Analysis of Using Nuclear, Wind, and Ground Solar Energy to Meet U.S. 2100 Per Capita Energy Needs

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Summary (1)

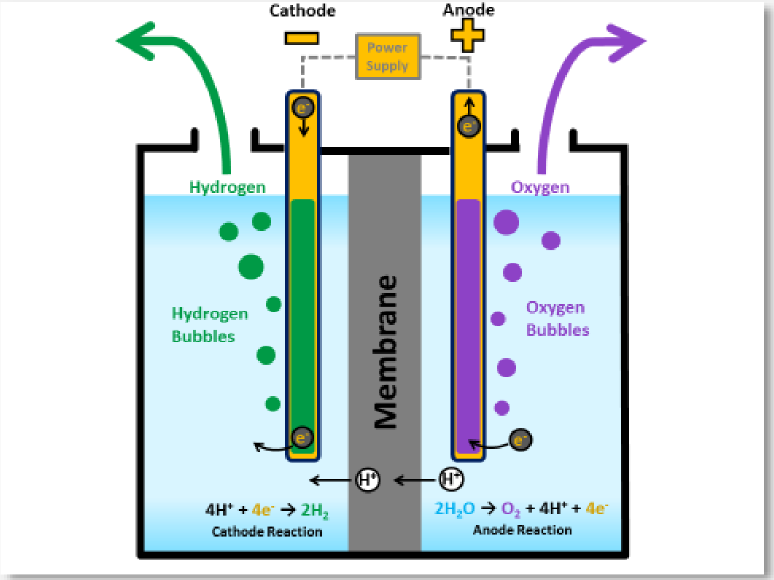
- For Americans in 2100:
  - Annual per capita energy demand is assumed to be 50 BOE, down from 57.749 BOE in 2007.

- To replace fossil fuels, each American in 2100 will require:
  - 85,805 kWh of baseload nuclear-electrical energy to provide 50 BOE of dispatched electricity and hydrogen fuel.
  - 99,066 kWh of variable wind or ground solar electrical energy to provide 50 BOE of dispatched electricity and hydrogen fuel.

Summary (2)

- To meet the U.S. 2100 per capita energy needs and using the DOE 2020 target electrolyzer efficiency:
  - Each 1-GW nuclear power plant, operating 95% of the time, will support 96,987 Americans.
    - No. of GW of nuclear power required per 100 million Americans served = 103 GW
  - Each sq. mi. of commercial wind farms, with a average net capacity factor of 34%, will support 196 Americans.
    - Net commercial wind farm land area required per 100 million Americans served = 510,204 sq. mi.
  - Each sq. mi. of commercial ground solar farms in the Southwest, with a net capacity factor of 20%, will support 1,519 Americans.
    - Net solar farm land area required per 100 million Americans srved = 65,833 sq. mi.

Hydrogen Production by Electrolysis



- Direct current electricity passing through water causes the bonds, holding the water's hydrogen and oxygen atoms together, to break.
- This releases oxygen at the positive anode and hydrogen at the negative cathode.

Hydrogen's Energy Content

- Energy content when used for electricity generation*:

$$H_{HHV} = 134{,}762\,\frac{Btu}{kg}$$

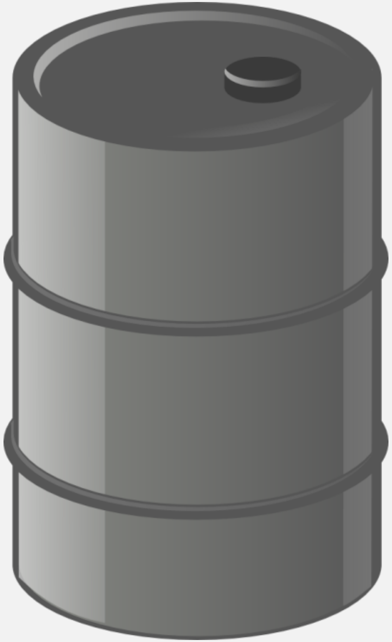
- Energy content when used for transportation**:

$$H_{LHV} = 113{,}939\,\frac{Btu}{kg}$$

* Higher Heating Value used with co-generation systems
**Lower Heating Value used for lower efficiency uses

Source: U.S. DOE Hydrogen Analysis Resources Center

Barrel of Oil Equivalent (BOE)



- Energy content of 42 U.S. gallons of oil
- BOE = 5,800,000 Btu

Mass of Hydrogen Per BOE

Higher Heating Value

$$\frac{5{,}800{,}000\,\frac{Btu}{BOE}}{134{,}672\,\frac{Btu}{kg}} = 43.039\,\frac{kg}{BOE}$$

Lower Heating Value

$$\frac{5{,}800{,}000\,\frac{Btu}{BOE}}{113{,}939\,\frac{Btu}{kg}} = 50.904\,\frac{kg}{BOE}$$

Megawatt-class Future Electrolyzer Efficiency

- U.S. DOE 2020 goal for MW-class electrolyzer*: $44.7 \frac{kWh}{kg}$

* Current experimental electrolyzes are operating in the range of 54–65 kWh per kg indicating that the calculations herein are optimistic.

