Solar Power for the United States (Spring, 2016)

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Abstract

What would it cost the United States to transition its electric power capacity to solar? Based on currently operating solar projects, this paper estimates the cost at $17 trillion. Great challenges would exist for a massive conversion to solar power, though none of these appear insurmountable. However, the cost itself would surpass some of the greatest expenditures in U.S. history, such as placing a man on the moon and even fighting World War II. While the posed question is in many respects solely academic, in other respects it confronts us with the costs and other challenges related to our limited carbon future.

Introduction

Interest in renewable energy sources continues to increase as the limitations of carbon fuels become better understood. These limitations manifest as increased cost, more extreme extraction requirements, pollution, and climate change threats. Fortuitously, technology improvements for renewable energy have increased efficiencies and decreased unit costs to the point that we may be on the verge of economic feasibility. However, scale will remain an issue. This paper examines one renewable energy source—photovoltaic conversion of solar energy to electricity—in terms of its requirements for satisfying all U.S. energy demand. About 39 percent of this total demand in the United States is for electricity.

The Nature of Solar Energy as a Renewable Energy Source

The energy contained in sunlight is a function of wavelength. The foolproof method of accounting for solar energy is to count photons, which would result in an insolation unit of Einsteins per unit area (of earth) per time. The more practical method commonly used is to account for insolation in terms of heat. By this means, the "solar constant" is generally recognized to be 2 cal/cm2 per second. About 40 percent of the solar radiation coming to earth is available at the surface. The average solar radiation on a horizontal surface in the United States is about 1.4 million Kcal/m2 year.[1] Seasonal variations and weather make this value vary by about a factor of two at any given time. Given the total surface area of the United States (3.81 million square miles), the total solar irradiation on the United States is 1.38 × 1019 Kcal/year. The average solar irradiation

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[1] W.E. Reifsnyder and H.W. Lull, *Radiant Energy in Relation to Forests,* Tech. Bull. No. 1344, U.S. Department of Agriculture, Forest Service (1965).

reaching the entire earth is about 500 × 1018 Kcal/year.[2],[3] This constant influx (until the sun's demise) represents the potential of "solar energy."

Conversion of this irradiation to useful energy is, of course, the tricky part. Several approaches, including biomass, thermal, and photovoltaics, are being pursued. From an engineering perspective, a successful conversion vehicle must be practical, reliable, and efficient (e.g., cost effective). For example, biomass conversion uses only visible light, which constitutes 50 percent of irradiation. The most efficient conversion (by algae) is perhaps only a few percent of this on the basis of a potential maximum biomass production rate of about 20 gm/m^2 day, gross (i.e., ignoring energy input requirements for aquaculture and harvesting), which would require at least 1 billion acres to satisfy the U.S. energy demand.

Photovoltaic panels currently convert about 15 percent of solar irradiation, at best (laboratory experiments have been as high as 40 percent). Current limitations on photovoltaic use include the cost of silicon-based panels, the effect of heat (most panels are less efficient as they heat up), lost photon-electron reactions (some electron excitations cannot currently be captured), and location requirements. Technology improvements, such as non-silicon-based panels and better electron capture, may someday provide solar panels that run at 30 percent efficiency or more, but the estimate below is based on *current* capabilities.

What Will It Take?

Although it is possible to paint a brighter picture by using theoretical capacities and cost factors, it is estimated that solar capacity to satisfy all US energy requirements would have a capital cost of $17 trillion ($2.4 trillion to satisfy just electricity demands) and a lifetime total cost of over five times that amount. This estimate is based on *actual* installations, today, according to the following basis (also, see Appendix):

- A large-scale photovoltaic system recently installed in Japan:[4]
  - 70-megawatt installed capacity in a 0.5-square-mile area.
  - At a capital cost of $44 million, but a "total investment cost" of $275 million.[5] Although the latter is not explained in the reference, the difference is probably due to land, infrastructure, and lifetime maintenance costs.

