050	$917	$13.17	$3.60
Advanced CC	400	6,430	$1,023	$15.37	$3.27
Advanced CC with CCS	340	7,525	$2,095	$31.79	$6.78
Conventional CT	85	10,850	$973	$7.34	$15.45
Advanced CT	210	9,750	$676	$7.04	$10.37
Fuel Cells	10	9,500	$7,108	$0.00	$43.00
Uranium					
Dual Unit Nuclear	2,234	N/A	$5,530	$93.28	$2.14
Biomass					
Biomass CC	20	12,350	$8,180	$356.07	$17.49
Biomass BFB	50	13,500	$4,114	$105.63	$5.26

Wind					
Onshore Wind	100	N/A	$2,213	$39.55	$0.00
Offshore Wind	400	N/A	$6,230	$74.00	$0.00
Solar					
Solar Thermal	100	N/A	$5,067	$67.26	$0.00
Photovoltaic	20	N/A	$4,183	$27.75	$0.00
Photovoltaic	150	N/A	$3,873	$24.69	$0.00
Geothermal					
Geothermal – Dual Flash	50	N/A	$6,243	$132.00	$0.00
Geothermal – Binary	50	N/A	$4,362	$100.00	$0.00
Municipal Solid Waste					
Municipal Solid Waste	50	18,000	$8,312	$392.82	$8.75
Hydroelectric					
Conventional Hydroelectric	500	N/A	$2,936	$14.13	$0.00
Pumped Storage	250	N/A	$5,288	$18.00	$0.00

Note: These costs are based on the nameplate generating capacity. The actual capacity factor and dispatchability of each type of plant needs to be taken into account when comparing costs.

To explain these cost estimates, the following is quoted from the above cited reference:

Developing updated estimates: key design considerations

The focus of the 2013 update was to gather current information on the "overnight" construction costs, operating costs, and performance characteristics for a wide range of generating technologies. The estimates were developed through costing exercises, using a common methodology across technologies. Comparing cost estimates developed on a similar basis using the same methodology is of particular importance to ensure modeling consistency.

Each technology is represented by a generic facility of a specific size and configuration, in a location that does not have unusual constraints or infrastructure requirements. Where possible, costs estimates were based on information derived from actual or planned projects known to the consultant. When this information was not available, the project costs were estimated using costing models that account for the current labor and materials rates necessary to complete the construction of a generic facility as well as consistent assumptions for the contractual relationship between the project owner and the construction contractor.

The specific overnight costs for each type of facility were broken down to include:

- **Civil and structural costs:** allowance for site preparation, drainage, the installation of underground utilities, structural steel supply, and construction of buildings on the site
- **Mechanical equipment supply and installation:** major equipment, including but not limited to, boilers, flue gas desulfurization scrubbers, cooling towers, steam turbine generators, condensers, photovoltaic modules, combustion turbines, and other auxiliary equipment

- **Electrical and instrumentation and control:** electrical transformers, switchgear, motor control centers, switchyards, distributed control systems, and other electrical commodities
- **Project indirect costs**: engineering, distributable labor and materials, craft labor overtime and incentives, scaffolding costs, construction management start up and commissioning, and fees for contingency
- **Owners costs:** development costs, preliminary feasibility and engineering studies, environmental studies and permitting, legal fees, insurance costs, property taxes during construction, and the electrical interconnection costs, including a tie-in to a nearby electrical transmission system

Non-fuel operations and maintenance (O&M) costs associated with each of the power plant technologies were evaluated as well. The O&M costs that do not vary significantly with a plant's electricity generation are classified as fixed, while the costs incurred to generate electricity are classified as variable. The heat rates were also evaluated for the appropriate technologies.

EIA's analysis of technology choice in the electric power sector

EIA's modeling employs a net present value (NPV) capital budgeting methodology to evaluate different investment options for new power plants. Estimates of the overnight capital cost, fixed and variable operations and maintenance costs, and plant heat rates for generic generating technologies serve as a starting point for developing the total cost of new generating capacity. However, other parameters also play a key role in determining the total capital costs. Because several of these factors are dynamic, the realized overall capital cost for given technologies can vary based on a variety of circumstances. Five of the most notable parameters are:

- **Financing:** EIA determines the cost of capital required to build new power plants by calculating a weighted average cost of capital using a mix of macro-economic parameters determined through EIA's modeling and an assumed capital structure for the electric power industry.
- **Lead Time:** The amount of time needed to build a given type of power plant varies by technology. Projects with longer lead times increase financing costs. Each year of construction represents a year of additional interest charges before the plant is placed in service and starts generating revenue.
- **Inflation of material and construction costs:** The projected relationship between the rate of inflation for the overall economy and key drivers of plant costs, such as materials and construction, are important elements impacting overall plant costs. A projected economy-wide inflation rate that exceeds the projected inflation rate for materials and construction costs results in a projected decline in real (inflation-adjusted) capital costs and vice versa.

- **Resource Supply:** Technologies such as wind, geothermal, or hydroelectric must be sited in suitable locations to take advantage of the particular resource. In order to capture the site specific costs associated with these technologies, EIA develops upward sloping supply curves for each of these technologies. These curves assume that the lowest-cost, most-favorable resources will be developed first, and that costs associated with the technology will increase as only higher-cost, less-favorable sites are left to be developed.
- **Learning by doing:** The overnight capital costs developed for the report serve as an input to EIA's long term modeling and represent the cost of construction for a project that could begin as early as 2013. However, these costs are assumed to decrease over time in real terms as equipment manufacturers, power plant owners, and construction firms gain more experience with certain technologies. The rate at which these costs decline is often referred to as the learning rate.

As the purpose of this analysis is to provide a ballpark cost estimate, while these five additional factors are noted, they are not included.

In addition to the overnight capital cost of the plant, an additional cost of $1000/kW is assumed for land purchase for the plant and pipeline and transmission right-of-way, building the transmission lines to link the plant with the power grid, building the pipeline to connect to the national hydrogen pipeline network, building the hydrogen electrolyzer plant, installing the hydrogen compressors and local hydrogen storage, and installing the initial fuel load.

$$Cost_{nuclear\_2012} := 5530 \cdot \frac{\$}{kW} + 1000 \cdot \frac{\$}{kW} = 6530 \ \frac{\$}{kW}$$

The components of all power plants age and either need replacing or, such as the fundamental concrete and steel structure, must be retired. Modern nuclear power plants are expected to have a life of over 100 years where almost all of the internal components are replaced as needed based on inspection results and engineering predictions of the useful safe life. This is the way the life of commercial airliners are managed. When the life of the fundamental structure is reached, the plant would be closed.

6.1.3 LHV hydrogen produced per plant-year

$$H\_production_{1\_GW\_nuclear} := \frac{\frac{Plant\_year_{1\_GW}}{yr}}{kWh_{H2\_LHV}} \cdot \frac{Weight\_BOE_{H2\_LHV}}{BOE}$$

$$H\_production_{1\_GW\_nuclear} = \left(20.491 \cdot 10^{3}\right) \ \frac{kg}{hr}$$

6.1.4 Cost of hydrogen electrolysis and compression

Using the earlier estimates, for a 1-GW nuclear power plant the initial electrolyzer cost will be about $400 million and the cost of the pipeline compressors will be about $12 million. These costs are assumed to be included in the additional $1000/kW addressed above.

$$Cost_{electrolyzer} \cdot 1 \cdot GW = \left(400 \cdot 10^{6}\right)\ \$$$

$$Cost_{compressor} \cdot H\_production_{1\_GW\_nuclear} = \left(12.295 \cdot 10^{6}\right)\ \$$$

It is expected that each electrolyzer plant will include a limited local storage capacity to enable the hydrogen supply to the pipeline to be maintained during a temporary shutdown of the nuclear power plant or hydrogen production equipment. This may be stored as liquid hydrogen or placed in high pressure gas storage. The cost of this storage is not explicitly estimated but is assumed to be included in the $1000/kW addressed above.

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

6.2.1 US 2100 zero net immigration case

To meet the energy needs of the 343 million in 2100, a total of 3,537 1-GW nuclear power plants would need to be operating. Each 1-GW plant would support 96,324 people.

As determined earlier:

$$Population\_2100_{US\_zero\_immigration} = 343 \cdot 10^{6}$$

$$GWh_{2100\_zero\_immigration} = \left(4.093 \cdot 10^{6}\right)\ GWh$$

$$Fuels_{2100\_zero\_immigration} = \left(10.744 \cdot 10^{9}\right)\ BOE$$

$$Plants\_el\_2100_{US\_zero\_pop} := \frac{GWh_{2100\_zero\_immigration}}{Plant\_year_{1\_GW}} = 492$$

$$Plants\_fuel\_2100_{US\_zero\_imm} := \frac{Fuels_{2100\_zero\_immigration} \cdot kWh_{H2\_LHV}}{Plant\_year_{1\_GW}} = 3045$$

$$Plants\_total\_2100_{US\_zero\_immigration} := Plants\_el\_2100_{US\_zero\_pop} + Plants\_fuel\_2100_{US\_zero\_imm}$$

$$Plants\_total\_2100_{US\_zero\_immigration} = 3537$$

Determine how many people each 1-GW plant will support:

$$\frac{Population\_2100_{US\_zero\_immigration}}{Plants\_total\_2100_{US\_zero\_immigration}} = 96986$$

For the US zero immigration case, the cost of building the 3,547 1-GW nuclear power plants would be roughly $23 trillion.

$$Plants\_total\_2100_{US\_zero\_immigration} \cdot Cost_{nuclear\_2012} \cdot 1 \cdot GW = \left(23.094 \cdot 10^{12}\right)\ \$$$

6.2.2 US 2100 most likely immigration case

To meet the energy needs of the 617.5 million in 2100, a total of 6,411 1-GW nuclear power plants would need to be operating – 2,850 more than the zero net immigration case.

As determined earlier:

$$Population\_2100_{US\_likely\_immigration} = 617.5 \cdot 10^{6}$$

$$GWh_{2100\_likely\_immigration} = \left(7.368 \cdot 10^{6}\right)\ GWh$$

$$Fuels_{2100\_likely\_immigration} = \left(19.342 \cdot 10^{9}\right)\ BOE$$

$$Plants\_el\_2100_{US\_likely\_imm} := \frac{GWh_{2100\_likely\_immigration}}{Plant\_year_{1\_GW}} = 885$$

$$Plants\_fuel\_2100_{US\_likely\_imm} := \frac{Fuels_{2100\_likely\_immigration} \cdot kWh_{H2\_LHV}}{Plant\_year_{1\_GW}} = 5481$$

$$Plants\_total\_2100_{US\_likely\_imm} := Plants\_el\_2100_{US\_likely\_imm} + Plants\_fuel\_2100_{US\_likely\_imm}$$

$$Plants\_total\_2100_{US\_likely\_imm} = 6367$$

$$Plants\_total\_2100_{US\_likely\_imm} - Plants\_total\_2100_{US\_zero\_immigration} = 2830$$

$$\frac{Population\_2100_{US\_likely\_immigration}}{Plants\_total\_2100_{US\_likely\_imm}} = 96986$$

For the US most likely immigration case, the cost of building the 6,367 1-GW nuclear power plants would be roughly $42 trillion – an additional $19 trillion over the zero immigration case.

$$Plants\_total\_2100_{US\_likely\_imm} \cdot Cost_{nuclear\_2012} \cdot 1 \cdot GW = \left(41.576 \cdot 10^{12}\right)\ \$$$

6.2.3 US 2100 population based on 2014 US Census Bureau update

To meet the energy needs of the 500 million in 2100, a total of 6,411 1-GW nuclear power plants would need to be operating – 2,850 more than the zero net immigration case.

As determined earlier:

$$Population\_2100_{US\_2014\_update} = 500 \cdot 10^{6}$$

$$GWh_{2100\_2014\_update} = \left(5.966 \cdot 10^{6}\right)\ GWh$$

$$Fuels_{2100\_2014\_update} = \left(15.662 \cdot 10^{9}\right)\ BOE$$

$$Plants\_el\_2100_{US\_2014\_update} := \frac{GWh_{2100\_2014\_update}}{Plant\_year_{1\_GW}} = 717$$

$$Plants\_fuel\_2100_{US\_2014\_update} := \frac{Fuels_{2100\_2014\_update} \cdot kWh_{H2\_LHV}}{Plant\_year_{1\_GW}} = 4438$$

$$Plants\_total\_2100_{US\_2014\_update} := Plants\_el\_2100_{US\_2014\_update} + Plants\_fuel\_2100_{US\_2014\_update}$$

$$Plants\_total\_2100_{US\_2014\_update} = 5155$$

$$\frac{Population\_2100_{US\_2014\_update}}{Plants\_total\_2100_{US\_2014\_update}} = 96986$$

For the US 2100 population, based on the US Census Bureau 2014 update, the cost of building the 5,155 1-GW nuclear power plants would be roughly $34 trillion.

$$Plants\_total\_2100_{US\_2014\_update} \cdot Cost_{nuclear\_2012} \cdot 1 \cdot GW = \left(33.665 \cdot 10^{12}\right)\ \$$$

7. Wind power

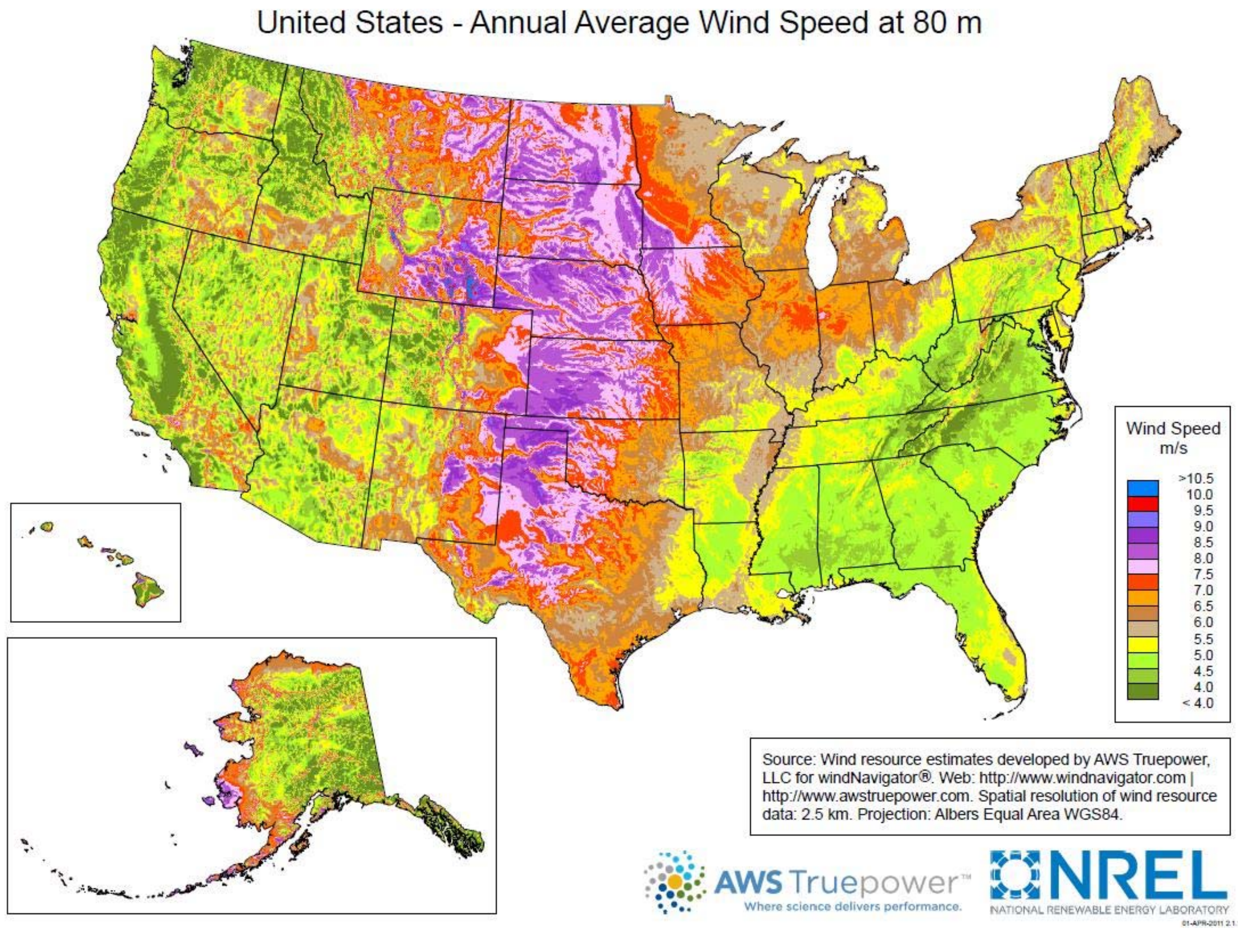
7.1 Wind power fundamentals

Wind farm in New York.
(Source: Michael Okoniewski, National Renewable Energy Laboratory, no restriction on use.)

Wind power is a form of solar energy. Sunlight and darkness, combined with the spinning of the Earth, create areas of the atmosphere with different densities. These differences cause air to move from regions of higher density to regions of lower density to reestablish equilibrium. This movement of the air is the wind.

A wind turbine uses its blades to intercept the moving air and extract power from the air, slowing the air down. The amount of power available to be extracted depends on the wind speed. When there is too little or too high wind speed, the wind turbine cannot extract any power because the wind cannot spin the blades or the blades would spin too fast causing damage. Only under certain wind conditions will a wind turbine produce its design or *nameplate* power output. Most of the time it is producing less than its design power output or no power at all.

Due to geography and seasonal weather patterns, some parts of the country have better wind power conditions than other parts. The map below illustrates the wind power potential in the continental U.S.



U.S. wind power map at a hub height of 80 m (262 ft).
(Source: National Renewable Energy Laboratory, no known restriction on publication.)