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

Hydrogen Compressor Energy Requirement

- To use the national gas pipeline infrastructure for distribution, hydrogen is assumed to be compressed to 1200 psi.
  - This requires 0.63 kWh per kg of hydrogen.
- To use hydrogen as a transportation fuel for cars and trucks, requires compression as high as 10,000 psi.
  - This could require 1.6-18 kWh per kg of hydrogen.
- Not all hydrogen will be require high compression.
  - A balanced need for 1.63 kWh per kg of hydrogen is assumed. (This is optimistic.)

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

Electrical Energy Required Per BOE of Hydrogen

- Higher Heating Value use

$$43.039\frac{kg}{BOE} \times (44.7\frac{kWh}{kg} + 1.63\frac{kWh}{kg}) = 1{,}994.0\frac{kWh}{BOE}$$

- Lower Heating Value use

$$50.904\frac{kg}{BOE} \times (44.7\frac{kWh}{kg} + 1.63\frac{kWh}{kg}) = 2{,}358.4\frac{kWh}{BOE}$$

United States Total Energy Use in 2007

- In 2007, prior to the start of the current recession, the United States consumed 101,026.566 trillion Btu from all energy sources.

$$\frac{101{,}026.566 \times 10^{12} Btu}{5{,}800{,}000\,\frac{Btu}{BOE}} = 17{,}418{,}373{,}448\,BOE$$

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

Thermal Energy Used to Generate Electricity in 2007

- Coal, oil, natural gas, nuclear, and renewable energy sources were used to generate electricity.
    - The total generated by each was accounted for.
    - The equivalent total BOE of thermal energy required by each was accounted for.

- A total of 4,156,746 GWh of electrical energy was generated using 6,506,207,055 BOE of thermal energy or nuclear/ renewable equivalent.

Ref: http://www.eia.gov/electricity/annual/html/epa_08_01.html
Ref: http://www.eia.gov/electricity/monthly/xls/table_1_01.xlsx

Breakdown of U.S. Energy Use in 2007

- Total: 17.418 billion BOE

- Electrical energy
  - 4,156,746 GWh
  - 6.506 billion BOE used to generate
  - 37.353%

- Fuels (thermal energy)
  - 17.418 billion BOE – 6.506 billion BOE = 10.916 billion BOE
  - 62.647%

U.S. Per Capita Energy Use in 2007

- U.S. population in 2007 = 301,621,157
- U.S. per capita energy use:

$$\frac{17{,}418{,}373{,}448\ BOE}{301{,}621{,}157} = 57.749\,\frac{BOE}{Per\ Capita}$$

U.S. Per Capita Electricity and Fuel Use in 2007

- U.S. per capita electrical energy use:

$$\frac{4{,}156{,}746 \text{ GWh} \times 1\, million \frac{kWh}{GWh}}{301{,}621{,}157} = 13{,}781 \frac{kWh}{Per\ Capita}$$

- U.S. per capita general fuel use (Lower Heating Value):

$$57.749\, BOE \times 62.647\% = 36.178\, BOE$$

Nuclear-electricity Required Per Capita (2007 Use)

- Annual direct electrical energy need in 2007 = 13,781 kWh

- Annual electrical energy needed to produce hydrogen fuel (Lower Heating Value):

$$36.178\,BOE \times 2{,}358.4\,\frac{kWh}{BOE} = 85{,}322\ \text{kWh}$$

- Total annual electrical energy needed based on 2007 usage:

$$13{,}781\ \text{kWh} + 85{,}322\ \text{kWh} = 99{,}103\ \frac{kWh}{American - year}$$

1-GW Nuclear Power Plant Annual Energy Generated

- Current nuclear power plants operate for about 83% of the year with the down time for refueling and maintenance.
- Assume new generation of nuclear power plant is able to operate for 95% of the time – an optimistic assumption.
- Such a 1-GW nuclear power plant will generate:

$$1\ GW \times 1{,}000{,}000 \frac{kW}{GW} \times 365 \frac{days}{year} \times 24 \frac{hours}{day} \times 95\%$$
$$= 8{,}322{,}000{,}000\ \frac{kWh}{year}$$

Americans Supported Today by 1-GW Nuclear Power Plant

- Using the 2007 per capita energy need, each new 1-GW nuclear power could produce sufficient electrical energy and hydrogen fuel to meet the needs of:

$$\frac{8{,}322{,}000{,}000\ \text{kWh}}{99{,}103\ \dfrac{kWh}{person}} = 83{,}973\ Americans$$

Americans Supported in 2100 by 1-GW Nuclear Power Plant

- 2007 per capita energy need = 57.749 BOE/year
- Assume by 2100, the per capita energy need has been reduced, through improved energy efficiencies and conservation, to 50 BOE/year.
- Each new 1-GW nuclear power plant would be able to meet the annual electrical energy and hydrogen fuel needs of:

$$83{,}973\ people \times \frac{57.749\ BOE}{50\ BOE} = 96{,}987\ \frac{Americans}{GW}$$

Note: The use of optimistic electrolyzer and hydrogen compressor efficiencies coupled with an assumed significant reduction in per capita energy needs means that the estimate above must be considered optimistic.