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[2] N.K. Boardman, "Solar Energy Conversion in Photosynthesis and Its Potential Contribution to World Demand for Liquid and Gaseous Fuels," Proc. Fourth Int. Cong. Photosyn., Great Britain (1977), 635–644.

[3] M. Slesser and C. Lewis, *Biological Energy Resources*, New York: John Wiley and Sons (1979), 192 p.

[4] American Society of Civil Engineers, *Civil Engineering* 84(1): 22 (January 2014).

[5] "KYOCERA Starts Operation of 70MW Solar Power Plant, the Largest in Japan," Kyocera website (November 5, 2013), accessed December 22, 2015, at: http://global.kyocera.com/news/2013/1101_nnms.html

- A small-scale system installed by the author in New Hampshire:
  - 7.95-kilowatt installed capacity (30 panels).
  - 8,300 kW hr/yr actually produced in 2015.
- U.S. energy demand:
  - 98.49 quads[6] in 2014.

A 2014 date for the U.S. energy demand was selected as the most recent reliable data, but demand and conservation variations make future predictions difficult. To put this value in perspective, the 1975 U.S. energy demand was 75 quads, and the United States used 2 quads in 1850.

Generation rates or efficiencies might be expected to vary with latitude or weather cycles. Surprisingly, the difference is minor. A survey by the Solar Energy Industries Association noted a variation of only about 25 percent around the country for an actual generation rate per installed capacity (e.g., kW hr/kW/yr), with Nevada at the top at about 1,700 kW hr/kW/yr and Vermont near the bottom at 1,200 kW hr/kW/yr.[7] In 2012, Arizona had 1,100 megawatts of installed capacity.[8] The author's own residential system will generate 8,300 kW hr/yr with 8 kilowatts of installed capacity, or 1,050 kW hr/kW/yr (only a partial year of data to date). It is unclear why this value is lower than the survey, but it might be due to different types of systems. Given the relatively small geographical variation of efficiency, the estimate of $17 trillion for the full United States remains reasonable for this analysis.

Discussion of Feasibility

This capital cost estimate is similar to the U.S. GDP, which was $17.4 trillion in 2014. However, vagaries abound, as shown in the cited references that indicate a "total investment cost" of over five times the capital cost. Although cost improvements continue, the spread between capital and "total" in the literature suggests the hidden costs of full implementation such as for land, transmission, maintenance, and replacement.

Scaling the experience in Japan of large-scale installed capacity (0.5 square miles/70 megawatts), an estimated area of 190,000 square miles, or 121 million acres—5 percent of the United States—would be required to satisfy the entire U.S. energy demand. For just electricity demands, 18 million acres would be required.

Cost, practicality (e.g., land availability), and the paradigm change of a new energy future are the significant challenges of a full conversion to photovoltaics. A GDP-magnitude cost implemented over decades is not impossible. For example, companies like Exxon-Mobil have annual revenues of

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[6] A quad is a quadrillion British thermal units. 1 kW hr = 3,400 BTU.

[7] Solar Energy Industries Association (SEIA), "What's In a Megawatt?" (2014), accessed November 11, 2014, at: www.seia.org/policy/solar-technology/photovoltaic-solar-electric/whats-megawatt

[8] Interstate Renewable Energy Council, Annual Update and Trends, Chicago (2013).

$500 billion, which makes their stake in this transition future feasible. Government intervention beyond current subsidies, which are actually useful and effective, will also be required to get these energy companies to retool. Although photovoltaics are growing at impressive rates,[9] they still offer only a tiny fraction of overall demand, and the government could do more now, such as *requiring* installation in new construction. Why not build every new house with photovoltaics and view the capital cost no differently than that of a furnace?