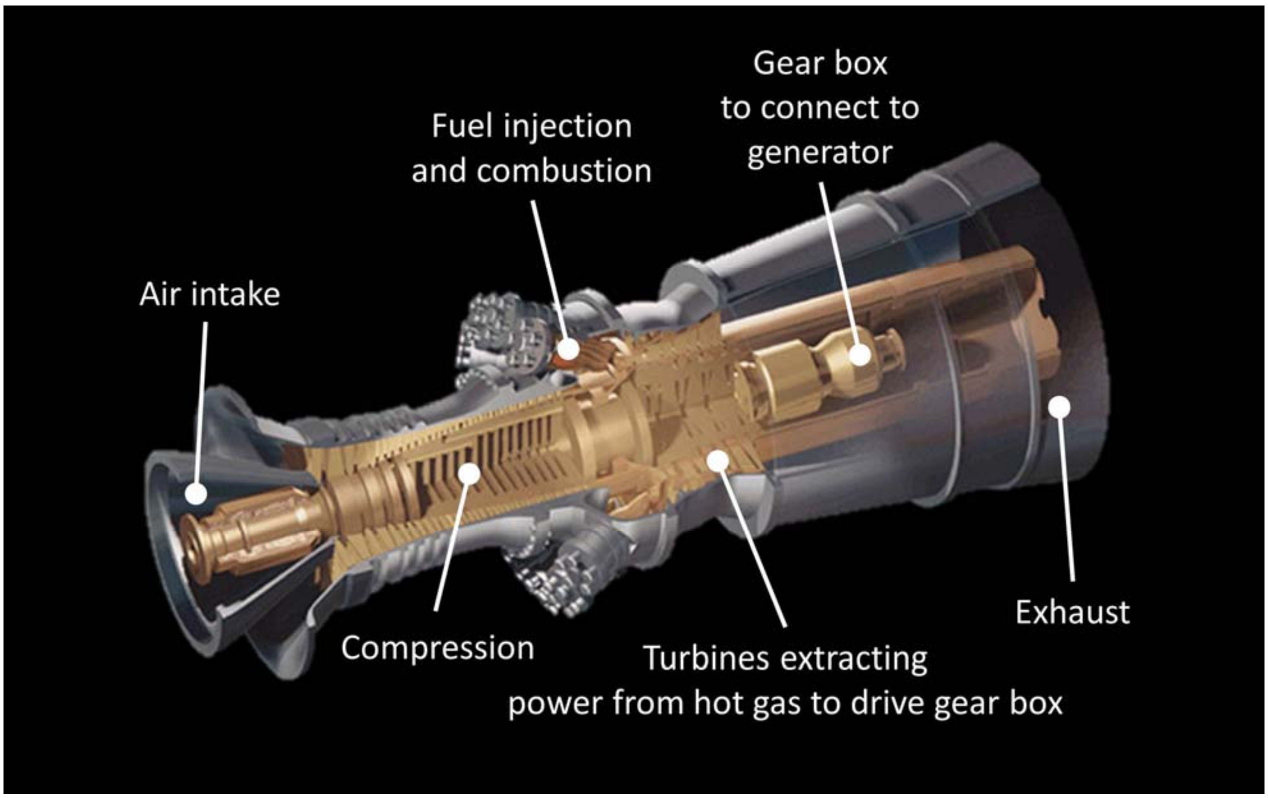
The wind's velocity increases with height above the ground. At the altitudes airliners fly, the wind speed may be well over a hundred miles per hour. Thus, the taller the wind turbine's hub, the greater wind power potential that can be accessed. Every doubling of the wind speed increases the available wind power by a factor of eight.

Until recently, hub heights of 80 m (262 ft), up from 50 m (164 ft) were the industry standard. As the above map shows, at this hub height, the U.S. has a broad band of good wind power potential down the center of the country. These are the areas in blue, purple, red, and orange. The rest of the country in green and yellow zones, where most people live, has low wind power potential that is not economical to tap.

Industry is now looking at wind turbines with 100 m (328 ft) hub heights and even taller. A 100-m turbine's blades will reach nearly 500 ft above the ground. These are immense machines far higher than the 80-m turbines shown in the above photograph. The 80-m turbines have a design power output of 1.65 MW. The 100-m turbines – taller with longer blades – will be in the range of 2.5 MW.

7.1.1 Inability to directly use wind-generated electrical power

Electricity supplied by an electric utility to the consumer is referred to as “dispatchable”. It takes less than a second for the electricity produced by a generator to travel through the transmission and distribution system to reach the end consumer. Every time each consumer turns on an electrical appliance, a feedback signal is sent through the system placing additional demand on the generator for power. Every time the appliance is turned off, the reverse happens. The utility monitors these changes in demand automatically, from hundreds of thousands of consumers, to adjust the settings on the generators to maintain the delivery of high-quality electricity. The utility also uses special methods to anticipate changes in demand, such as time of day and the weather, to prepare for sudden demand increases. When added capacity is needed, additional generators are brought into operation so that their generation capacity can be added when needed. The ready availability of nuclear and fossil fuel powerplants, such as gas turbines, to provide dispatchable power enables our electric utilities to provide high-quality electricity literally at the flip of a switch.



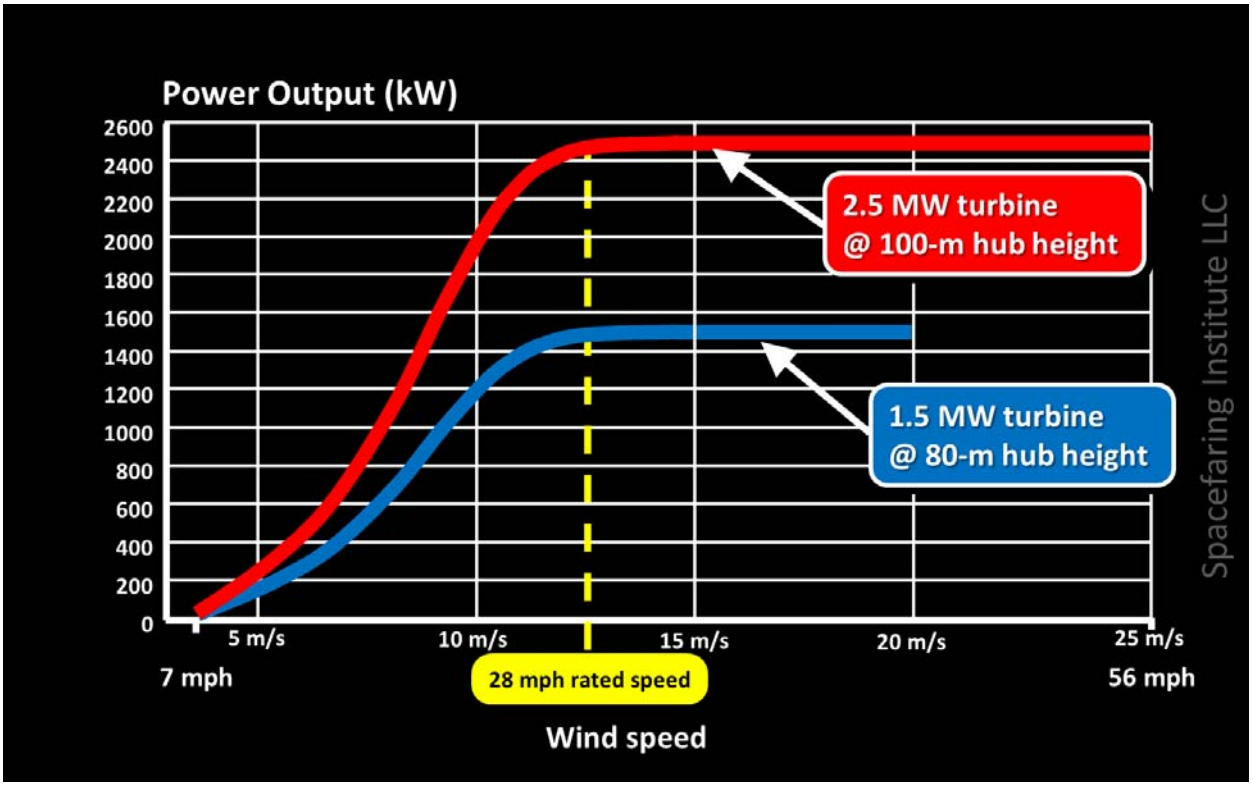
Cut-away view of a gas turbine used to drive an electrical generator.
(Original graphic source: U.S. Government, Wikimedia, public domain image.)

The generation of high-quality electricity is not simply. The utility provides alternative current electricity. In the U.S. the cycle rate is 60 cycles per second. This doesn’t mean somewhere around 60 cycles per second, but usually within 0.05 cycles/sec.

For traditional generators, the rotational speed of the generator is controlled to produce the 60 cycles per second alternative current. Every time an additional demand is placed on a generator – turning on a light in your home, for example—the spinning generator wants to slow down just a bit just as your car engine does when starting up a hill. The generator control system senses this and increases the input mechanical power to compensate. When multiple generators are feeding the same distribution system, they all have to work together properly to maintain the synchronized high-quality electricity. The more generators involved makes this more difficult to manage.

Each wind turbine is a generator but one where the input mechanical power—the wind—is highly variable and unpredictable. Even in wind farms, the actual wind conditions at each each turbine varies due to location in the farm, terrain, wind direction, weather conditions, turbulence from upwind turbines, etc. This all makes producing high-quality, dispatchable electricity using wind-electricity very challenging with the complexity increasing as the percentage of electricity coming from the wind turbines increases. For this reason, the percentage of the supplied wind power is limited to only a small percentage of the total online generation capacity. The more predictable nuclear, fossil fuel, and hydroelectric generators are used to “smooth out” quality variations in the wind-electricity and to also provide stand-by generation capacity to fill in for drop-offs in available wind-electricity. The key point is that the variability of the wind makes planning for its direct use difficult, as the real-life experiences discussed in the following illustrate.

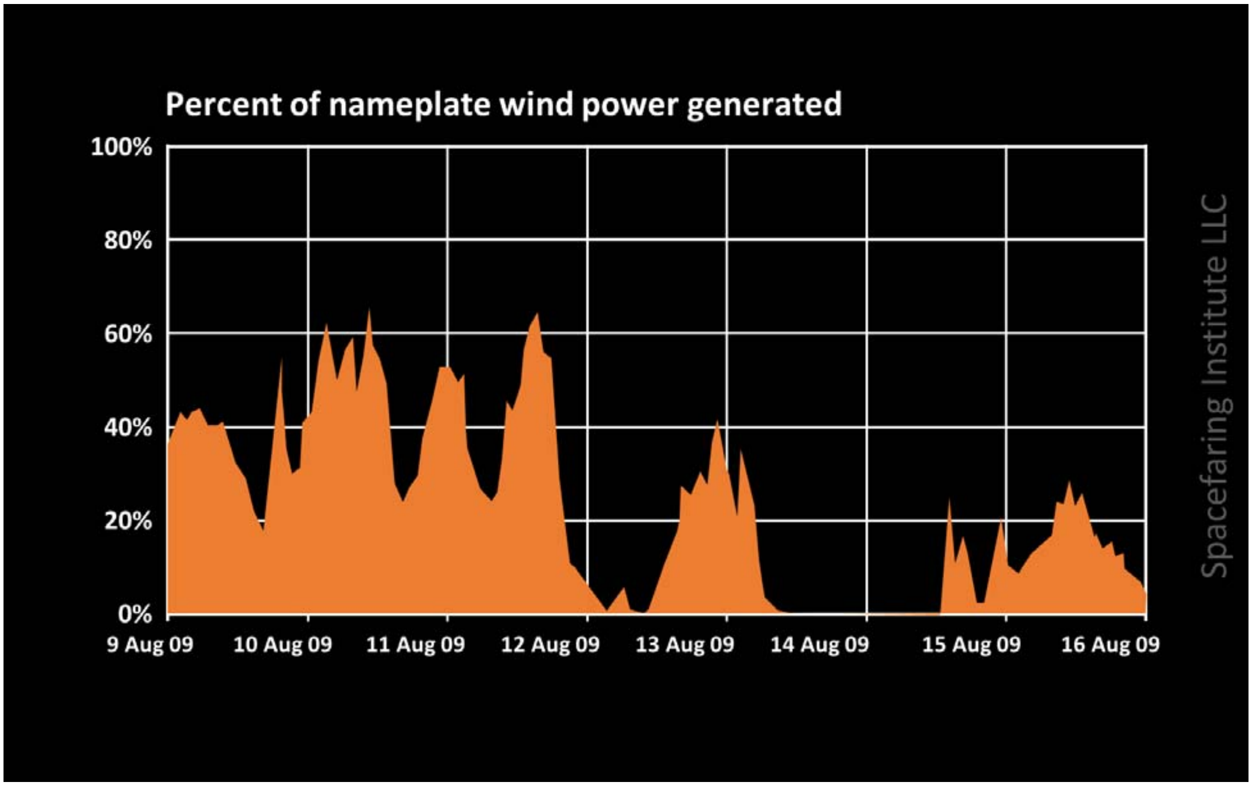
7.1.2 Wind turbine power output curves



1.5 MW and 2.5 MW wind turbine power output curves

The power produced by 1.5 MW and 2.5 MW wind turbines as a function of the wind speed is shown above. The turbines will start to spin when the wind speed reaches around 7 mph. The smaller 1.5 MW wind turbines have a maximum operational wind speed of 20 m/s or about 45 mph. When the wind speed exceeds this value, the turbine is stopped. The maximum speed for the 2.5 MW turbines is about 56 mph. Above 28 mph, both turbines are producing their design nameplate power output.

Unfortunately, the wind speed is variable meaning that the turbines rarely produce their design output for any extended period of time. In fact, even in locations that are excellent for wind power according to the map, there are periods when there is no wind-electricity production. The chart below plots the percentage of the total nameplate power produced during a one week time period picked at random. At no time did the turbines reach 100 percent of their rated output. This shows the fundamental problem with wind energy – its unpredictability that does not have any correlation to the energy needs of the consumer. In other words, wind-electricity may not be available when the consumer needs it.



Percent of nameplate power generated at a wind farm in Alberta, Canada, over a one week period picked at random.

7.1.3 Wind turbine capacity factor

The way this variability is handled is with a "capacity factor". The capacity factor is the percentage of the turbine's electrical energy generation potential that is being produced or is expected to be produced over a period of time. The upper bound for capacity factors in the very best locations is generally 45-55 percent. In most locations of commercial wind farm interest, the capacity factor falls in the range of 30-40 percent. Generally, the areas of yellow and green in the above map have capacity factors below 25 percent and are not of commercial interest.

Let's look at an example calculation of the electrical energy produced over a year's time for a wind turbine with a 2.5 MW nameplate power generation capability. With a 50 percent average capacity factor, in a year's time the turbine would produce 10,950 MWh/yr or 10.95 GWh/yr. However, depending on the location, this could fall to only 6.57 GWh/yr at a 30 percent capacity factor.

Define the unit MWh: $MWh := MW \cdot hr$

Define a value for the capacity factor: $CF_{wind} := 0.5$

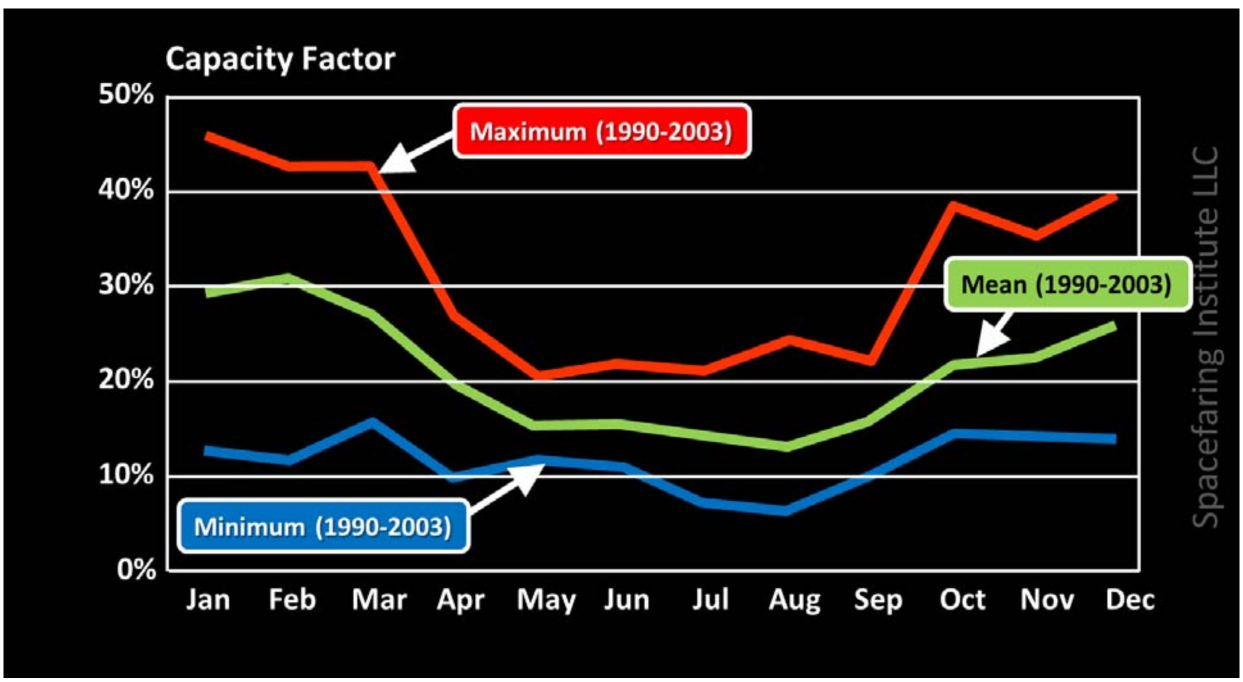
$$2.5 \cdot MW \cdot 365 \cdot day \cdot 24 \cdot \frac{hr}{day} \cdot CF_{wind} = 10950\ MWh$$

Set: $CF_{wind} := 0.3$

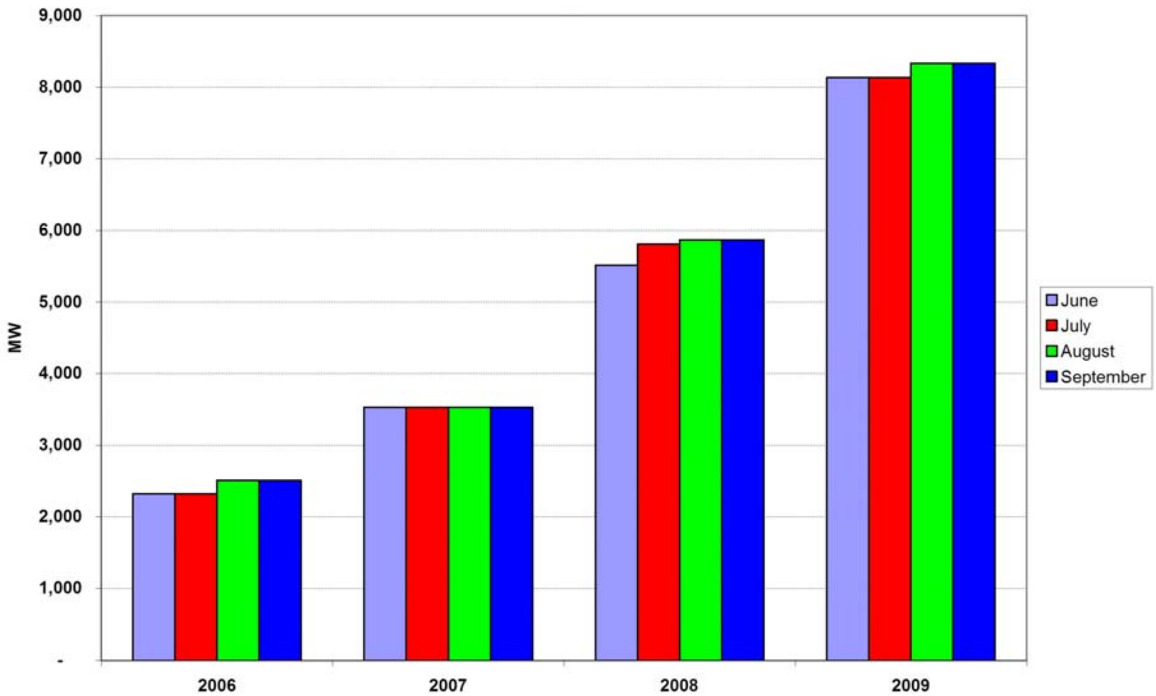
$$2.5 \cdot MW \cdot 365 \cdot day \cdot 24 \cdot \frac{hr}{day} \cdot CF_{wind} = 6.57\ GWh$$

Recognizing the variability of the weather is common sense. If a coal or nuclear power plant is operational, it will produce its design nameplate power. While a wind turbine may be operational, the amount of wind power available governs its power output. From month-to-month and from year-to-year, the actual capacity factor of wind turbines varies at every location.