No. of Nuclear Power Plants Required in 2100

- No. of GW of nuclear power required per 100 million Americans served:

$$\frac{100{,}000{,}000\ Americans}{96{,}987\ \frac{Americans}{GW}} = 1031.1\ GW$$

Note: In the Spacefaring Institute Energy & Environmental Security YouTube video series, for ease of understanding the calculations used in the video, a value of 100,000 Americans per GW in 2100 was used.

Annual Per Capita Nuclear-electricity Need in 2100

- 2007 per capita nuclear-electricity needed to supply dispatched electrical energy and hydrogen fuel = 99,103 kWh per year
- Assume by 2100, the per capita energy need has been reduced, through improved energy efficiencies and conservation, to 50 BOE/year.
- Annual nuclear-electrical energy need in 2100:

$$99{,}103 kWh \times \frac{50\ \frac{BOE}{year}}{57.749\frac{BOE}{year}} = 85{,}805\frac{kWh}{American - year}$$

Wind and Ground Solar Renewable Energy

- The two primary terrestrial renewable energy sources capable of significant expansion in the United States are wind and ground solar.

Use of Variable Wind and Ground Solar Electricity

- Unlike a nuclear power plant, wind turbines and ground solar arrays do not produce continuous electrical power.
- To compensate for this, the variable wind- and ground solar-electricity is converted to hydrogen fuel.
- The hydrogen fuel is used to generate electrical power, on demand, at local electric utilities and is used as a fuel.
- This infrastructure is shown in the following chart.

Wind Energy Infrastructure Model

Variable wind-electricity

Hydrolysis plants

H2

H2 Storage at utility

H2

Gas turbine dispatched electrical power generation

H2

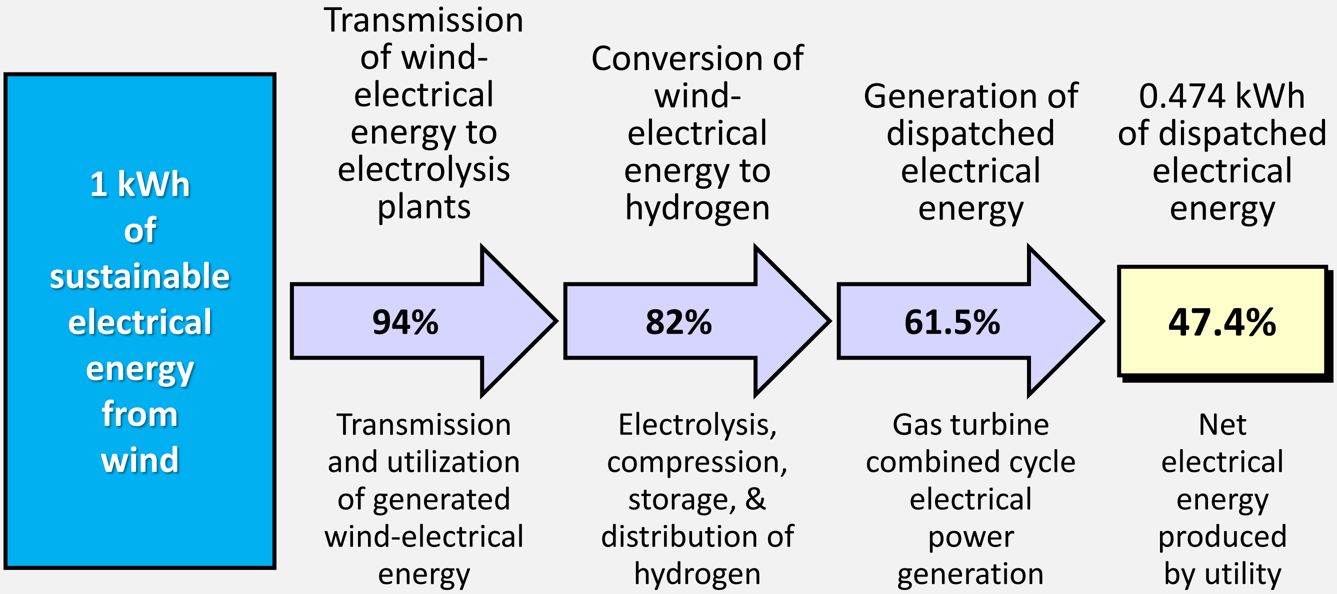
Direct hydrogen fuel use

Converting Variable Wind-electrical Energy into Dispatched Electrical Energy

- Variable wind-electrical energy (or ground solar-electrical energy) can be used to provide “on demand” electrical energy by, first, converting the wind-electrical energy into hydrogen and, then, using the hydrogen to fuel gas turbine generators at the local electric utility when the customer “demands” energy.