Since our carbon future is clearly limited, a more important question for the paradigm change is: how far should photovoltaics go? Using photovoltaics for electricity needs is an easy consideration, because it would replace the same form of energy and the economics, although painful, might be reasonable. But can solar energy also satisfy other carbon fuel demands, such as for transportation? Another interesting question: is solar energy best generated by a distributed versus a centralized system, or what is the best combination of the two? It is more likely that photovoltaics will play a partial, albeit increased, role in the total U.S. energy future. To put the costs into further perspective, consider some recent major events: the U.S. man-on-the-moon project cost an estimated $200 billion, while World War II cost an estimated $1.6 trillion in today's dollars.

Another challenge will be power transmission. To a large degree, the existing grid can be used and will be particularly adaptable to a distributed system. The existing grid may also be necessary for transmission during dark periods, depending on the final system design (e.g., local storage versus alternative fuel generation). Large, centralized generation in remote locations will still be likely, however, and such transmission will add to the total cost. The amount will depend on the mix of distributed and centralized generating capacity.

Everyone hopes that yet another "technology fix" will bail us out of today's dim energy trajectory. There is no question that photovoltaics will benefit from technology improvements, such as with panel efficiencies and battery improvements. Feasibility is a function of both cheaper solar cells and the higher price of carbon fuels. Every single percentage point of increased operating efficiency might translate to about a $500 billion savings in installed capacity and 8 million fewer acres required. However, photovoltaics look half as feasible with gas at $2 per gallon compared to $4 per gallon.

In addition to these basic economics, we must also focus on bigger matters such as project phasing, the right government–private combination, the best system design, fuel-type substitution, land use, and manufacturing capacity. We tend to be amazingly shortsighted when it comes to energy, perhaps because petroleum has been subsidized for so long in the United States, but one fact is inescapable—our carbon future is limited. Whether carbon fuels last 50 or 500 more years misses the point.

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[9] SEIA (2014).

Appendix: Costs of Solar Power for U.S. Demand

Basis of Analysis

Metric	Figure Used in Analysis	Reference
U.S. Energy Demand	98.49 Quads	For 2014: www.eia.gov *
Large-System Installed Cost	$44 million for 70 MW, "all in"	*Civil Engineering* **
Small-System Installed Cost	$35,000 for 7.95 kW, "all in"	Personal experience
Small-System Generation	8,300 kW hr/yr from 7.95 kW system	Personal experience

* U.S. Energy Information Administration, accessed January 13, 2016.

** American Society of Civil Engineers, *Civil Engineering* 84(1): 22 (January 2014).

Conversions

$$1\ kW\ hr = 3{,}400\ BTU$$

$$1\ Quad = 1 \times 10^{15}\ BTU$$

Calculations

Annual power requirement (total U.S. energy demand):

$$98.49 \times 10^{15} BTU * \frac{1\ kW\ hr}{3{,}400\ BTU}$$

$$= 2.9 \times 10^{13} kW\ hr$$

Unit generation capability:

$$8{,}300\ kW\ hr/yr\ * \frac{1\ yr}{7.95\ kW}$$

$$=\ 1{,}044\ kW\ hr\ /\ kW/yr$$

Total U.S. capacity requirement:

$$\frac{Power\ Requirement}{Unit\ Generation\ Capability}$$

$$= \frac{2.9\ x\ 10^{13} kW\ hr}{1,044\ kW\ hr\ /\ kW/yr}$$

$$= 2.77 \times 10^{10}\ kW$$

$$= 2.77 \times 10^{10}\ kW * \frac{1\ MW}{1{,}000\ kW}$$

$$= 2.77 \times 10^{7}\ MW$$

Cost of total U.S. installed capacity:

$$U.S.\,Capacity\ Requirement\ *\ Large\ System\ Installed\ Cost$$

$$=\ 2.77\times10^{7}\ MW\ *\ \frac{\$44\ Million}{70\ MW}$$

$$=\$1.74\times10^{13}$$

Total Installed Cost of Solar Capacity to Provide Total U.S. Demand: $17 Trillion***

*** Based on New Hampshire generation rates