The chart below shows this capacity factor variation over a 13-year period in Germany. Note the yearly maximum–to–minimum variations for each month as well as the mean variation throughout the year where the capacity factor is highest in the winter and least in the summer.



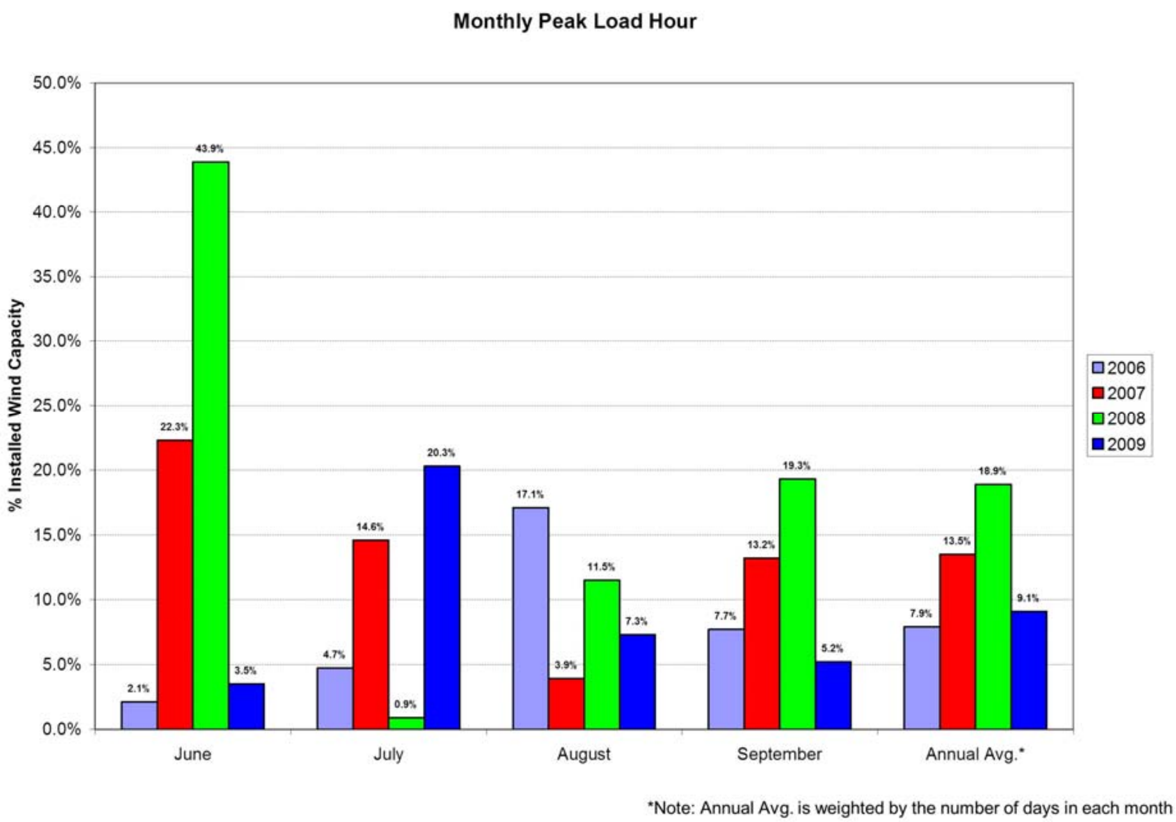
Variation of the wind capacity factor from 1990-2003 in Germany.
(Data source: European Wind Energy Association web site publication.)



Total installed nameplate generation capacity available for use in Texas in June-September, 2006-2009. (Source: Electric Reliability Council of Texas website, Capacity Value of Wind 2006-2009.)

Texas has installed a significant number of wind turbines. These two charts, from the Electric Reliability Council of Texas, show the total installed nameplate generation capacity for 2006-2009 and the percentage of the nameplate generation capacity—the actual measured capacity factor—for the critical summer months of June-September during their hot summer. This is when the available of sustainable wind energy to replace fossil fuels would be most beneficial.

The above chart shows that the total installed wind generation capacity increased from around 2200 MW (2.2 GW) to around 8200 MW (8.2 GW) indicating these are large wind farms having thousands of wind turbines spread across hundreds of sq. mi.



Actual monthly peak load hour capacity factors for Texas wind farms in June-September, 2006-2009. (Source: Electric Reliability Council of Texas website, Capacity Value of Wind 2006-2009.)

While the wind energy potential of Texas appears to be quite good on the map, in the critical summer cooling months when electricity is needed to run air conditioners, the actual measured capacity factors are quite variable and generally low, as seen above. Monthly peak load hour capacity factors range from 2.1 percent to 43.9 percent. The average summer peak hour values fall in the range of 10-15 percent, well below the ideal 30-40 percent assumed. In September, 2009, for instance, only 5.2% or 426 MW of the total 8200 MW installed was effectively available. Also, it is important to note that quadrupling the size of the total generation capacity from 2 GW to 8 GW did not significantly increase the overall capacity factors.

What these variations in actual capacity factors indicate is that a wind energy infrastructure must be designed and sized to accommodate these variations. A real wind energy infrastructure must be able to dispatch high-quality electricity and hydrogen fuels when needed at any time of the year, not just when the wind is blowing.

7.2 Wind energy infrastructure model

In the all-nuclear energy infrastructure, nuclear power plants provided dispatchable electrical power that could be provided to the customer. For the wind energy infrastructure sized to meet the energy needs of 618 million Americans in 2100, the variability of the wind-generated electrical power must be accommodated. The solution is to immediately convert all such wind-generated electrical power into hydrogen fuel. The hydrogen fuel would be distributed by pipeline to electric utilities where it would be stored until needed to provide fuel to the end consumer and to be used to fuel gas turbine generators to generate dispatched electrical power. While some wind-generated electrical power may be used directly by end consumers, for sizing this infrastructure such direct use is ignored. This is the only practical solution to handling the daily, seasonal, and year-to-year variability in capacity factor of the wind-generated electrical power.

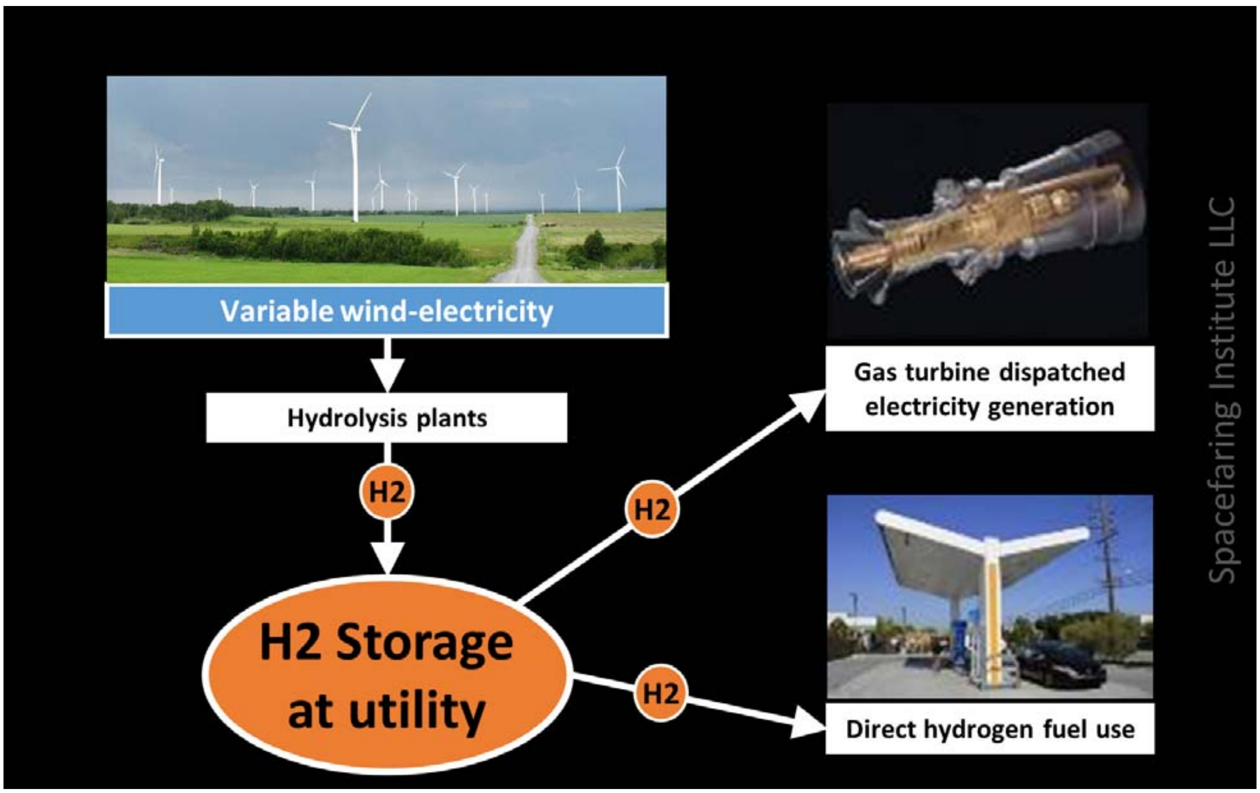
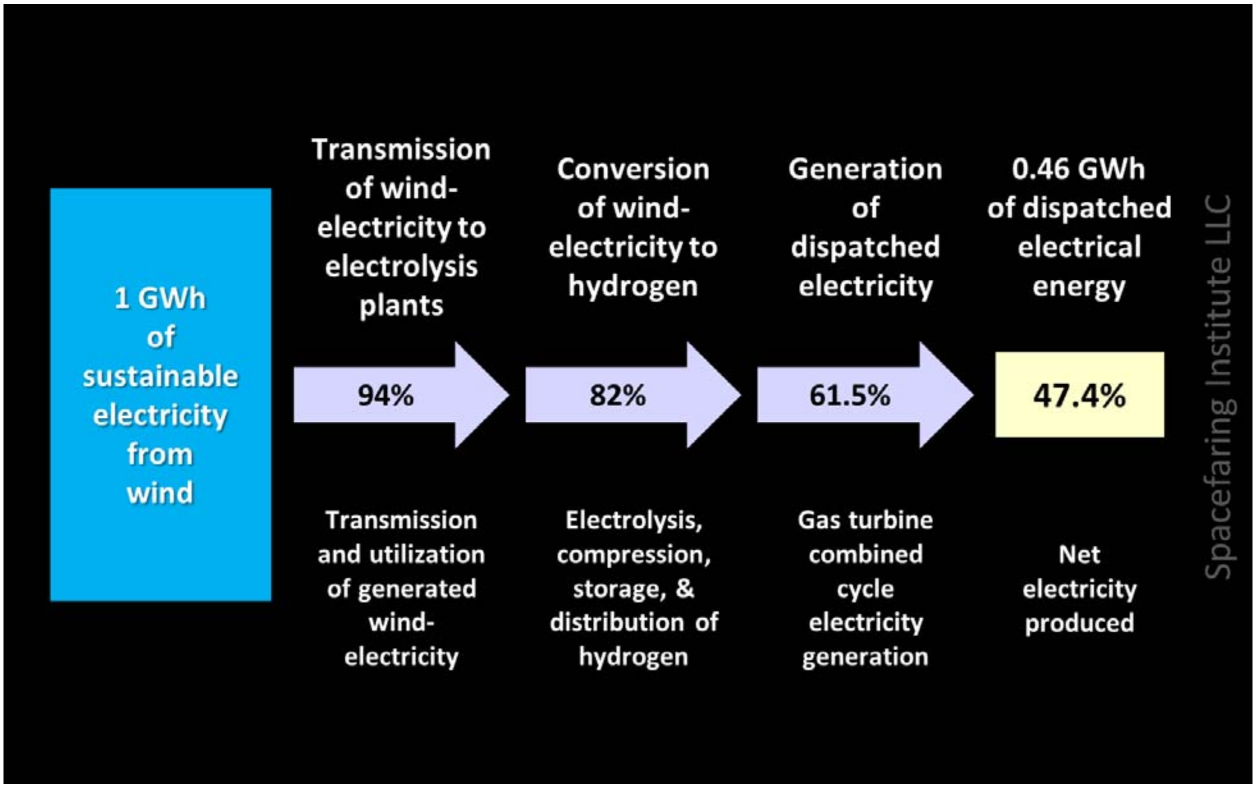


Diagram of how variable wind-electrical power would be converted into dispatchable electricity and hydrogen fuel.

7.3 Sizing the needed wind infratructure

7.3.1 Efficiency of converting wind-generated electrical power into utility dispatched electrical power

The wind-generated electrical power is variable. To produce utility dispatched electrical power, this will be generated using hydrogen-fueled combined-cycle gas turbine generators. For this analysis, the overall efficiency in the conversion of variable wind electrical power into dispatched electrical power is 47.4 percent. It would take about 2 watts of variable wind electrical power to yield 1 watt of dispatched electrical power.



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1. http://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3
2. http://www.siemens.com/press/en/feature/2014/corporate/2014-02-lausward.php

- The Energy Information Administration reports that the average power loss through transmission and distribution is 6 percent.
- A major combined-cycle gas turbine generator company reports reaching 61.5 percent energy conversion efficiency using natural gas.

An estimate is required for the overall efficiency in converting the input variable electrical power into hydrogen gas stored under high pressure at the local utility ready to generated dispatched electrical power. The starting point is the electrolyzer efficiency in converting the input electrical power into hydrogen. As noted previously, the US Department of Energy has established a goal of achieving 75 percent electrolyzer efficiency when the hydrogen is used yielding the LHV. As a combined-cycle gas turbine generator enables the release of the HHV, this increases this electrolyzer efficiency to 88.7 percent.

$$LHV_{hydrogen} = 51682 \, \frac{Btu}{lb} \qquad HHV_{hydrogen} = 61127 \, \frac{Btu}{lb}$$

$$0.75 \cdot \frac{HHV_{hydrogen}}{LHV_{hydrogen}} = 88.706\%$$

The hydrogen produced by the electrolyzer is compressed to 1200 psi and sent through a high-pressure hydrogen pipeline network to the local utility. There the hydrogen will be further compressed, likely to 10,000 psi, for storage until needed. Both of these compression steps, along with any step-up compression needed along the pipeline distribution, require additional electrical power. For this analysis, an overall electrolyzer–compression efficiency of 82 percent is assumed. When combined with the initial transmission and distribution energy efficiency and the generator efficiency, this yields an overall energy conversion efficiency estimate of 47.4 percent.

$$e_{variable\_disptched} := 0.94 \cdot 0.82 \cdot 0.615 = 47.404\%$$

7.4 Nameplate wind power needed in 2100

7.4.1 Zero net immigration case

As determined earlier:

$$Population\_2100_{US\_zero\_immigration} = 343 \cdot 10^{6}$$

$$GWh_{2100\_zero\_immigration} = \left(4.093 \cdot 10^{6}\right) \, GWh$$

$$Fuels_{2100\_zero\_immigration} = \left(10.744 \cdot 10^{9}\right) \, BOE$$

Using the variable–to–dispatched conversion efficiency, the total wind-generated electrical energy needed to provide dispatched electrical power in 2100 is:

$$W\_GWh_{US\_zero\_imm\_electrical} := \frac{GWh_{2100\_zero\_immigration}}{e_{variable\_disptched}} = \left(8.634 \cdot 10^{6}\right) \, GWh$$

The total wind-generated electrical energy needed to produce the hydrogen fuel (LHV) in 2100 is:

$$W\_GWh_{US\_zero\_imm\_fuel} := Fuels_{2100\_zero\_immigration} \cdot kWh_{H2\_LHV} = \left(25.339 \cdot 10^{6}\right)\ GWh$$

The total GWh of wind-generated electrical energy needed in 2100 for the zero net immigration case is:

$$W\_GWh_{US\_zero\_imm} := W\_GWh_{US\_zero\_imm\_electrical} + W\_GWh_{US\_zero\_imm\_fuel} = \left(33.972 \cdot 10^{6}\right)\ GWh$$

7.4.2 Most likely immigration case

As determined earlier:

$$Population\_2100_{US\_likely\_immigration} = 617.5 \cdot 10^{6}$$

$$GWh_{2100\_likely\_immigration} = \left(7.368 \cdot 10^{6}\right)\ GWh$$

$$Fuels_{2100\_likely\_immigration} = \left(19.342 \cdot 10^{9}\right)\ BOE$$

Using the variable–to–dispatched conversion efficiency, the total wind-generated electrical energy needed to provide dispatched electrical power in 2100 is:

$$W\_GWh_{US\_likely\_imm\_electrical} := \frac{GWh_{2100\_likely\_immigration}}{e_{variable\_disptched}} = \left(15.543 \cdot 10^{6}\right)\ GWh$$

The total wind-generated electrical energy needed to produce the hydrogen fuel (LHV) in 2100 is:

$$W\_GWh_{US\_likely\_imm\_fuel} := Fuels_{2100\_likely\_immigration} \cdot kWh_{H2\_LHV} = \left(45.617 \cdot 10^{6}\right)\ GWh$$

The total GWh of wind-generated electrical energy needed in 2100 for the most likely immigration case is:

$$W\_GWh_{US\_likely\_imm} := W\_GWh_{US\_likely\_imm\_electrical} + W\_GWh_{US\_likely\_imm\_fuel} = \left(61.16 \cdot 10^{6}\right)\ GWh$$

7.4.3 US 2100 population based on US Census Bureau 2014 update

As determined earlier:

$$Population\_2100_{US\_2014\_update} = 500 \cdot 10^{6}$$

$$GWh_{2100\_2014\_update} = \left(5.966 \cdot 10^{6}\right)\ GWh$$

$$Fuels_{2100\_2014\_update} = \left(15.662 \cdot 10^{9}\right)\ BOE$$

Using the variable–to–dispatched conversion efficiency, the total wind-generated electrical energy needed to provide dispatched electrical power in 2100 is:

$$W\_GWh_{US\_2014\_update\_electrical} := \frac{GWh_{2100\_2014\_update}}{e_{variable\_disptched}} = \left(12.585 \cdot 10^{6}\right)\ GWh$$

The total wind-generated electrical energy needed to produce the hydrogen fuel (LHV) in 2100 is:

$$W\_GWh_{US\_2014\_update\_fuel} := Fuels_{2100\_2014\_update} \cdot kWh_{H2\_LHV} = \left(36.937 \cdot 10^{6}\right)\ GWh$$