- The overall efficiency of this conversion is estimated to be 47.4%, using advanced electrolyzes:
    - 1 kWh of wind-electrical energy will yield 0.474 kWh of utility-provided electrical energy.

Efficiency of Converting Wind-electrical Energy into Dispatched Electrical Energy



Ref: http://www.eia.gov/tools/faqs/faq.cfm?id=105&t=3

Ref: http://www.siemens.com/press/en/feature/2014/corporate/2014-02-lausward.php

U.S. Per Capita Electrical Energy and Fuel Use in 2100

- U.S. per capita energy use in 2007 = 57.749 BOE/yr
- Assumed U.S. per capita energy used in 2100 = 50 BOE/yr
- Percent reduction by 2100:

$$\frac{50\ BOE}{57.749\ BOE} = 86.6\%$$

- Assumed U.S. 2100 per capita electrical energy need:

$$13{,}781\ kWh \times 86.6\% = 11{,}934\ kWh$$

- Assumed U.S. 2100 per capita hydrogen fuel need:

$$57.749\ BOE \times 62.647\% \times 86.6\% = 31.33\ BOE$$

U.S. Per Capita Wind-electrical Energy Required to Meet 2100 Energy Needs

- Wind-electrical energy per capita required to meet annual dispatched electrical energy needs:

$$\frac{11{,}934\ kWh}{47.4\%} = 25{,}177\ kWh$$

- Wind-electrical energy per capita required to meet annual hydrogen fuel needs:

$$31.33\ BOE \times 2{,}358.4 \frac{kWh}{BOE} = 73{,}889\ kWh$$

- Total: $25{,}177\ kWh + 73{,}889\ kWh = 99{,}066\ \frac{kWh}{American - year}$

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Wind Turbine Capacity Factor

- If a power plant operates continuous for the entire year, it has a 100% capacity factor.
- Wind turbines generate useful levels of power only up to about 50% of the year – depending on the location and hub height.
- For commercial wind farms, an average national gross capacity factor of 40%, with an additional operational loss of 15%, is optimistically assumed for hub heights of 100 meters.
  - The assumed average effective net capacity factor is:

$$40\% \times (1 - 0.15) = 34\%$$

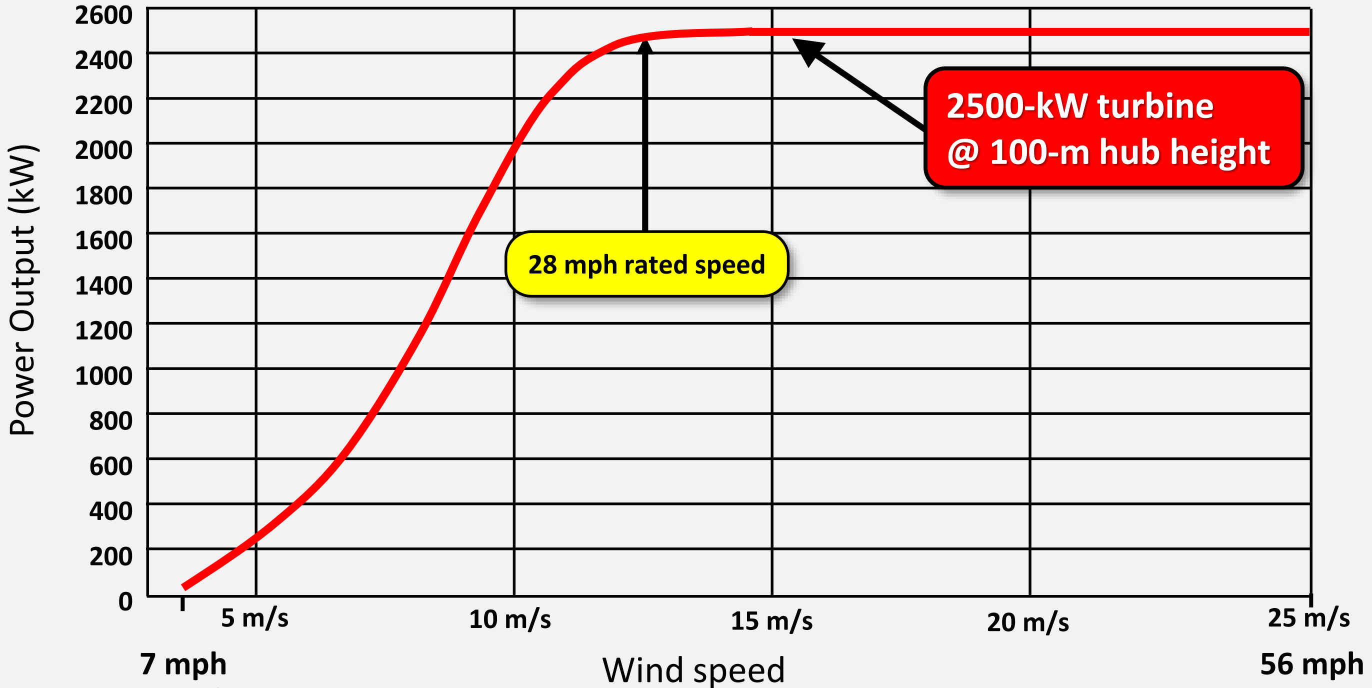
Wind-electricity Available from 2500-kW Wind Turbine