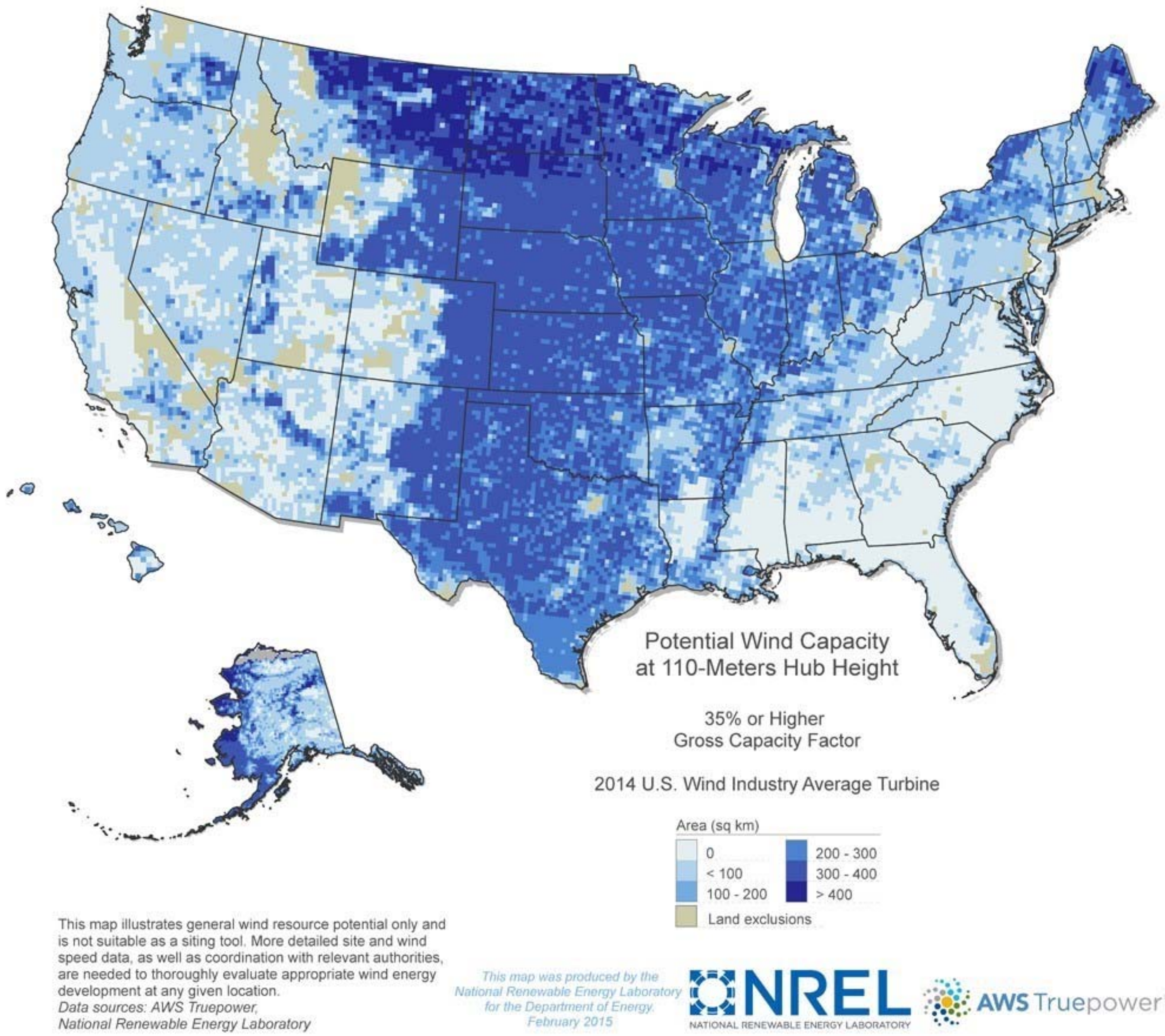
The total GWh of wind-generated electrical energy needed in 2100 is:

$$W\_GWh_{US\_2014\_update} := W\_GWh_{US\_2014\_update\_electrical} + W\_GWh_{US\_2014\_update\_fuel} = \left(49.522 \cdot 10^{6}\right)\ GWh$$

The per capita wind-generated electrical energy need in 2100 is:

$$W\_GWh_{US\_2014\_update\_per\_capita} := \frac{W\_GWh_{US\_2014\_update}}{Population\_2100_{US\_2014\_update}} = \left(99.045 \cdot 10^{3}\right)\ kWh$$

7.5 US wind power potential

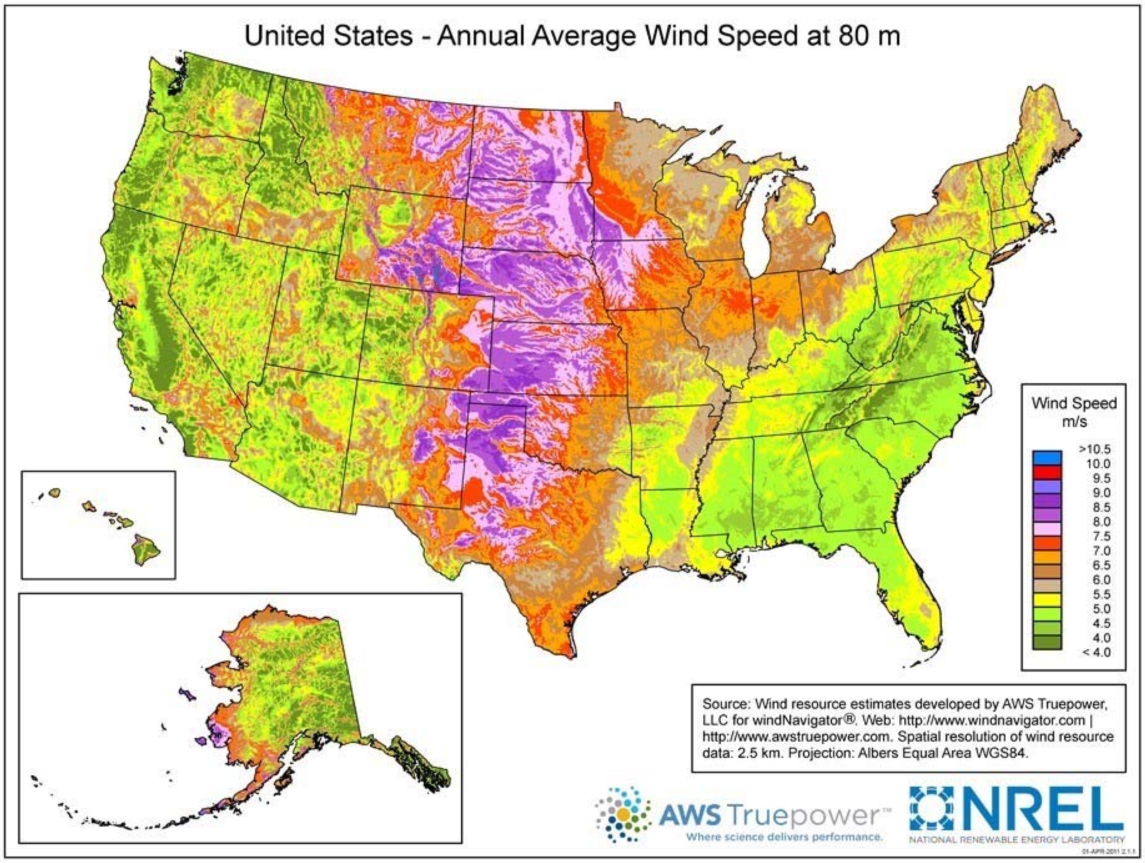


Ref: http://apps2.eere.energy.gov/wind/windexchange/images/windmaps/us_110m_potential.jpg

The National Renewable Energy Laboratory assesses the wind energy potential of the United States. It provides maps of locations suitable for commercial wind farm locations. The raw wind power potential is highly dependent on the height of the turbine above the ground. The higher the elevation of the turbine's hub, mounted on the tower, the faster the wind's average speed.

Wind turbines have been increasing in hub height and turbine blade span. The current state-of-the-art is for hub heights at 110 meters or 361 ft. With turbine rotor spans of up to 100 m or 328 ft, the turbine blade tip can be as high as 160 m or 525 ft above the ground. Future hub heights may approach 140 m or 459 ft with a 124 m or 407 ft turbine rotor span. These blade tips would be 202 m or 663 ft above the ground.

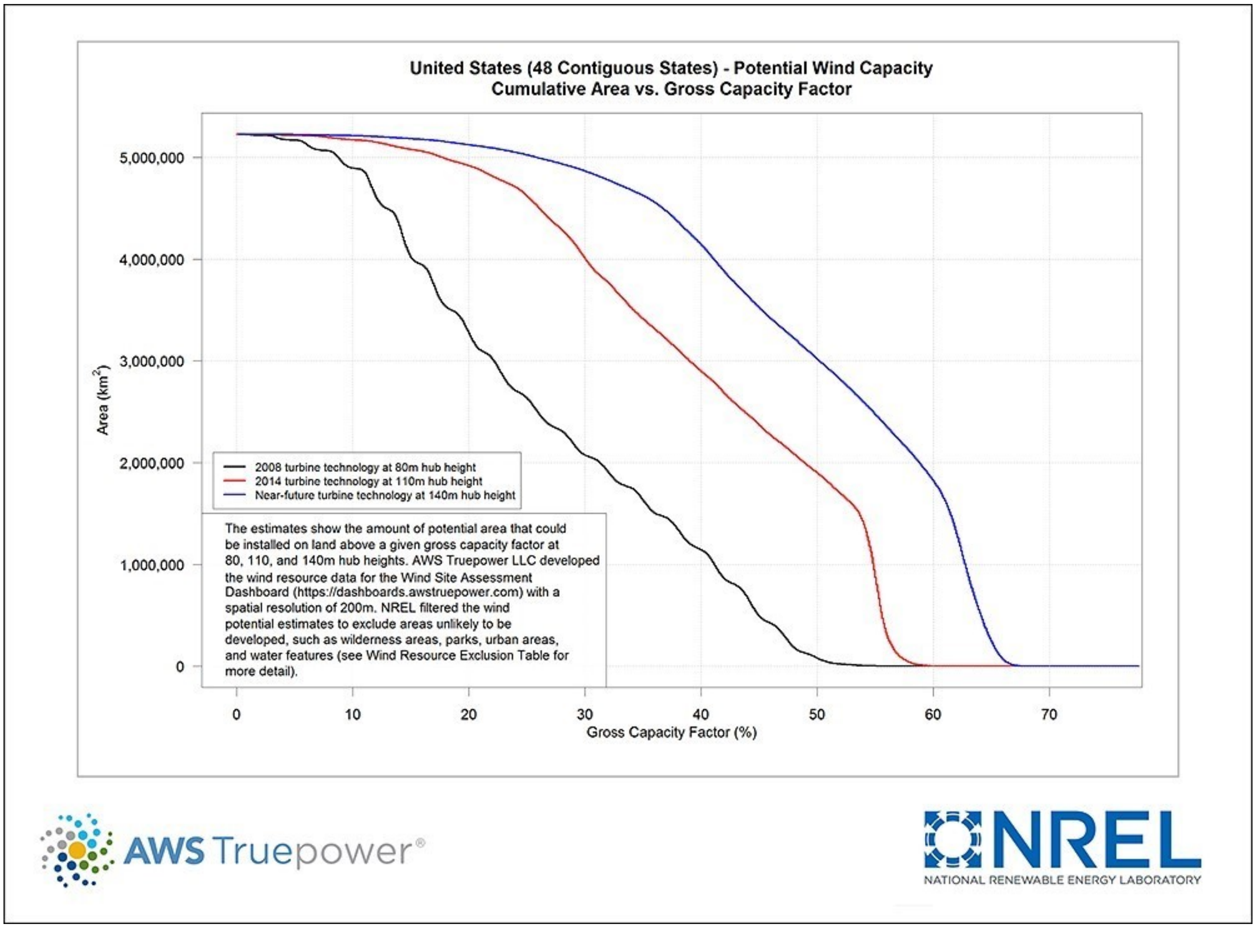
The advantage of higher hub heights can be seen by comparing the preceding map with the map below for a 80-m hub height.



Ref: http://apps2.eere.energy.gov/wind/windexchange/images/windmaps/us_windmap_80meters.jpg

Using this mapping technology, the land area suitable for wind farms and the installed nameplate capacity is estimated. The minimum gross capacity factor is 35 percent, corresponding to a 30 percent net capacity factor. This is the minimum value believed to be commercially viable.

The following chart compares the impact of increasing the hub height on the usable land area.



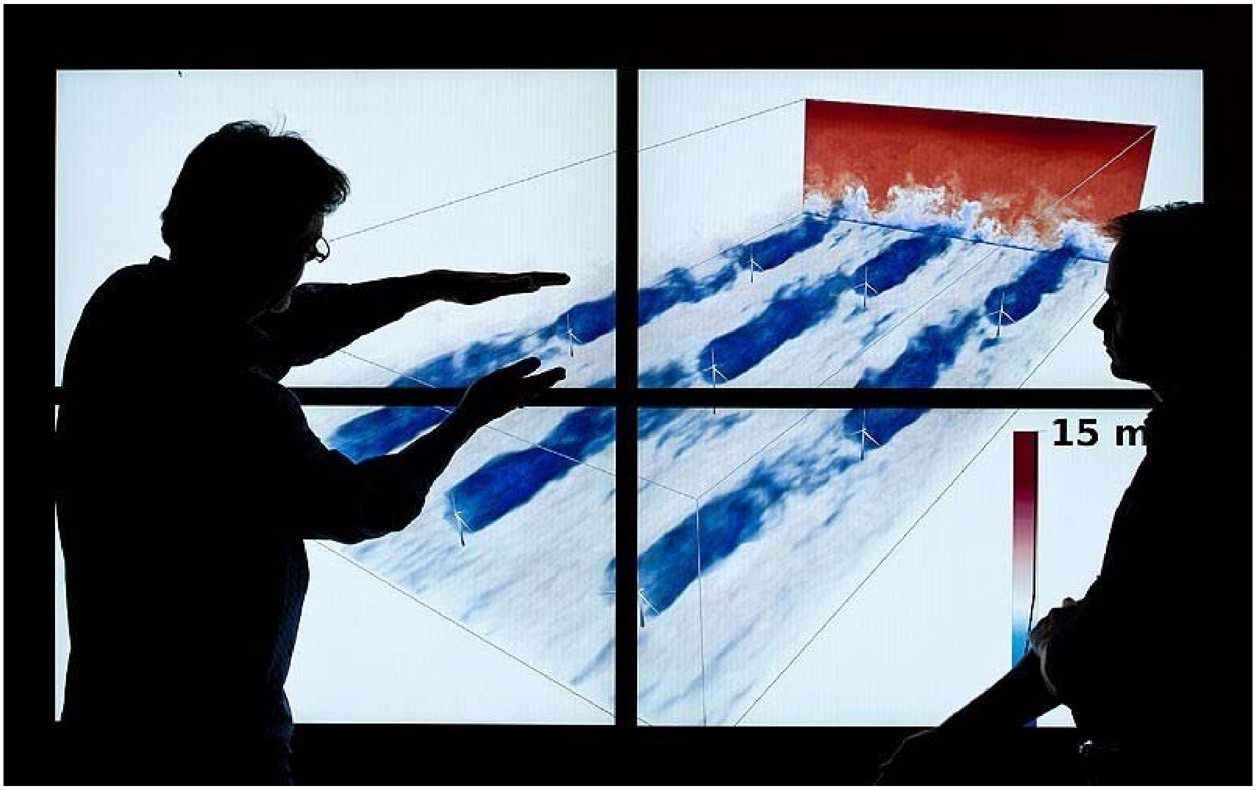
Ref: http://apps2.eere.energy.gov/wind/windexchange/images/windmaps/us_contiguous_wind_potential_chart.jpg

The National Renewable Energy Laboratory, in referenced spreadsheet, estimated the available wind power in the contiguous United States. The table below summarizes this information, converting from km to mi.

Ref: http://apps2.eere.energy.gov/wind/windexchange/docs/
wind_potential_80m_110m_140m_35percent.xlsx

Hub height/ Rotor diameter (meter)	Contiguous US Land area (sq. mi.)	Nameplate power (GW)	Nameplate power (GW/sq. mi.)	Power density (MW/sq. mi.)	8 Rotor diameter turbine spacing (mi.)
80/80	634,476	8,019	0.01264	12.639	0.398
110/100	1,320,625	8,654	0.00655	6.553	0.497
140/124	1,787,155	8,471	0.00474	4.74	0.616

While ideally the available wind power per sq. mi. increases with increasing hub height, the summary table shows that there is a practical limit. This is because of the power lost in downstream turbines from the turbulence created by the upstream turbine. The summary table assumes a spacing of 8 turbine rotor diameters between turbines. The impact of this is seen where the installed nameplate power per sq. mi. falls as the hub height and rotor diameter are increased.



Scientists use computer modeling to evaluate the turbulence produced by turbines in a wind farm. (Source: National Renewable Energy Laboratory, image used as permitted.)

From the summary table above, the US potential wind power resource could provide 8,654 GW of installed nameplate power, with a minimum gross capacity factor of 35 percent. This would occupy 1.3 million sq. mi. with about four 500-ft tall 1.6-MW wind turbines per sq. mi.

To estimate the available annual GWh of wind-generated electrical energy, an average gross capacity factor of 40 percent is assumed. This is reduced, by the NREL assumed 15 percent operational losses, to a net capacity factor of 34 percent. This is about 2 percent more than the current US actual value.

$$0.4 \cdot (1 - .15) = 34\%$$

Assuming all 1.3 million sq. mi. of wind farms are built, this would provide, in a typical year, 25.8 million GWh of variable wind-generated electrical energy.

$$E\_wind_{potential} := 8654 \cdot GW \cdot 365 \cdot day \cdot 24 \cdot \frac{hr}{day} \cdot 0.34 = \left(25.775 \cdot 10^{6}\right)\ GWh$$

Expressed in terms of nuclear plant-years:

$$\frac{E\_wind_{potential}}{Plant\_year_{1\_GW}} = 3097$$

7.6 Meeting US 2100 energy needs with wind power alone

7.6.1 Net zero immigration case

The total GWh of wind-generated electrical energy needed in 2100 for the zero net immigration case is:

$$W\_GWh_{US\_zero\_imm} = \left(33.972 \cdot 10^{6}\right)\ GWh$$

Expressed in terms of nuclear plant-years needed:

$$\frac{W\_GWh_{US\_zero\_imm}}{Plant\_year_{1\_GW}} = 4082$$

Wind power would only be able to meet 76 percent of the energy needs of the projected 343 million Americans in 2100.

$$\frac{E\_wind_{potential}}{W\_GWh_{US\_zero\_imm}} = 75.9\%$$

7.6.2 Most likely immigration case

The total GWh of wind-generated electrical energy needed in 2100 for the most likley immigration case is:

$$W\_GWh_{US\_likely\_imm} = \left(61.16 \cdot 10^{6}\right)\ GWh$$

Expressed in terms of nuclear plant-years needed:

$$\frac{W\_GWh_{US\_likely\_imm}}{Plant\_year_{1\_GW}} = 7349$$

Wind power would only be able to meet 42 percent of the energy needs of the projected 618 million Americans in 2100.

$$\frac{E\_wind_{potential}}{W\_GWh_{US\_likely\_imm}} = 42.1\%$$

7.6.3 US 2100 propulsion based on US Census Bureau 2014 update

The total GWh of wind-generated electrical energy needed in 2100 for the 500 million is:

$$W\_GWh_{US\_2014\_update} = \left(49.522 \cdot 10^{6}\right)\ GWh$$

Expressed in terms of nuclear plant-years needed:

$$\frac{W\_GWh_{US\_2014\_update}}{Plant\_year_{1\_GW}} = 5951$$

Wind power would only be able to meet 52 percent of the energy needs of the projected 500 million Americans in 2100.

$$\frac{E\_wind_{potential}}{W\_GWh_{US\_2014\_update}} = 52\%$$

7.7 Americans served per sq. mi. of wind farms

Ref: http://apps2.eere.energy.gov/wind/windexchange/docs/wind_potential_80m_110m_140m_35percent.xlsx

Hub height/ Rotor diameter (meter)	Contiguous US Land area (sq. mi.)	Nameplate power (GW)	Nameplate power (GW/sq. mi.)	Power density (MW/sq. mi.)	8 Rotor diameter turbine spacing (mi.)
80/80	634,476	8,019	0.01264	12.639	0.398
110/100	1,320,625	8,654	0.00655	6.553	0.497
140/124	1,787,155	8,471	0.00474	4.74	0.616

From the above table, each sq. mi. of wind farm would average 6.553 MW of installed nameplate power. With a 34% capacity factor, this would generate 19.5 GWh per sq. mi. per year, on average. This would meet the annual electrical energy needs of about 197 Americans in 2100.

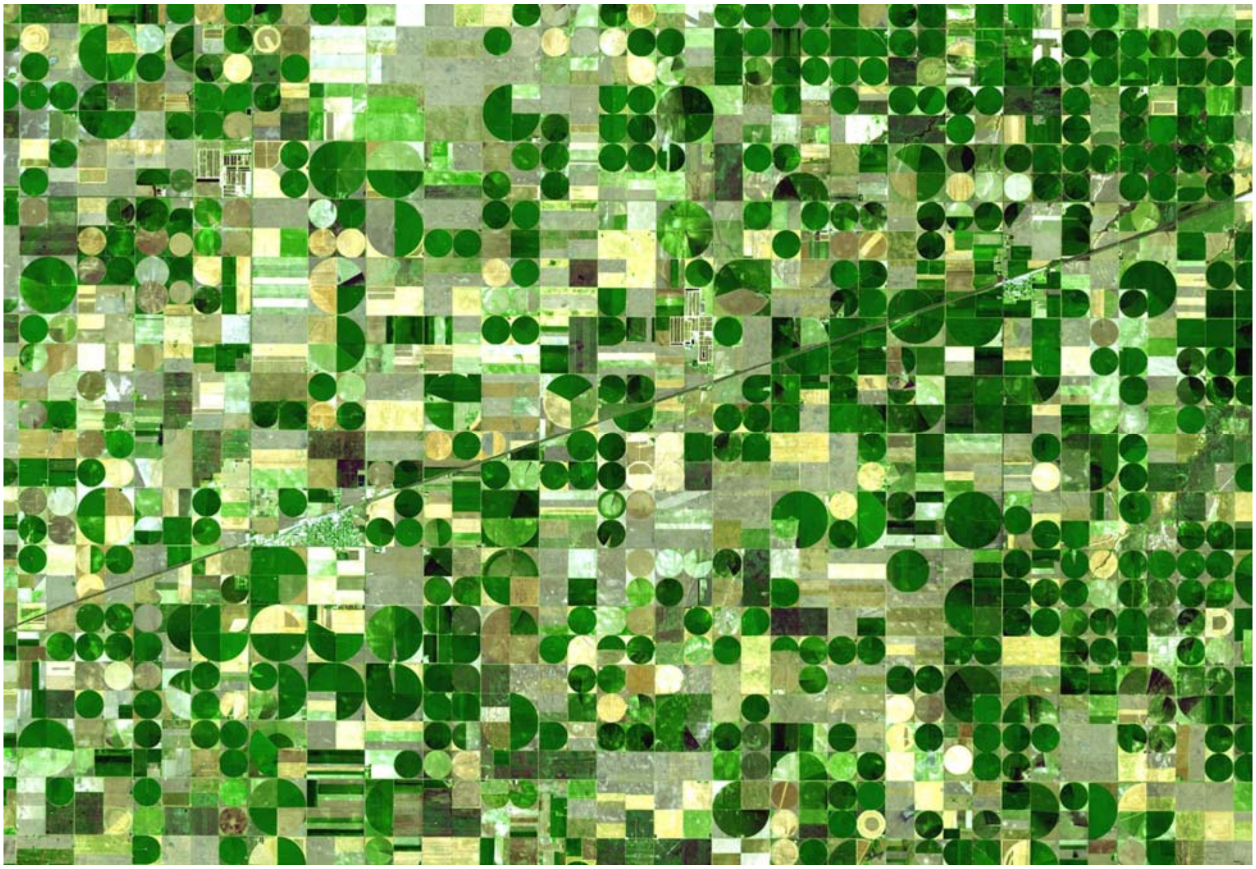
$$W\_GWH_{sq\_mi} := 6.553 \cdot \frac{MW}{mi^2} \cdot 365 \cdot day \cdot 24 \cdot \frac{hr}{day} \cdot 0.34 = 19.517 \frac{GWh}{mi^2}$$

$$W\_Americans_{sq\_mi} := \frac{W\_GWH_{sq\_mi}}{W\_GWh_{US\_2014\_update\_per\_capita}} = 197.057 \frac{1}{mi^2}$$

7.8 Wind farm land area required to meet US 2100 energy needs using US Census Bureau 2014 update

$$\frac{Population\_2100_{US\_2014\_update}}{W\_Americans_{sq\_mi}} = \left(2.537 \cdot 10^6\right) mi^2$$

7.9 Practicality of building extensive wind farms



Landsat image of Kansas showing land survey. The image covers an area about 15 miles by 21 miles. Each small square is one-half mile square. (Source: U.S. Government.)

The above is a Landsat image of Kansas. The United States has been surveyed using the acre-mile system. Land ownership and the road structure are based on this system. In the image below, each small square is 0.5 mile by 0.5 mile. From the summary table above, the ideal spacing for the 110-meter hub height/100-m rotor diameter 2.5-MW turbines is 0.5 miles. Thus, the reality of installing 1.3 million sq. mi. of wind farms means that all across the central United States, one of these 500-ft tall wind turbines would be built at every 0.5-mile intersection. The central United States would be covered by a forest of spinning turbines.

As seen in the photographs below, the installation of these turbines requires substantial foundation construction. Roughly 5.4 million of these foundations would need to be built.

$$8654 \cdot GW \cdot \frac{1000 \cdot \frac{MW}{GW}}{1.6 \cdot MW} = 5.409 \cdot 10^{6}$$

Each wind tower requires a steel rebar and concrete base approximately 50 ft in diameter 8 feet belowground. (Source: U.S. Bureau of Land Management, public domain image.)

Each wind turbine must be anchored using a heavy steel and concrete base buried underground. First a 200 ft square work pad is cleared at the tower location. Next the ground is excavated to about eight feet and prepared for installing the steel rebar followed by pouring the concrete. A typical base requires about 24 tons of rebar and about 250 cubic yards of concrete requiring about 28 cement truck loads. To install the bases for the needed 5.4 million towers will require 1.35 billion cubic yards of concrete. For comparison, the Hoover Dam used 3.25 million yards. The wind farms would require 400X the concrete used in the Hoover Dam.

Once installed, who will pay to have them removed?

Installation of a typical wind turbine.
(Original image source: U.S. Bureau of Land Management, public domain images.)

As the photographs above show, the installation of the large wind turbines requires considerable on-site activity using large cranes to position the components. This extends beyond the immediate base of the tower.

Roads must be graded, if not already available, to provide access for the tower components, the construction equipment and cranes, and the concrete trucks. Permanent right-of-ways are needed for maintenance access to the towers and for the underground cables needed to connect each tower to the local electrical power substation. The extent of this is seen in the photograph below. Unlike the location used in the photograph below, the majority of the 5.4 million wind turbines needed to build the 1.3 million sq. mi. of wind farms would be in prime agricultural land as seen in the Landsat image above. The long-term impact of the construction on the land, along with the installations of 5.4 million foundations, would be significant.

Installing the towers requires access roads during construction and right-of-way for buried cables and maintenance access. (Source: NASA, public domain image.)

8. Ground solar energy

8.1 Ground solar energy fundamentals

The direct use of sunlight in the design of our homes is not new. Passive solar energy architecture has been used throughout human history to provide light and warmth. In modern times, advances in materials, construction methods, and architectural design enable new homes to very effectively use sunlight to meet much of the homes heating needs. Such artificial energy conservation methods will help America achieve the anticipated roughly 20 percent overall reduction in per capita energy demand used in this book to forecast America's energy needs in 2100. However, this passive solar energy is not the type of ground solar energy that provides the electricity and fuel needed by our modern culture. Hence, the focus here is on the production of ground solar-electricity to replace fossil fuels.

8.1.1 Types of ground solar energy

Solar tower concentrator where mirrors on the ground focus sunlight on the thermal receiver at the top of the tower that heats the working fluid. (Source: National Renewable Energy Laboratory, Greg Glatzmaier, Gemasolar Plant owned by Torresol Energy; image used as permitted.)

The ground solar energy systems of interest capture sunlight and convert this into solar-electricity. There are two approaches to achieve this. The first are large solar-thermal systems that use mirrors to focus the sunlight to achieve the high temperatures necessary to boil water to produce the steam used to drive a turbine to generate solar-electricity. Concentrated sunlight replaces the fossil fuel or nuclear energy used to heat the boilers. The complexity of these systems comes from having to move the mirrors to track the movement of the sun across the sky in order to maintain the necessary temperatures in the boiler.

The primary disadvantage of the concentrating solar systems is that they generally only achieve the necessary temperatures to generate electricity while using direct sunlight without cloud cover and, then, only during the mid-day hours. A second disadvantage is the complexity added by the boiler and steam turbine generator. Also, the mirrors require periodic cleaning to maximize the overall system efficiency. For these reasons, pure solar concentrator thermal systems are not widely used. Hybrid systems using natural gas to provide auxiliary heat to the boiler during cloud cover and outside of mid-day periods are being investigated in order to be able to produce dispatchable, high-quality electricity when needed.

Ground solar photovoltaic array. (Source: National Renewable Energy Laboratory, Dennis Schroeder; image used as permitted.)

The second approach uses special materials to transform sunlight directly into electricity. These are called photovoltaic systems. They are fashioned into large flat panels mounted in arrays on the ground. The panels may be fixed in position or they may be moved to track the sun to achieve maximum output throughout the day.

In these systems, the solar panels do not capture all of the sunlight falling on the solar farm. The arrays must be spaced apart to allow for the movement of the sun across the sky and its seasonal elevation changes. It is also important to note that the ground must be prepared for the installation of the arrays. As seen above, the ground is generally scraped clear of rocks and vegetation, leveled to ease array installation, and graveled to minimize unwanted plant growth and ease maintenance. Also, the arrays are usually anchored in concrete to withstand high wind conditions and snow loads.

8.1.2 Ground solar energy variability

Like wind power, sunlight is variable. The sun's movement across the sky from dawn to dusk, the changes in the length of time sunlight is available each day throughout the year, the variations in the sun's angle above the horizon throughout the year, the weather conditions, whether it is daylight or night, the orientation of the solar arrays and whether they track the sun or not, and the type of solar arrays all factor into the amount of solar-electricity available. As mentioned, many solar thermal system designs now add auxiliary fuel combustion to maintain dispatchable electricity generation. This enables solar energy to be used when available and fossil fuels only at other times. This approach conserves fossil fuel use and reduces combustion emissions. Whether it makes economic sense depends on the circumstances.

The direct use of solar-electricity from ground solar photovoltaic arrays is more challenging due to the direct impact of changes in the available sunlight. From dawn to around 9 AM and from around 3 PM to dusk, the output of fixed arrays is meager due to the extreme sun angle. This means that for only about 6 hours per day under the best solar conditions—25 percent of the time—the array is producing useful solar-electricity. Add the impact of weather and changes in available sunlight due to seasonal changes, and the average capacity factor falls to about 20 percent even in areas of the country with good solar insolation conditions. While this solar-electricity can be used if available, it is not dispatchable and an all-ground solar energy infrastructure must take this into account.

8.2 Ground solar energy infrastructure model

Due to the variable and non-dispatchable nature of large-scale ground solar-electricity, the model used for the conversion of ground solar-electricity into dispatched electricity and hydrogen fuel is the same as used for the all-wind energy infrastructure. All variable solar-electricity is assumed to be used to produce hydrogen using electrolysis. The hydrogen is compressed and stored until needed to generate dispatched electricity and distributed to the end consumer as thermal fuel.

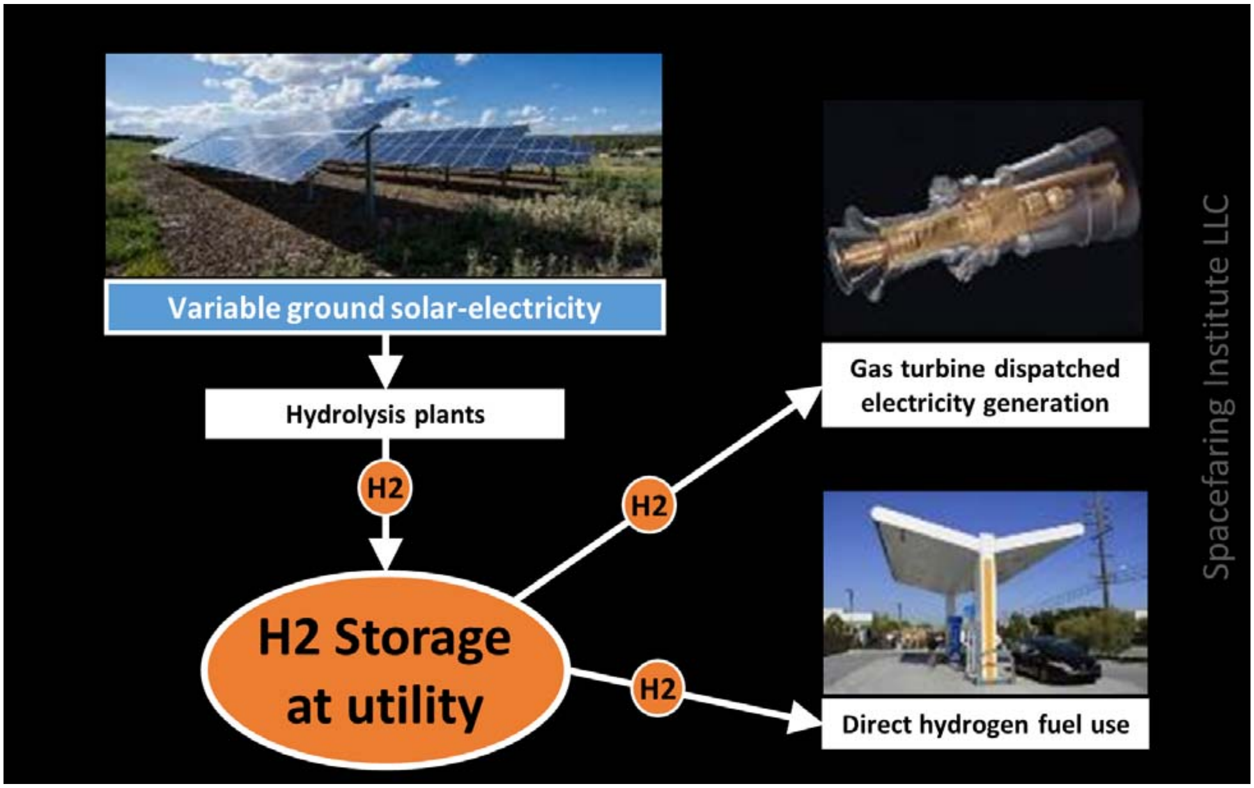


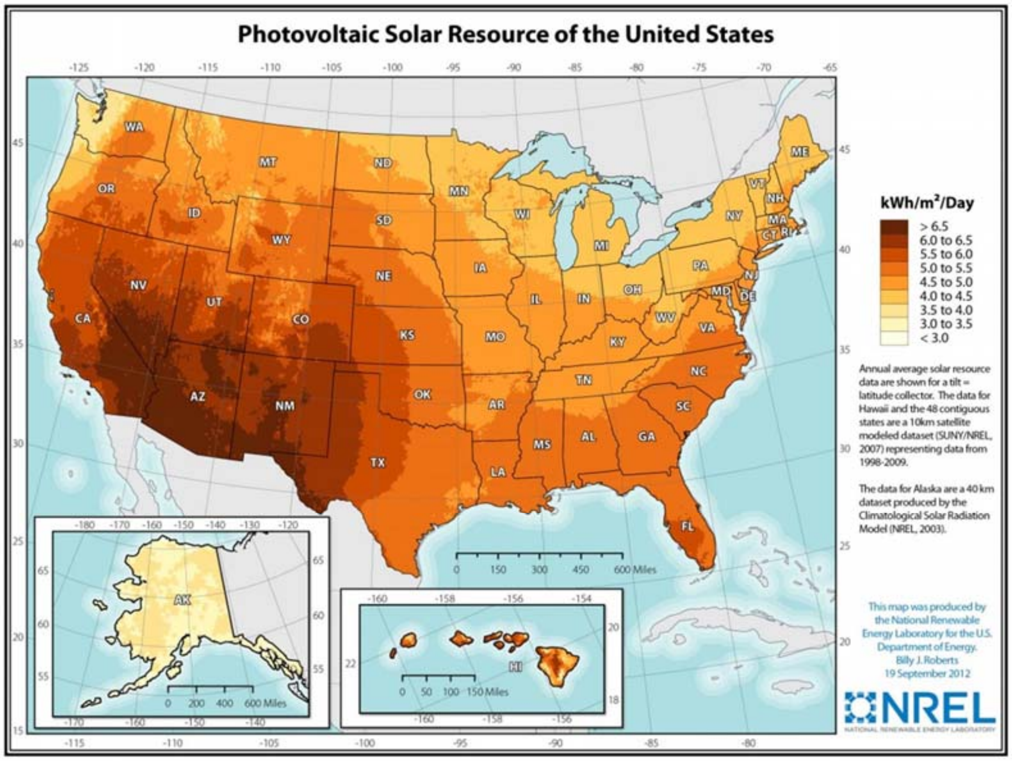
Diagram of how variable solar-electricity would be converted into dispatchable electricity and hydrogen fuel.