- Commercial wind farms are now installing 500-ft tall wind turbines with a nameplate electrical power generation capacity of 2,500 kW
- A hub height of 100 meters yields an overall ground-to-tip height of around 500 ft.

Assembly of a Commercial Wind Turbine

Installing the Base of a Commercial Wind Turbine

2500-kW Wind Turbine Power Output Curve



Average Annual Wind-electrical Energy Produced by 2500-kW Turbine

- Assumptions:
  - Nameplate electrical power output =2500 kW
  - Capacity factor = 34%

- Annual average wind-electrical energy produced per turbine:

$$2500\, kW \times 365 \frac{days}{year} \times 24 \frac{hours}{day} \times 34\% = 7{,}446{,}000\, kWh$$

No. of Americans Supported by Each 2500-kW Wind Turbine

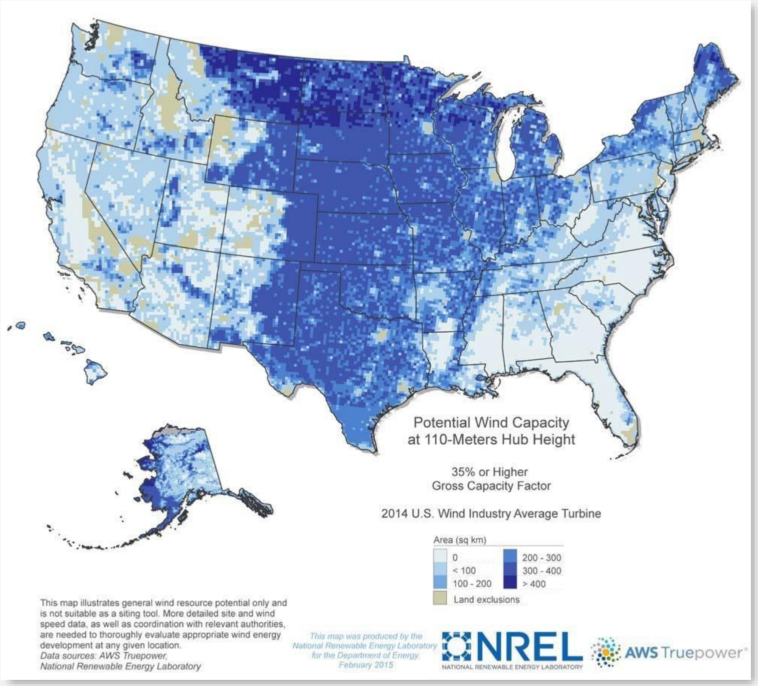
- Average annual variable wind-electrical energy produced by 2500-kW wind turbine = 7,446,000 kWh

- Annual per capita wind-electrical energy needed in 2100 to supply the total dispatched electrical energy and hydrogen fuel needed per capita = 99,066 kWh

- No. of Americans supported by each 2500-kW wind turbine:

$$\frac{7{,}446{,}000\ kWh}{99{,}066\ kWh} = 75\ Americans$$

United States Wind Energy Potential



- The U.S. DOE's National Renewable Energy Laboratory (NREL) provides maps identifying the commercial wind farm energy production potential for various hub heights.
- This map is for a 110-meter hub height.

Variable Electricity Supplied per Sq. Mi. of Wind Farm

- Per the NREL reference, for hub heights of 100 – 110 meters, the installed total nameplate power per sq. mi. is 6,533 kW.
- The number of 2500-kW wind turbines installed per sq. mi. is:

$$\frac{6{,}533\ kW}{2500\ kW} = 2.61$$

- Wind-electricity supplied per sq. mi. of wind farms:

$$7{,}446{,}000\ \frac{kWh}{2500\ kW\ turbine} \times 2.61\,\frac{2500\ kW\ turbines}{sq.mi.} = 19{,}434{,}060\,\frac{kWh}{sq.mi.}$$

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

No. of Americans in 2100 Supported per Sq. Mi. of Wind Farm

- No. of Americans, in 2100, supported per sq. mi. of wind farms:

$$75\ \frac{Americans}{2500\ kW\ \ turbine} \times 2.61\ \frac{2500\ kW\ \ turbines}{sq.mi.} = 196\ \frac{Americans}{sq.mi.}$$

No. of Sq. Mi. of Wind Farms Required

- No. of sq. mi. of commercial wind farms required per 100 million Americans served:

$$\frac{100{,}000{,}000\ Americans}{196\,\frac{Americans}{sq.mi.}} = 510{,}204\ sq.mi.$$

Variable Ground Solar Energy

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The information contained herein does not constitute a proposal and is subject to revision to correct errors and omissions.
No guarantee of the accuracy or usefulness of this information is made.