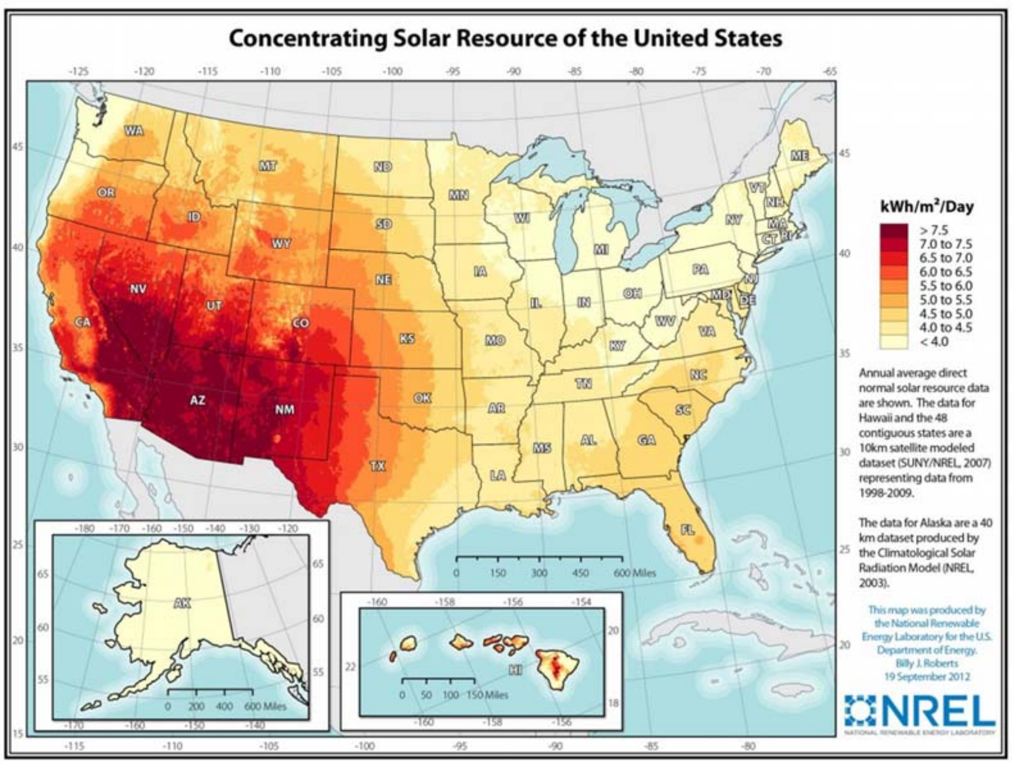
8.3 Sizing the needed ground solar energy infrastructure

8.3.1 US ground solar energy potential

The National Renewable Energy Laboratory provides maps of the U.S. showing the average annual solar insolation available to be used by solar systems. Two maps are shown below. The first is the average solar insolation available —raw sunlight—expressed in kWh per sq. meter per day to a flat solar array. The solar array is assumed to be a fixed flat panel tilted south at an angle equal to the location's latitude from the horizontal. The second map is the same average daily solar insolation but for the conditions of a concentrating solar array that tracks the sun's movement. In both maps, the darker areas have the best average insolation indicating that the southwestern part of the continental U.S. is best for ground solar farms.

What is important to understand is these maps represent the gross solar energy falling on the ground. Terrain, existing land use, protected land use, etc., all contributed to reducing the land available and suitable for installing ground solar energy systems. Thus, while these maps imply that large areas of the United States have good ground solar energy potential, a more detailed analysis is required to identify the actual resource potential.





Solar resource maps for the U.S. (Source: National Renewable Energy Laboratory.)

8.3.2 Ground commercial photovoltaic solar generation installed per sq. mi.

The most likely location in the United States for commercial ground solar farms is in the Southwest. The terrain, weather, and variation in daily and seasonal insolation, however, prevents the preparation of broad estimates of the solar power potential as was done for wind power. The approached used for this analysis is to draw upon the actual data from recent large commercial ground solar photovoltaic installations.

Topaz solar farm fixed solar panels.
(Source: U.S. Fish & Wildlife Service, Sarah Swenty, public domain image.)

Four recent large solar farms in the Southwestern United States have these characteristics:

- The Topaz Solar Farm in San Luis Obispo County, California, has 550 MW of peak nameplate AC power covering 9.5 sq. mi. or 57.9 MW per sq. mi. This farm used fixed flat panel solar arrays. This solar farm was completed in 2014. The effective land use percentage appears to be about 50 percent.
- The Agua Caliente Solar Project in Yuma County, Arizona, has 290 MW of peak DC nameplate power covering 3.75 sq. mi. or 77.3 MW(DC) per sq. mi. A DC-AC conversion efficiency of 77.5 percent is applied to yield an estimate of 59.9 MW of peak nameplate AC power per sq. mi. This farm uses fixed arrays. This farm was completed in 2014.

- The Desert Sunlight Solar Farm in Riverside County, California, has 550 MW of peak nameplate AC power covering 6.2 sq. mi. or 88.7 MW per sq. mi. This farm uses fixed flat panel solar arrays. The farm was completed in 2015.
- The Solar Star farm in Rosamond, California, has 747.3 MW of peak nameplate power and 579 MW of peak nameplate AC power covering 5 sq. mi. or 115.8 MW of AC nameplate power per sq. mi. This farm uses vertically-pivoting photovoltaic arrays. This solar farm was completed in 2015.

(Note that while wind turbine generators produce alternating current electricity, solar photovoltaic arrays produce direct current – like a battery – which must first be converted to alternating current for transmission outside the solar farm. This conversion loses about 20-25 percent of the direct current power. For this reason, the solar farm nameplate power is often expressed in terms of the nameplate AC production.)

The average value for these four solar farms, representing nearly 2 GW of nameplate power, is about 81 MW of nameplate AC power per sq. mi.

$$\frac{59.9+57.9+88.7+115.8}{4}=80.575$$

8.3.3 Average solar PV nameplate AC power per sq. mi. used in this analysis

Table 9. Summary of Total Land-Use Requirements for PV and CSP Projects in the United States

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

Ref: http://www.nrel.gov/docs/fy13osti/56290.pdf

The National Renewable Energy Laboratory has evaluated the land use needs for existing ground solar farms. The results are summarized in the table above. For fixed photovoltaic arrays, the average installed nameplate generation capacity (AC) was 33 MW per sq. km. This equates to 85.5 MW per sq. mi. This is very close to the average value for the four recent large farms calculated above. Thus, the value in this table will be used.

$$Solar\_PV_{unit\_capacity} := 33 \cdot \frac{MW}{km^2} = 85.47 \frac{MW}{mi^2}$$

The above table includes an estimate of the amount of electrical energy (GWh) produced per unit land area. These are not actual values but were based on simulated production.

8.3.4 US commerical solar PV capacity factor

The US Energy Information Administration publishes summaries of the electrical power generation capacity and electrical energy generated. From the January, 2016, report, the corresponding values for utility-scale photovoltaic facilities in 2014 are reported. The installed utility solar photovoltaic capacity was 8,656.6 MW. The net generation was 15,250 GWh.

Table 6.1.A. Net Summer Capacity for Utility Scale Solar Photovoltaic and Distributed Solar Photovoltaic Capacity (Megawatts)
2008 - November 2015

Period	Utility Solar Photovoltaic	Estimated Distributed Solar Photovoltaic	Estimated Total Solar Photovoltaic
Annual Totals			
2008	70.8	N/A	N/A
2009	145.5	N/A	N/A
2010	393.4	N/A	N/A
2011	1,052.0	N/A	N/A
2012	2,694.1	N/A	N/A
2013	5,336.1	N/A	N/A
2014	8,656.6	6,221.4	14,878.0

Table 1.1.A. Net Generation from Renewable Sources: Total (All Sectors), 2005-November 2015 (Thousand Megawatthours)

	Generation at Utility Scale Facilities					
Period	Wind	Solar Photovoltaic	Solar Thermal	Wood and Wood-Derived Fuels	Landfill Gas	Biogenic Municipal Solid Waste
Annual Totals						
2005	17,811	16	535	38,856	5,142	8,330
2006	26,589	15	493	38,762	5,677	8,478
2007	34,450	16	596	39,014	6,158	8,304
2008	55,363	76	788	37,300	7,156	8,097
2009	73,886	157	735	36,050	7,924	8,058
2010	94,652	423	789	37,172	8,377	7,927
2011	120,177	1,012	806	37,449	9,044	7,354
2012	140,822	3,451	876	37,799	9,803	7,320
2013	167,840	8,121	915	40,028	10,658	7,186
2014	181,655	15,250	2,441	42,340	11,220	7,228

Ref: http://www.eia.gov/electricity/monthly/pdf/epm.pdf

The actual capacity factor is 20.11%. Note that this includes a fixed, 1-axis, and 2-axis tracking PV arrays.

$$Capacity\_factor_{PV} := \frac{15250 \cdot GWh}{8656.6 \cdot MW \cdot 365 \cdot day \cdot 24 \cdot \frac{hr}{day}} = 20.11\%$$

8.3.5 Required 2100 size of an all-ground solar PV energy infrastructure

8.3.5.1 Zero net immigration case

As determined earlier:

$$Population\_2100_{US\_zero\_immigration} = 343 \cdot 10^{6}$$

$$GWh_{2100\_zero\_immigration} = \left(4.093 \cdot 10^{6}\right)\ GWh$$

$$Fuels_{2100\_zero\_immigration} = \left(10.744 \cdot 10^{9}\right)\ BOE$$

The total GWh of wind-generated electrical energy needed in 2100 for the zero net immigration case is:

$$W\_GWh_{US\_zero\_imm} = \left(33.972 \cdot 10^{6}\right)\ GWh$$

As the ground solar PV energy infrastructure operates the same as the wind energy infrastructure, the amount of variable renewable electrical energy needed in 2100 remains the same.

If the energy infrastructure was ideal with electrical power being produced continuously, 3,878 GW of nameplate power would be needed.

$$\frac{W\_GWh_{US\_zero\_imm}}{365 \cdot day \cdot 24 \cdot \frac{hr}{day}} = 3878.119\ GW$$

However, the day–night solar cycle and weather must be accounted for by introducing the capacity factor calculated above. This increases the needed 2100 capacity to 19,284 GW.

$$Solar\_PV\_capacity_{US\_zero\_imm} := \frac{W\_GWh_{US\_zero\_imm}}{365 \cdot day \cdot 24 \cdot \frac{hr}{day} \cdot Capacity\_factor_{PV}} = 19284\ GW$$

A total of 225,627 sq. mi. of solar PV farms would be needed to supply the energy required by 343 million Americans in 2100.

$$Solar\_PV\_land\_area_{US\_zero\_imm} := \frac{Solar\_PV\_capacity_{US\_zero\_imm}}{Solar\_PV_{unit\_capacity}} = 225627\ mi^2$$

8.3.5.2 Most likely immigration case

As determined earlier:

$$Population\_2100_{US\_likely\_immigration} = 617.5 \cdot 10^6$$

$$GWh_{2100\_likely\_immigration} = \left(7.368 \cdot 10^6\right)\ GWh$$

$$Fuels_{2100\_likely\_immigration} = \left(19.342 \cdot 10^9\right)\ BOE$$

The total GWh of wind-generated electrical energy needed in 2100 for the most likely immigration case is:

$$W\_GWh_{US\_likely\_imm} = \left(61.16 \cdot 10^6\right)\ GWh$$

As the ground solar PV energy infrastructure operates the same as the wind energy infrastructure, the amount of variable renewable electrical energy needed in 2100 remains the same.

If the energy infrastructure was ideal with electrical power being produced continuously, 6,982 GW of nameplate power would be needed.

$$\frac{W\_GWh_{US\_likely\_imm}}{365 \cdot day \cdot 24 \cdot \frac{hr}{day}} = 6981.744\ GW$$

However, the day–night solar cycle and weather must be accounted for by introducing the capacity factor calculated above. This increases the needed 2100 capacity to 34,717 GW.

$$Solar\_PV\_capacity_{US\_likely\_imm} := \frac{W\_GWh_{US\_likely\_imm}}{365 \cdot day \cdot 24 \cdot \frac{hr}{day} \cdot Capacity\_factor_{PV}} = 34717\ GW$$

A total of 406,194 sq. mi. of solar PV farms would be needed to supply the energy required by 618 million Americans in 2100.

$$Solar\_PV\_land\_area_{US\_likely\_imm} := \frac{Solar\_PV\_capacity_{US\_likely\_imm}}{Solar\_PV_{unit\_capacity}} = 406194\ mi^2$$

8.3.5.3 US 2100 population based on the US Census Bureau 2014 update

As determined earlier:

$$Population\_2100_{US\_2014\_update} = 500 \cdot 10^6$$

$$GWh_{2100\_2014\_update} = \left(5.966 \cdot 10^6\right)\ GWh$$

$$Fuels_{2100\_2014\_update} = \left(15.662 \cdot 10^9\right)\ BOE$$

The total GWh of wind-generated electrical energy needed in 2100 for the 500 million Americans, per the US Census Bureau 2014 update, is:

$$W\_GWh_{US\_2014\_update} = \left(49.522 \cdot 10^6\right)\ GWh$$

As the ground solar PV energy infrastructure operates the same as the wind energy infrastructure, the amount of variable renewable electrical energy needed in 2100 remains the same.

If the energy infrastructure was ideal with electrical power being produced continuously, 5,643 GW of nameplate power would be needed.

$$\frac{W\_GWh_{US\_2014\_update}}{365 \cdot day \cdot 24 \cdot \frac{hr}{day}} = 5653.234\ GW$$

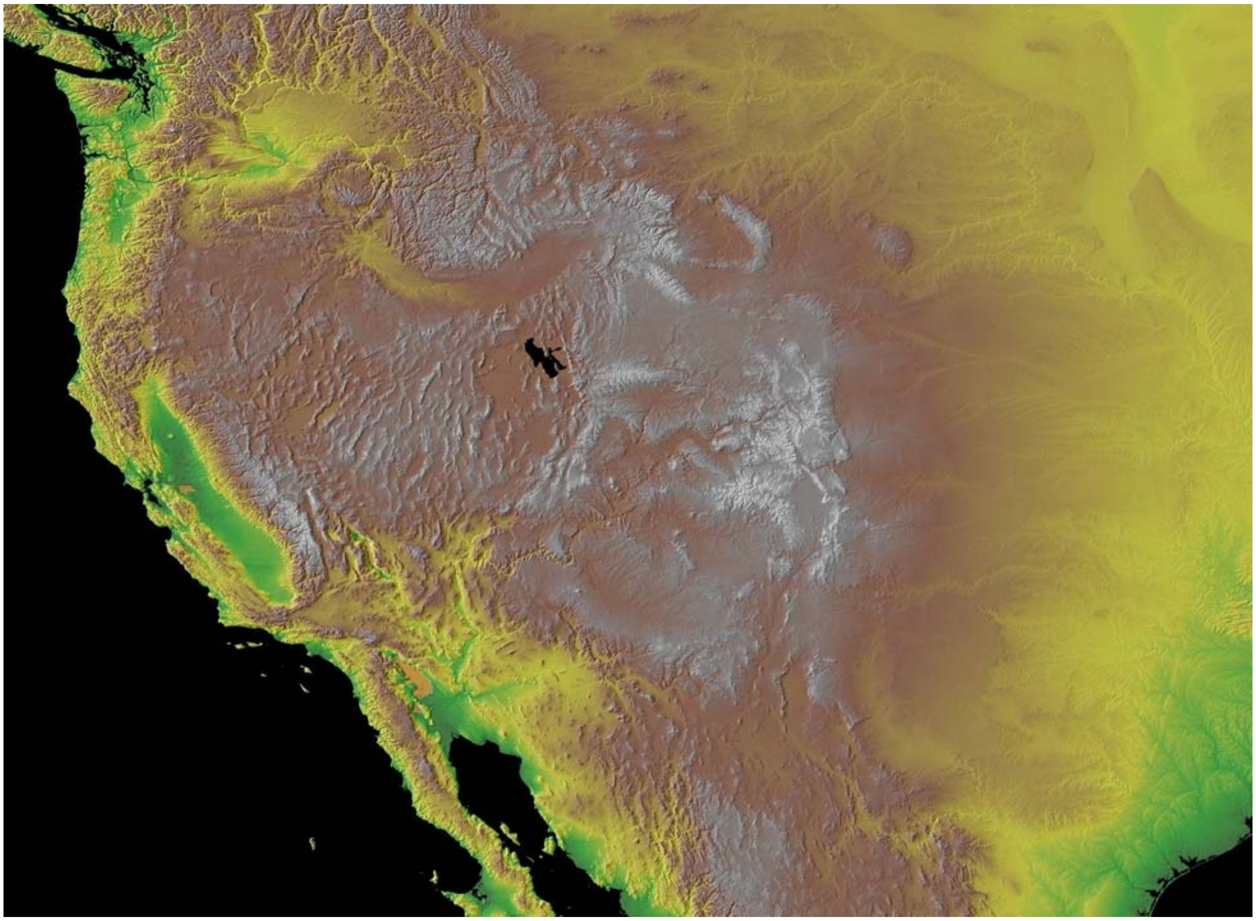
However, the day–night solar cycle and weather must be accounted for by introducing the capacity factor calculated above. This increases the needed 2100 capacity to 28,111 GW.

$$Solar\_PV\_capacity_{US\_2014\_update} := \frac{W\_GWh_{US\_2014\_update}}{365 \cdot day \cdot 24 \cdot \frac{hr}{day} \cdot Capacity\_factor_{PV}} = 28111\ GW$$

A total of 328,902 sq. mi. of solar PV farms would be needed to supply the energy required by 500 million Americans in 2100.

$$Solar\_PV\_land\_area_{US\_2014\_update} := \frac{Solar\_PV\_capacity_{US\_2014\_update}}{Solar\_PV_{unit\_capacity}} = 328902\ mi^2$$

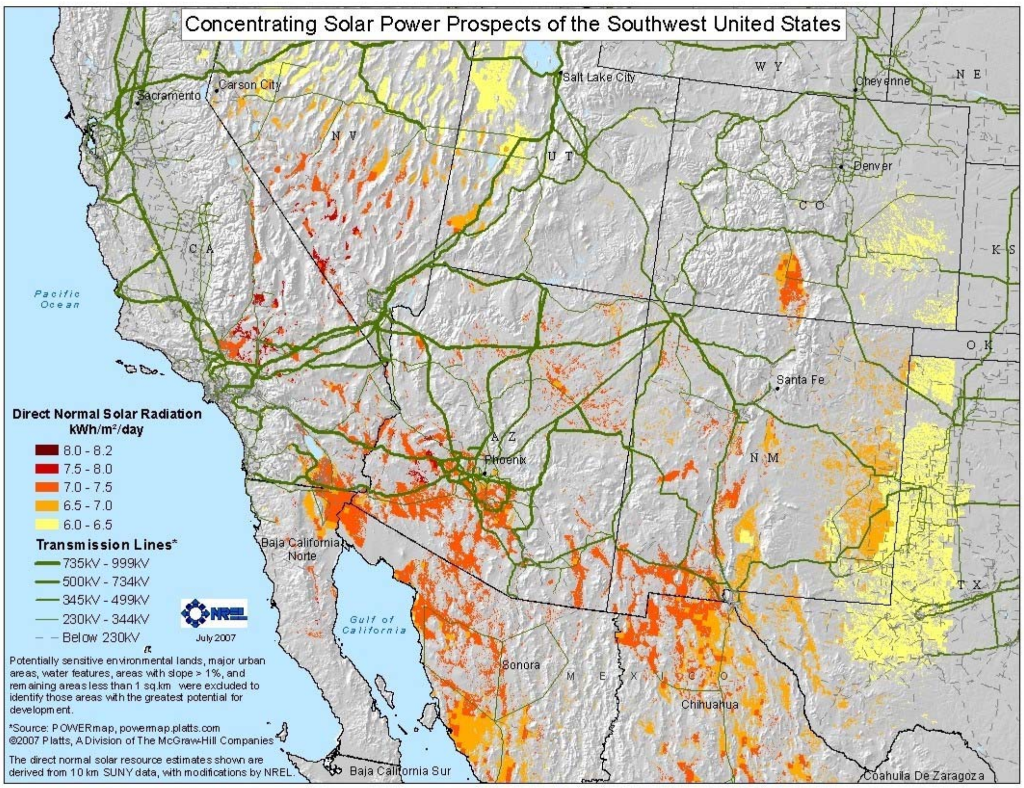
8.4 Available land for solar PV in the Southwestern United States

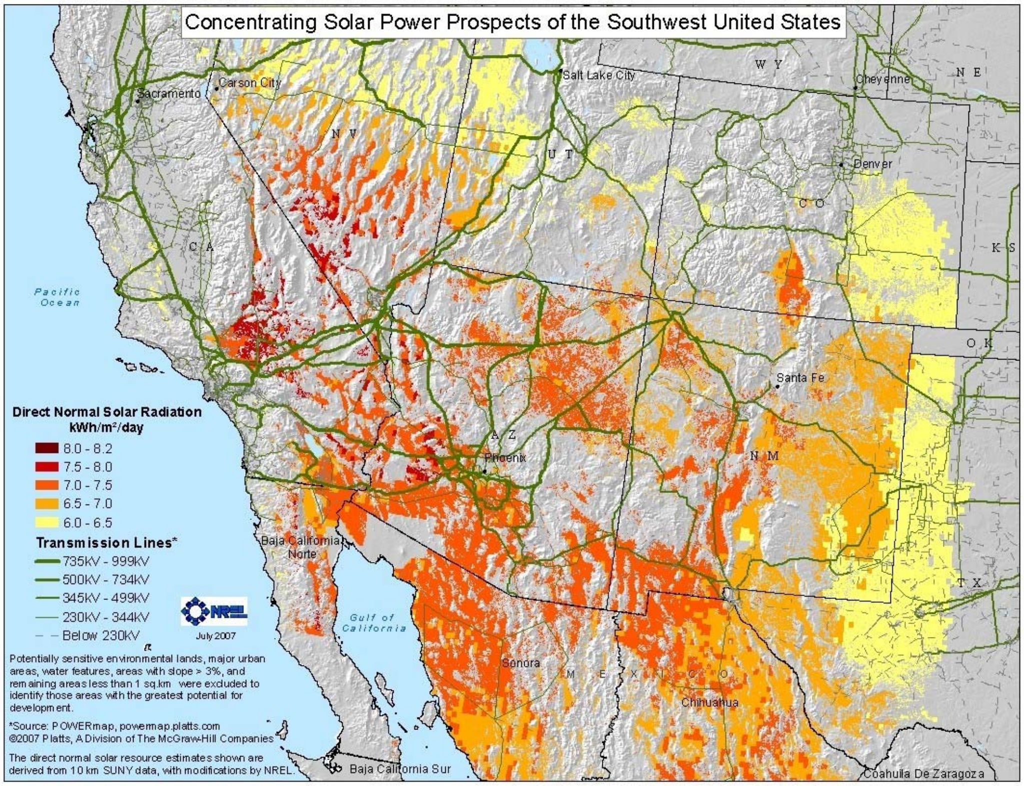


Shaded topographical map of the western United States.
(Source: National Oceanic and Atmospheric Administration)

The earlier maps of the ground solar energy potential imply immense areas of land available for installing commercial solar farms. The map above illustrates the actual terrain of the western United States covering the areas with the highest levels of ground solar isolation. As seen, much of the land is unsuitable or unavailable for installing solar farms.