Ground Solar Energy Infrastructure Model

Variable ground solar-electrical energy

Hydrolysis plants

H2

H2 Storage at utility

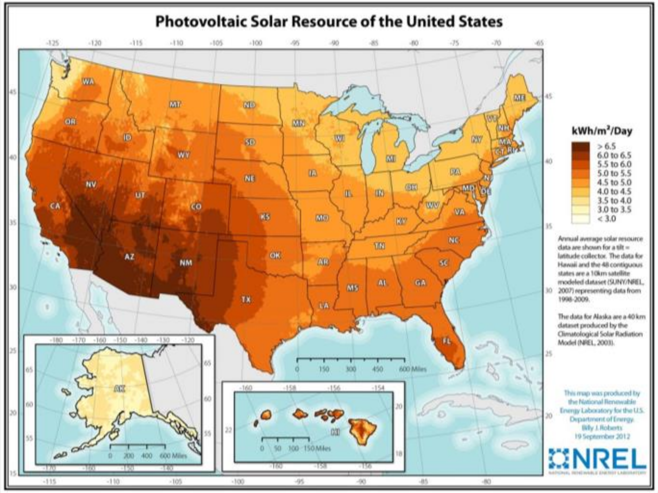
H2

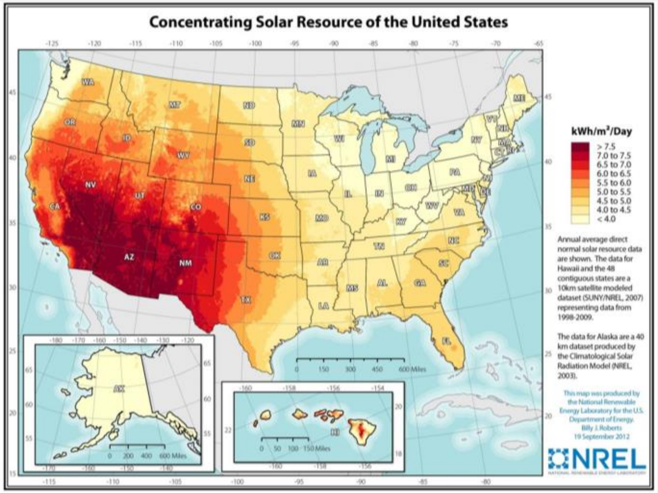
Gas turbine dispatched electrical energy generation

H2

Direct hydrogen fuel use

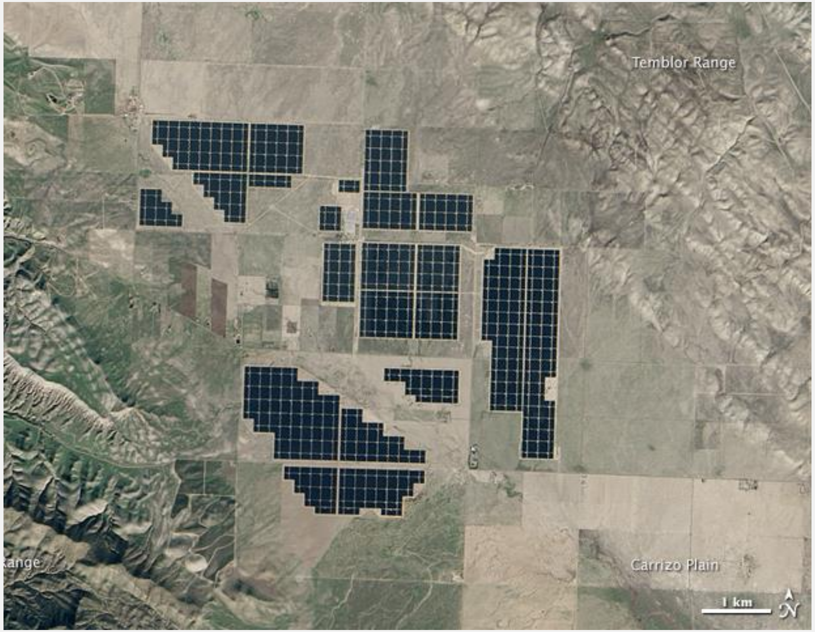
Ground Solar Insolation Maps





Large-scale, commercial ground solar farms will be primarily located in the southwestern states of California, Nevada, Arizona, New Mexico, Utah, southern Colorado, and western Texas.