The following two maps show the land available with slopes less than 1° and 3° and with land area greater than 1 sq. km.





The above maps were prepared for the installation of concentrating solar systems. The requirement that these systems track the movement of the sun across the sky makes their placement on sloped or uneven terrain difficult. While fixed PV arrays can be located on sloped or uneven terrain, this also becomes difficult due to need to terrace sloped land, to grade the land to level it, and the need to accommodate water runoff without erosion. Thus, the above maps are also indicative of the land that could be used for PV farms.

The below referenced NREL presentation noted that the top chart above – identifying land area with a slope under 1 degree and parcels of land greater than 1 sq. km. – had 87,232 sq. mi. deemed suitable. This would only meet 39 percent of the 2100 energy need for the zero immigration case, 21 percent of the 2100 energy need for the most likely immigration case, and 27% of the 2100 energy need of 500 million Americans based on the US Census Bureau 2014 update.

$$\frac{87232 \cdot mi^2}{Solar\_PV\_land\_area_{US\_zero\_imm}} = 39\%$$

$$\frac{87232 \cdot mi^2}{Solar\_PV\_land\_area_{US\_likely\_imm}} = 21\%$$

$$\frac{87232 \cdot mi^2}{Solar\_PV\_land\_area_{US\_2014\_update}} = 27\%$$

Ref: http://votesolar.org/wp-content/uploads/2011/02/NREL_Solar_Tools.pdf

8.5 Combination of maximum wind plus balance from ground solar

8.5.1 Zero net immigration case

The total GWh of wind-generated electrical energy needed in 2100 for the zero net immigration case is:

$$W\_GWh_{US\_zero\_imm} = \left(33.972 \cdot 10^{6}\right)\ GWh$$

1,320,625 sq. mi. of wind farms could be built providing 25.8 million GWh of variable wind-generated electrical power.

Hub height/ Rotor diameter (meter)	Contiguous US Land area (sq. mi.)	Nameplate power (GW)	Nameplate power (GW/sq. mi.)	Power density (MW/sq. mi.)	8 Rotor diameter turbine spacing (mi.)
80/80	634,476	8,019	0.01264	12.639	0.398
110/100	1,320,625	8,654	0.00655	6.553	0.497
140/124	1,787,155	8,471	0.00474	4.74	0.616

$$E\_wind_{potential} = \left(25.775 \cdot 10^{6}\right)\ GWh$$

The deficit in needed variable electrical power is:

$$W\_GWh_{US\_zero\_imm} - E\_wind_{potential} = \left(8.197 \cdot 10^{6}\right)\ GWh$$

Recall:

$$Solar\_PV_{unit\_capacity} = 85.47\ \frac{MW}{mi^{2}} \qquad Capacity\_factor_{PV} = 20.11\%$$

The variable solar-generated electrical power produced per sq. mi. per year is:

$$Solar\_PV\_energy_{unit\_capacity} := Solar\_PV_{unit\_capacity} \cdot 365 \cdot day \cdot 24 \cdot \frac{hr}{day} \cdot Capacity\_factor_{PV}$$

$$Solar\_PV\_energy_{unit\_capacity} = 150.569\ \frac{GWh}{mi^{2}}$$

Required land area of solar farms to provide the balance of variable electrical energy needed for the zero net immigration case:

$$\frac{W\_GWh_{US\_zero\_imm} - E\_wind_{potential}}{Solar\_PV\_energy_{unit\_capacity}} = 54442\ mi^2$$

8.5.2 Most likely immigration case

The total GWh of wind-generated electrical energy needed in 2100 for the most likely immigration case is:

$$W\_GWh_{US\_likely\_imm} = \left(61.16 \cdot 10^6\right)\ GWh$$

The deficit in needed variable electrical power is:

$$W\_GWh_{US\_likely\_imm} - E\_wind_{potential} = \left(35.385 \cdot 10^6\right)\ GWh$$

Required land area of solar farms to provide the balance of variable electrical energy needed for the most likely immigration case:

$$\frac{W\_GWh_{US\_likely\_imm} - E\_wind_{potential}}{Solar\_PV\_energy_{unit\_capacity}} = 235009\ mi^2$$

8.5.3 US 2100 population based on the US Census Bureau 2014 update

The total GWh of wind-generated electrical energy needed in 2100 for the most likely immigration case is:

$$W\_GWh_{US\_2014\_update} = \left(49.522 \cdot 10^6\right)\ GWh$$

The deficit in needed variable electrical power is:

$$W\_GWh_{US\_2014\_update} - E\_wind_{potential} = \left(23.747 \cdot 10^6\right)\ GWh$$

Required land area of solar farms to provide the balance of variable electrical energy needed for the US 2100 population based on the US Census Bureau 2014 update:

$$\frac{W\_GWh_{US\_2014\_update} - E\_wind_{potential}}{Solar\_PV\_energy_{unit\_capacity}} = 157717\ mi^2$$

9. Other US terrestrial renewable energy sources

9.1 Hydroelectricity

Beaver Dam, AR; 112 MW of generating capacity.
(Source: Sean Franklin, Wikimedia Commons, public domain image.)

The US Energy Information Administration reports that the U.S. has 78.6 GW of nameplate hydroelectric generation power. In 2014, the U.S. Department of Energy released an updated assessment of the U.S. potential additional hydroelectric power potential. For this, they evaluated over 3 million streams and rivers. Within those areas where hydroelectric plants could be legally installed, an additional 65 GW of nameplate power could be generated. The estimated average capacity factor was about 60 percent. With growing public opposition to building new dams and with calls for removing some large existing dams, the potential for increasing the US hydroelectric generation capacity is minimal.

Ref: http://www.energy.gov/articles/energy-dept-report-finds-major-potential-grow-clean-sustainable-us-hydropower

9.2 Geothermal-electricity

The Sonoma Calpine 3 geothermal-electricity power station at The Geysers, north of San Francisco, California. (Source: Stepheng3, Wikimedia, public domain image.)

The photograph above is of the world's largest geothermal-electricity power station complex at The Geysers in California. The source of thermal energy is a large magma chamber four miles underground. Water pumped into deep wells flashes to steam from the surrounding hot rock. The steam is brought to the surface where it drives turbine generators. The entire complex at the Geysers has an installed nameplate power of 1.5 GW and operates with an average capacity factor of 63 percent.

The U.S. Energy Information Administration reports that, as of 2013, the U.S. had 193 geothermal-electricity plants with a total installed nameplate power of 3.8 GW producing 15,772 GWh of electrical energy. The average capacity factor was 47 percent. The amount of geothermal-electricity produced in 2013 was only 3 percent of the total renewable energy produced.

In 2008, the USGS completed a survey of geothermal-electricity growth potential. The following quote is taken from their survey's summary. (Note that the units have been changed from MW to GW to be consistent with the above discussion.)

Ref: http://pubs.usgs.gov/fs/2008/3082/pdf/fs2008-3082.pdf

Scientists with the U.S. Geological Survey (USGS) recently completed an assessment of our Nation's geothermal resources. Geothermal power plants are currently operating in six states: Alaska, California, Hawaii, Idaho, Nevada, and Utah. The assessment indicates that the electric power generation potential from identified geothermal systems is 9.057 GW, distributed over 13 states. The mean estimated power production potential from undiscovered geothermal resources is 30.033 GW. Additionally, another estimated 517.8 GW could be generated through implementation of technology for creating geothermal reservoirs in regions characterized by high temperature, but low permeability, rock formations.

As with hydroelectricity, the potential for expanding geothermal-electricity production is very modest—perhaps by 9-40 GW. Hence, with conventional technologies, the potential for geothermal expansion is limited compared to US 2100 energy needs.

Note that the reference to 517.8 GW of additional capacity is for creating new geothermal reservoirs at "great depth" and extracting the thermal energy using new enhanced technologies. The estimated energy generation potential in these areas is only 1.3 MW per sq. mi. This is substantially less than the average value of 85 MW per sq. mi. for ground solar farms which required about 400,000 sq. mi. to meet US 2100 energy needs. Hence, even enhanced geothermal would likely not provide a practical large sustainable energy source.

9.3 Biomass

Biomass, primarily wood, has been an energy source for humans for hundreds of thousands of years. With the decline of wood fuel as a primary U.S. energy source at the end of the 1800s, the use of biomass for energy substantially declined.

According to the U.S. Energy Information Administration, wood fuel provided about 375 million BOE of energy in 2014 – almost as much as hydroelectricity and more than wind and ground solar. This was about 2 percent of the total energy consumed in the U.S. At 50 BOE per capita, wood fuel would be able to meet the energy needs of about 7.5 million people.

$$\frac{375 \cdot 10^6 \cdot BOE}{50 \cdot BOE} = 7.5 \cdot 10^6$$

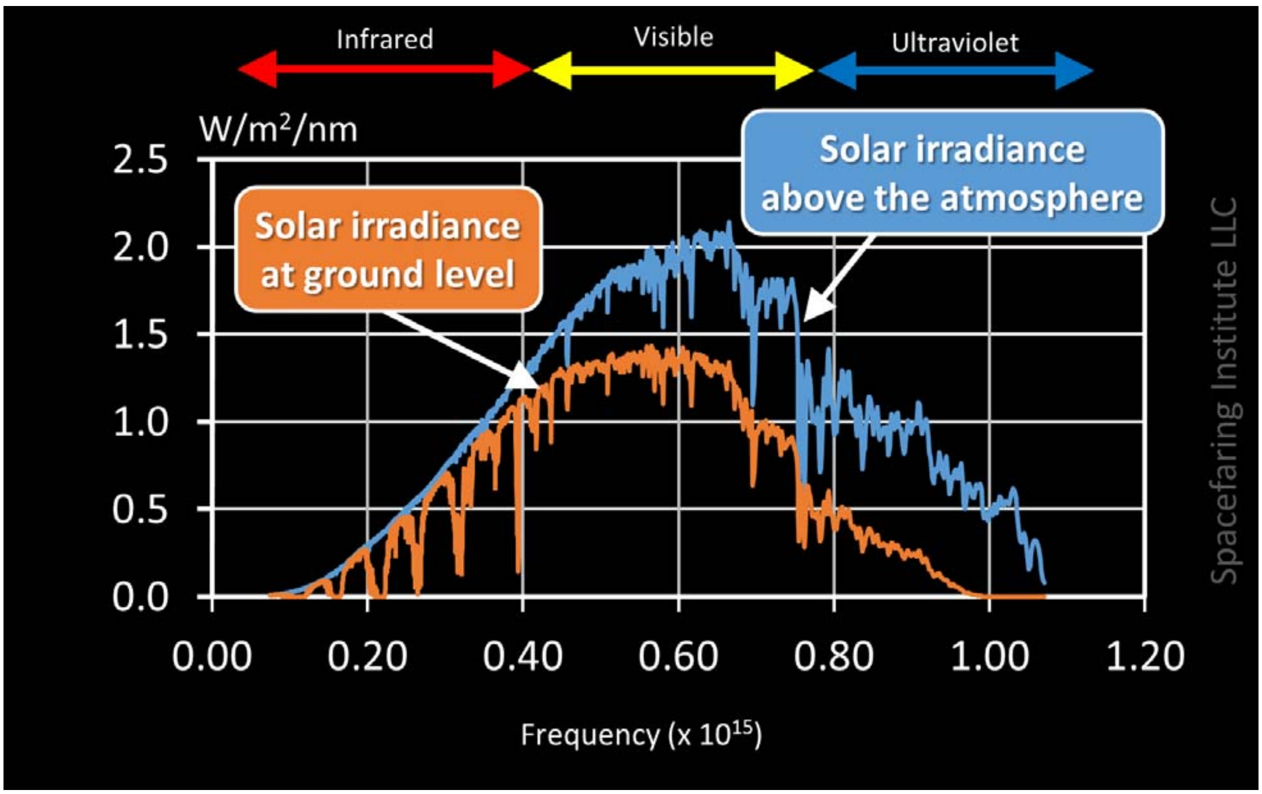
For 2014, corn ethanol provided 190 million BOE. Biodiesel and waste biomass produced another 115 million BOE. In total, biomass produced 680 million BOE or about 4 percent of the energy consumed in the U.S.

10. Space solar power (SSP)

10.1 Space solar power fundamentals

An understanding that sunlight harvested in space could become a power source for human civilization was first mentioned in science fiction in 1941, during World War II, by Isaac Asimov. Peter Glaser received a patent on how this could be accomplished in 1973 – over 40 years ago. This was right after the first oil supply crisis when American oil prices rose dramatically. The concept of the beamed transmission of space-based solar power to the Earth was formally evaluated by a joint NASA-industry team starting in 1978, just prior to the second oil supply crisis. What these investigations found was that the concept was technically feasible.

10.1.1 Solar irradiance level in space



Solar irradiance above the atmosphere and at ground level when looking at the sun. (Data source: National Renewable Energy Laboratory.)

The power (watts per sq. meter) available in sunlight above the atmosphere and at ground level are compared in the chart above. A substantial percentage of the power in the visible and ultraviolet frequencies is absorbed by the atmosphere. This difference provides a power advantage to solar photovoltaic arrays placed in space.

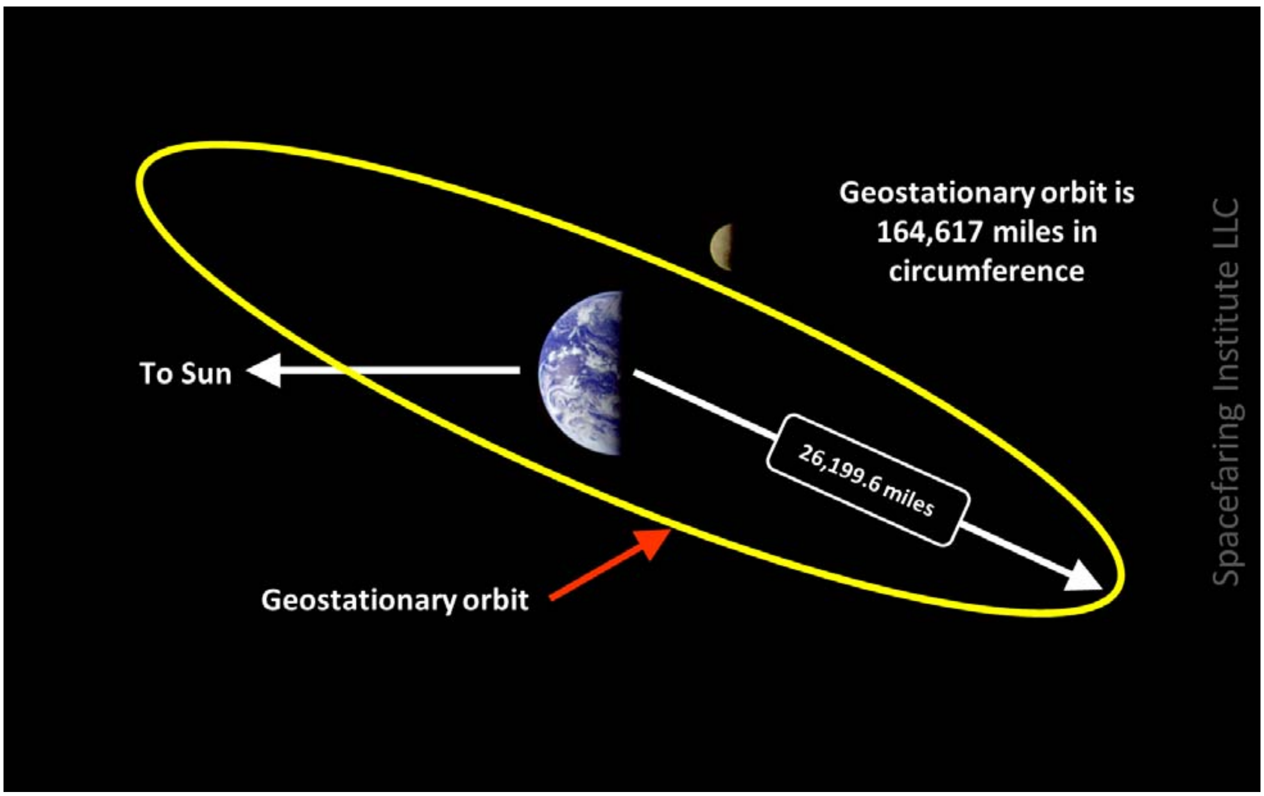
10.1.2 Solar energy available in Earth orbit

In Earth orbit, sunlight delivers about 1,361 watts per sq. meter to a solar array orientated perpendicular to the Sun. This falls to about 1000 watts per sq. meter on the ground. As sunlight is continuous, every 24 hours the available solar isolation will total about 33 kWh per sq. meter. This compares with about 6.5 kWh per sq. meter for the best locations in the United States. Thus, solar arrays in space have a raw solar energy advantage of about 5X every 24 hours.

$$1361 \cdot \frac{W}{m^2} \cdot 24 \cdot hr = 32.664 \frac{kWh}{m^2}$$

$$\frac{32.664 \frac{kWh}{m^2}}{6.5 \cdot \frac{kWh}{m^2}} = 5.025$$

10.1.3 Geostationary Earth orbit (GEO)



Geostationary Earth orbit (GEO.