Topaz Solar Farm



- Land use by commercial solar farms is governed by the local terrain.
- Not all land is suitable for solar farms.

Nameplate AC Power of Existing Commercial Solar Farms

- Topaz Solar Farm (San Luis Obispo County, California)
  - 57.9 MW per sq. mi.
- Agua Caliente Solar Project (Yuma County, Arizona)
  - 59.9 MW per sq. mi.
- Desert Sunlight Solar Farm (Riverside County, California)
  - 88.7 MW per sq. mi.
- Solar Star Farm (Rosamond, California)
  - 115.8 MW per sq. mi.
- Average installed AC electrical power per sq. mi.:

$$\frac{57.9 + 59.9 + 88.7 + 115.8}{4} = 80.6 \ \frac{MW}{sq.mi.}$$

NREL Estimate of Installed AC Power per Sq. Km.

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

Installed Power to Use for Ground Solar Farms

- Per the NREL study, for large photovoltaic solar farms, the average installed AC power is 33 MW per sq. km.
  - This converts to 85.47 MW per sq. mi.

- NREL value closely matches the average of four large solar farms.

Capacity Factor to Use for Ground Solar Farms

- NREL study of utility-grade solar farms established for 2014:
  - Total installed capacity was 8,656.6 MW.
  - Total generated electrical energy was 15,250,000 MWh.

- Actual capacity factor:

$$\frac{15{,}250{,}000\ \frac{MWh}{year}}{8{,}656.6MW \times 365\frac{days}{year} \times 24\frac{hours}{day}} = 20.1\%$$

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

kWh of Ground Solar-electrical Energy Generated per Sq. Mi.

- Installed AC nameplate power per sq. mi. = 85.47 MW
- Capacity factor = 20.1%

- Average ground solar-electrical energy produced per year:

$$85.47\,\frac{MW}{sq.mi.} \times 1000\,\frac{kW}{MW} \times 365\,\frac{days}{year} \times 24\,\frac{hours}{day} \times 20.1\%$$
$$= 150{,}492{,}157\,\frac{kWh}{sq.mi.-year}$$

U.S. Per Capita Ground Solar-electrical Energy Required to Meet 2100 Energy Needs

- These values are the same as for wind-electrical energy.
- Ground solar-electrical energy per capita required to meet annual dispatched electrical energy needs:

$$\frac{11{,}934\ kWh}{47.4\%} = 25{,}177\ kWh$$

- Ground solar-electrical energy per capita required to meet annual hydrogen fuel needs:

$$31.33\ BOE \times 2{,}358.4 \frac{kWh}{BOE} = 73{,}889\ kWh$$

- Total: $25{,}177\ kWh + 73{,}889\ kWh = 99{,}066\ \frac{kWh}{American - year}$

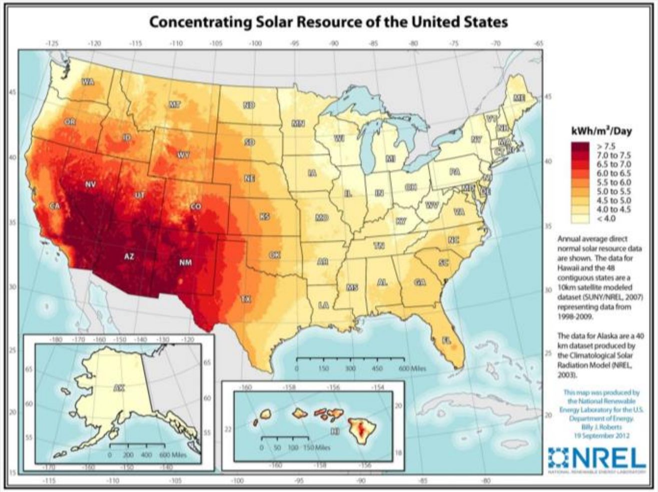
Net Land Area of Solar Farms Required

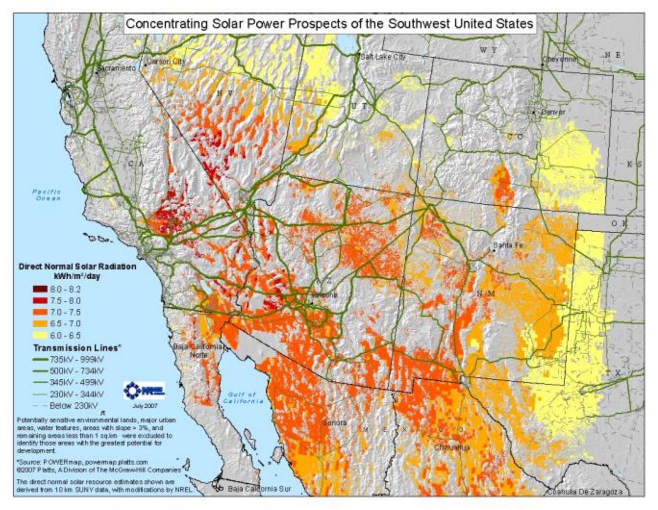
$$\frac{150{,}492{,}157 \, \frac{kWh}{sq.mi.-year}}{99{,}066 \, \frac{kWh}{American - year}} = 1{,}519 \, \frac{Americans}{sq.mi.}$$

- Net solar farm land area per 100 million Americans served in 2100:

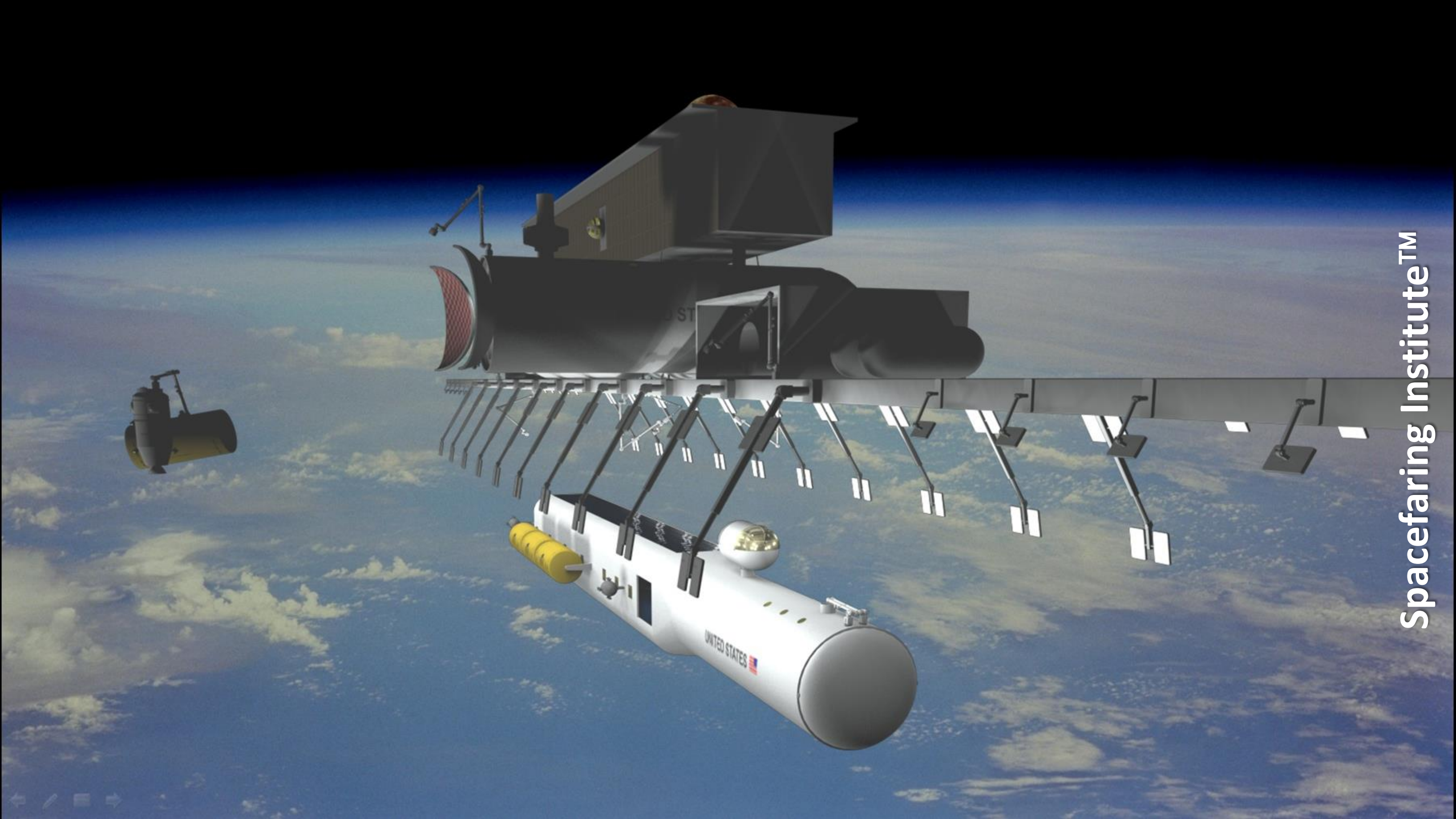
$$\frac{100{,}000{,}000 \; Americans}{1{,}519 \, \frac{Americans}{sq.mi.}} = 65{,}833 \; sq.mi.$$

Land Suitability for Ground Solar Farms





While the map on the left implies that large areas of the southwest can be used for concentrating solar, the map on the right shows that, in reality, only a modest percentage is flat enough. The same is true for photovoltaic farms, as seen in the earlier photo of the Topaz Solar Farm. Hence, the gross land area impacted will be several times the net solar farm land area.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