Because the Earth rotates, orbital mechanics determines that satellites placed in a circular orbit, above the equator, at a height of 26,199.6 miles from the center of the Earth, will circle the Earth in exactly one sidereal day – the time from noon one day to noon the next. Because the satellite appears stationary in its position in the sky for a ground observer, this is called geostationary earth orbit or GEO. The circumference of GEO is 164,617 miles.

Define the geocentric gravitational constant: $\mu := 398600.4418 \cdot \frac{km^3}{s^2}$

Define the length of a sidereal day: $t_{sidereal} := 86164.09054 \cdot s$

Calculate the angular speed of a satellite in GEO: $\omega := \frac{2 \cdot \pi}{t_{sidereal}} = 0.000072921158545 \ \frac{1}{s}$

Calculate the radius of GEO from the Earth's center: $r_{GEO} := \sqrt[3]{\frac{\mu}{\omega^2}} = 26199.6 \ mi$

Define the Earth's equatorial radius: $r_{Earth} := 6378.1 \cdot km = 3963.168 \ mi$

Calculate the height of GEO above the Earth's equator: $h_{GEO} := r_{GEO} - r_{Earth} = 22236.433 \ mi$

Calculate the circumference of GEO: $Circumference_{GEO} := 2 \cdot \pi \cdot r_{GEO} = 164616.944 \ mi$

Calculate the orbital speed in GEO: $v_{GEO} := \sqrt{\frac{\mu}{r_{GEO}}} = 6877.819 \ \frac{mi}{hr}$

Calculate the approximate time required for a SSP platform to pass through the Earth's shadow during the spring and fall equinoxes:

$$\frac{2 \cdot r_{Earth}}{v_{GEO}} = 1.152 \ hr$$

10.1.4 Space solar power platform illustration

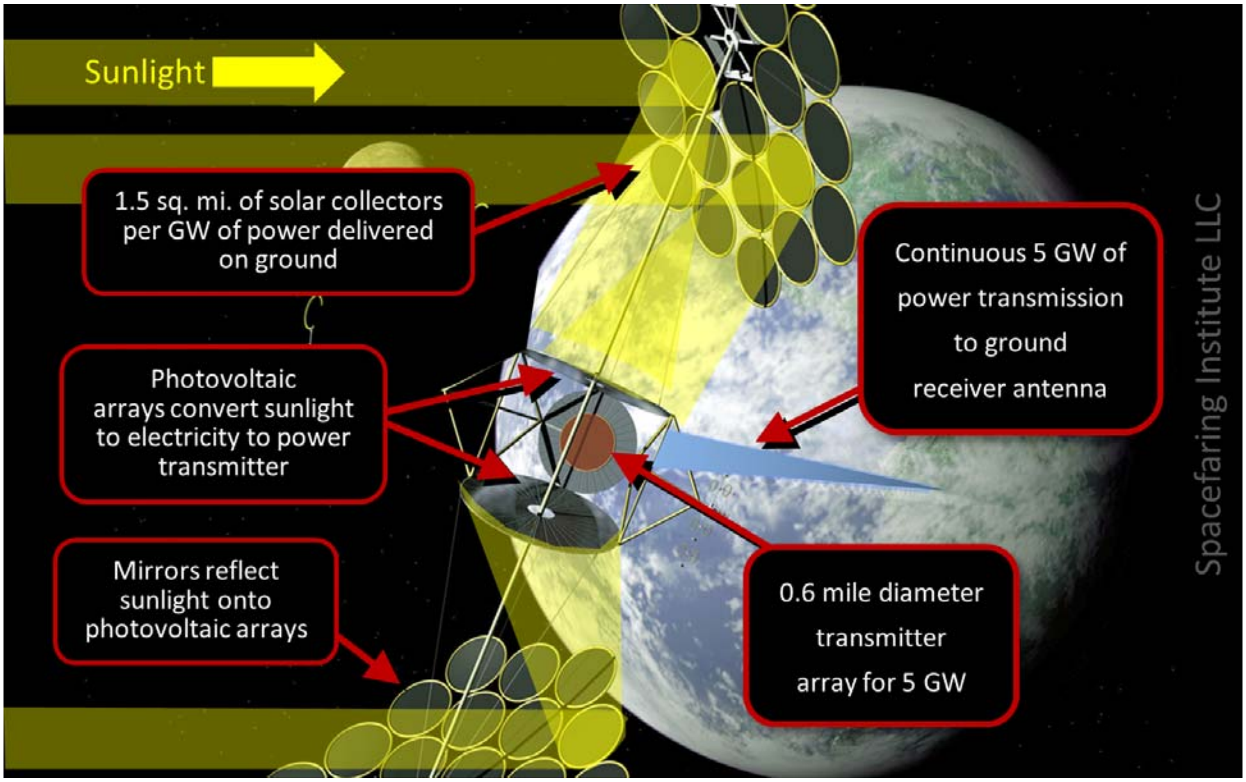


Illustration of a notional GEO space solar power platform. (Original image source: NASA.)

10.1.5 Electrical power produced by space solar power

The above illustration shows how a space solar power platform may function. Large mirrors reflect sunlight onto photovoltaic arrays where the sunlight is converted into electrical power. This electrical power is sent to the transmitting array where it is converted into electromagnetic (EM) radio waves. The array directs the EM radio waves to a ground receiver. The ground receiver converts the EM radio waves back into electrical power and sends this to the utility.

The overall efficiency of intercepting sunlight and delivering this as electrical power to the utility's transmission grid involves several steps, each of which has a conversion efficiency. The total transmission efficiency is a product of each of these individual efficiencies.

Define the solar irradiance at GEO:

$$P_{sunlight\_GEO} := 1361 \cdot \frac{W}{m^2}$$

The following values are believed to be representative of achievable capabilities:

Define the mirror efficiency: $e_{mirror} := 0.90$

Define the GEO PV array efficiency: $e_{PV\_GEO} := 0.35$

Define the internal power transfer and transmitter efficiency: $e_{transmitter} := .80$

Define the air transmission efficiency: $e_{air} := 0.90$

Define the ground receiver/rectifier efficiency: $e_{receiver} := .85$

$$e_{SSP\_overall} := e_{mirror} \cdot e_{PV\_GEO} \cdot e_{transmitter} \cdot e_{air} \cdot e_{receiver} = 19.278\%$$

$$P_{SPS} := P_{sunlight\_GEO} \cdot e_{SSP\_overall} = 0.68 \frac{GW}{mi^2}$$

$$\frac{1}{P_{SPS}} = 1.472 \frac{mi^2}{GW}$$

A notional space solar power platform with these efficiencies would deliver 0.68 GW of baseload electrical power to the utility per sq. mi. of intercepted sunlight.

Ref: John Mankins, *The Case for Space Solar Power*, 2014.

10.1.6 Space solar power ground receiving station

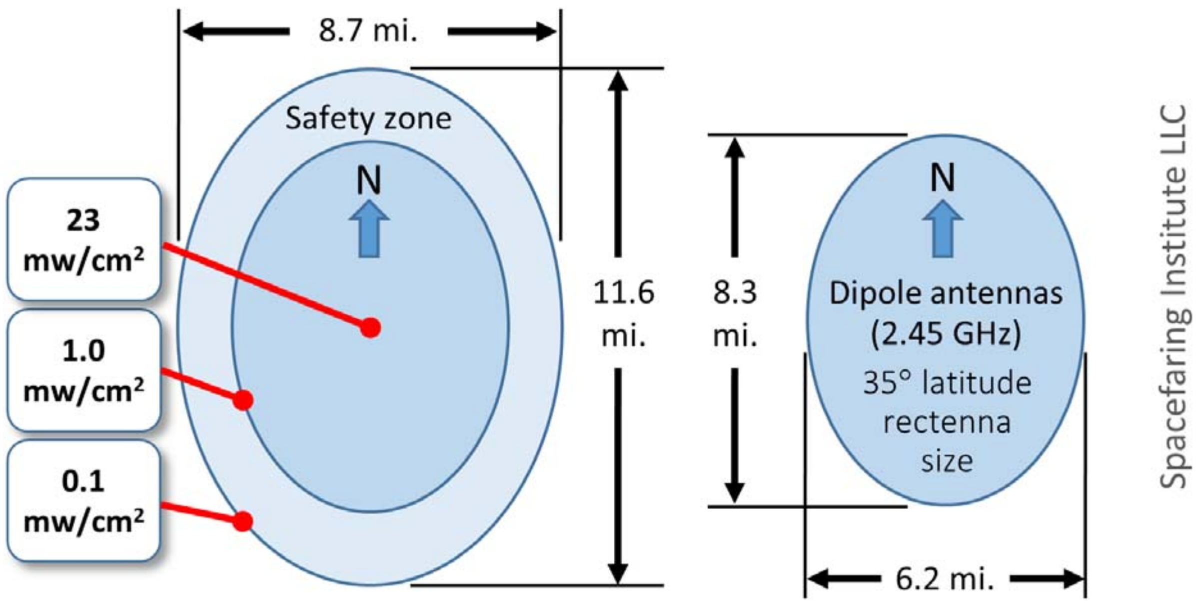


Diagram of a space solar power ground receiving station sized to produce 5 GW of electrical power using 2.45 GHz power transmission. This configuration is designed to prevent dangerous levels of microwave power at the ground level. The power level in the transmission beam is maximum at the center and diminishes to a very low level at the edge of the safety zone. Because of the sparse configuration of the dipole elements in the receiving antenna, the land under the antenna and in the safety zone can be used for normal agricultural activities.

The configuration of a typical space solar power ground receiving station is shown above. This is sized to produce 5 GW of baseload electrical AC power. This particular configuration corresponds to the needs of a GEO space solar power platform transmitting at the 2.45 GHz frequency. The total land area required is about 8 sq. mi. per GW.

$$Land\_area_{SSP} := \pi \cdot \frac{6.2 \cdot mi}{2} \cdot \frac{8.3 \cdot mi}{2} \cdot \frac{1}{5 \cdot GW} = 8.083 \ \frac{mi^2}{GW}$$

$$Land\_area_{SSP\_plus\_safety} := \pi \cdot \frac{8.7 \cdot mi}{2} \cdot \frac{11.6 \cdot mi}{2} \cdot \frac{1}{5 \cdot GW} = 15.852 \ \frac{mi^2}{GW}$$

(Note that the elliptical shape is representative for a receiving station located in the contiguous United States where the northern latitude makes the shape of the transmission beam appear to be elliptical on the ground.)

10.2 Size of all-space solar energy infrastructure required to meet US 2100 energy needs

Using the notional space solar power electrical power generation modeled above, the size of an all-space solar power energy infrastructure is estimated. For this analysis, the capacity factor of space solar power is assumed to be the same as that used previously for modern nuclear power plants. Thus, each GW of space solar power will provide 8,322 GWh of baseload electrical energy.

10.2.1 Zero net immigration case

To meet the energy needs of the 343 million in 2100 using space solar power, a total of 5,204 sq. mi. of space solar arrays would be needed. This would require about 29,000 sq. mi. of land for the ground receiving stations, not including the safety perimeter. Adding the safety perimeter would about double this to 56,000 sq. mi.

As determined earlier:

$$Population\_2100_{US\_zero\_immigration} = 343 \cdot 10^{6}$$

$$GWh_{2100\_zero\_immigration} = \left(4.093 \cdot 10^{6}\right) \, GWh$$

$$Fuels_{2100\_zero\_immigration} = \left(10.744 \cdot 10^{9}\right) \, BOE$$

$$Plants\_total\_2100_{US\_zero\_immigration} = 3537$$

Determine the size of the space solar power arrays needed in 2100:

$$\frac{1}{P_{SPS}} \cdot Plants\_total\_2100_{US\_zero\_immigration} \cdot 1 \cdot GW = 5204 \, mi^{2}$$

Determine the land area required for the ground receiving station:

$$Land\_area_{SSP} \cdot Plants\_total\_2100_{US\_zero\_immigration} \cdot 1 \cdot GW = 28587 \, mi^{2}$$

Determine the land area required for the ground receiving station plus the safety perimeter:

$$Land\_area_{SSP\_plus\_safety} \cdot Plants\_total\_2100_{US\_zero\_immigration} \cdot 1 \cdot GW = 56064 \, mi^{2}$$

Determine the number of 5-GW space solar power platforms needed in 2100:

$$\frac{Plants\_total\_2100_{US\_zero\_immigration}}{5} = 707$$

10.2.2 Most likely immigration case

To meet the energy needs of the 618 million in 2100 using space solar power, a total of 9,369 sq. mi. of space solar arrays would be needed. This would require about 51,500 sq. mi. of land for the ground receiving stations, not including the safety perimeter. Adding the safety perimeter would about double this area to 101,000 sq. mi.

As determined earlier:

$$Population\_2100_{US\_likely\_immigration} = 617.5 \cdot 10^{6}$$

$$GWh_{2100\_likely\_immigration} = \left(7.368 \cdot 10^{6}\right)\ GWh$$

$$Fuels_{2100\_likely\_immigration} = \left(19.342 \cdot 10^{9}\right)\ BOE$$

$$Plants\_total\_2100_{US\_likely\_imm} = 6367$$

Determine the size of the space solar power arrays needed in 2100:

$$\frac{1}{P_{SPS}} \cdot Plants\_total\_2100_{US\_likely\_imm} \cdot 1 \cdot GW = 9369\ mi^{2}$$

Determine the land area required for the ground receiving station:

$$Land\_area_{SSP} \cdot Plants\_total\_2100_{US\_likely\_imm} \cdot 1 \cdot GW = 51465\ mi^{2}$$

Determine the land area required for the ground receiving station plus the safety perimeter:

$$Land\_area_{SSP\_plus\_safety} \cdot Plants\_total\_2100_{US\_likely\_imm} \cdot 1 \cdot GW = 100931\ mi^{2}$$

Determine the number of 5-GW space solar power platforms needed in 2100:

$$\frac{Plants\_total\_2100_{US\_likely\_imm}}{5} = 1273$$

10.2.3 US 2100 population based on US Census Bureau 2014 update

To meet the energy needs of the 500 million in 2100 using space solar power, a total of 9,369 sq. mi. of space solar arrays would be needed. This would require about 41,672 sq. mi. of land for the ground receiving stations, not including the safety perimeter. Adding the safety perimeter would about double this area to 81,725 sq. mi.

As determined earlier:

$$Population\_2100_{US\_2014\_update} = 500 \cdot 10^{6}$$

$$GWh_{2100\_2014\_update} = \left(5.966 \cdot 10^{6}\right)\ GWh$$

$$Fuels_{2100\_2014\_update} = \left(15.662 \cdot 10^{9}\right)\ BOE$$

$$Plants\_total\_2100_{US\_2014\_update} = 5155$$

Determine the size of the space solar power arrays needed in 2100:

$$\frac{1}{P_{SPS}} \cdot Plants\_total\_2100_{US\_2014\_update} \cdot 1 \cdot GW = 7586\ mi^{2}$$

Determine the land area required for the ground receiving station:

$$Land\_area_{SSP} \cdot Plants\_total\_2100_{US\_2014\_update} \cdot 1 \cdot GW = 41672\ mi^{2}$$

Determine the land area required for the ground receiving station plus the safety perimeter:

$$Land\_area_{SSP\_plus\_safety} \cdot Plants\_total\_2100_{US\_2014\_update} \cdot 1 \cdot GW = 81725\ mi^{2}$$

Determine the number of 5-GW space solar power platforms needed in 2100:

$$\frac{Plants\_total\_2100_{US\_2014\_update}}{5} = 1031$$

11. Summary of results

Comparison of US Non-Fossil Fuel Energy Sources for 2100

Energy Source	618 million (Most likely immigration)	343 million (Zero net immigration)	500 million (2014 update)
Nuclear	6,367 GW-years	3,537 GW-years	5,155 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)	52% of 2100 need (3,097 GW-years generated)
Ground Solar	406,200 sq. mi.	225,600 sq. mi.	328,900 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)	1,321,000 sq. mi. (wind) + 158,000 sq. mi. (solar) (49% 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)	41,700 sq. mi. (82,000 sq. mi. with safety perimeter)

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Summary of results:

- Nuclear in 2100
    - Most likely immigration case: 6,367 1-GW nuclear reactors needed
    - Zero net immigration case: 3,537 1-GW nuclear reactors needed
    - 2014 update: 5,155 1-GW nuclear reactors needed
- Wind
    - Available 1.32 million sq. mi. of commercial wind farms in contiguous United States provides:
        - 42 percent of the energy needs of the most likely immigration case
        - 76 percent of the energy needs of the zero net immigration case
        - 52 percent of the energy needs of the US population in 2100 based on the US Census Bureau 2014 update

- Ground solar in 2100
  - Most likely immigration case: 406,200 sq. mi. of solar farms
  - Zero net immigration case: 225,600 sq. mi. of solar farms
  - 2104 update case: 328,900 sq. mi. of solar farms
- Combination of maximum wind from 1.32 million sq. mi. of wind farms with balance from ground solar:
  - Most likely immigration case: 235,000 sq. mi. of solar farms needed
    - Total land use, assuming no combined use, is 52 percent of the land area of the contiguous United States.
  - Zero net immigration case: 54,000 sq. mi. of solar farms needed
    - Total land use, assuming no combined use, is 46 percent of the land area of the contiguous United States.
  - 2014 update case: 158,000 sq. mi. of solar farms needed
    - Total land use, assuming no combined use, is 49 percent of the land area of the contiguous United States.
- Space solar power in 2100:
  - Most likely immigration case: 51,500 sq. mi. of ground receiving station land area with a total of 101,000 sq. mi. needed to include the safety perimeter.

End of the analysis

    - Total land use, assuming no overlapping safety zones, is 3.4 percent of the land area of the contiguous United States.
  - Zero net immigration case: 28,600 sq. mi. of ground receiving station land area with a total of 56,000 sq. mi. needed to include the safety perimeter.
    - Total land use, assuming no overlapping safety zones, is 1.9 percent of the land area of the contiguous United States.
  - 2014 update case: 41,700 sq. mi. of ground receiving station land area with a total of 82,000 sq. mi. needed to include the safety perimeter.
    - Total land use, assuming no overlapping safety zones, is 2.7 percent of the land area of the contiguous United States.

12. Author information

James Michael "Mike" Snead is a professional engineer and Associate Fellow of the American Institute of Aeronautics and Astronautics. He is president of the Spacefaring Institute LLC. His primary focus is on establishing the integrated spacefaring logistics infrastructure required to enable commercial human spacefaring operations throughout the Earth-Moon system. His previous publications can be found at mikesnead.net. He authors the blog SpacefaringAmerica.net and publishes the website SpacefaringInstitute.com.