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The future of solar energy: A personal assessment

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ABSTRACT

To reduce global carbon dioxide emissions substantially by mid-century, electricity generation from solar energy will likely have to be increased dramatically. While the intermittency of the solar resource and the use of rare elements in some current solar technologies are concerns, the most important barrier to a massive scale-up is the current high cost of solar electricity, which will make a dramatic increase in solar deployment politically difficult in many countries. Ambitious publicly-funded research and development efforts aimed at fundamental advances constitute the most plausible approach to substantial cost reductions. Current deployment support programs are generally inefficient, particularly those that favor residential-scale systems, and are less likely to reduce costs substantially.

1. Introduction

Solar energy is a very minor player in global electricity markets today. Globally, solar generating capacity did grow at an average annual rate exceeding 50% from 2004 through the end of 2013 (REN21, 2014). But that growth was from a tiny base, and solar energy accounted for only around 1% of global electricity generation in 2014 (MIT Energy Initiative, MITEI, 2015, ch. 1).

One could easily make a case that solar energy will not become much more important by mid-century than it is today. As discussed further below, despite decades of experience with solar power and substantial recent declines in the prices of photovoltaic (PV) modules, solar electricity remains expensive relative to electricity produced by conventional fossil-fueled plants and even, in many locations, by wind generators. The rapid growth of grid-connected solar electricity, the focus of this essay, has thus necessarily been driven in large part by significant subsidies and binding regulations of various sorts.

At current costs of solar and alternative generating technologies, the subsidy cost of giving solar energy a major global role in electricity generation would be staggering. It is difficult to imagine developing nations bearing such costs, and renewables subsidy fatigue has already emerged in even some rich countries since the Great Recession. There have been significant cuts in solar subsidies in Germany, Italy, and Spain. In the United States, no state has enacted a Renewable Portfolio Standard (which requires distribution utilities to purchase electricity from generators powered by renewable energy) since 2009, and the main federal subsidy for solar facilities, a 30% corporate investment tax credit, is scheduled to be cut by two-thirds at the end of 2016. (The 30% individual income tax credit for residential-scale solar facilities is scheduled to be eliminated completely at that time.)

Not only is it expensive to use the solar resource to generate electricity, the solar energy received at any particular place is *intermittent*: it varies over time, and that variation is only imperfectly predictable. Diurnal and seasonal variations are predictable but troublesome: less solar energy is available in the winter than in the summer, and without bulk energy storage, solar generation cannot help meet demand that occurs between sunset and sunrise. Peak solar generation occurs at noon, while most power systems experience daily demand peaks either considerably earlier or considerably later in the day. In addition, within and between days, rapid and relatively unpredictable variations in insolation can arise from shifting cloud cover.

Despite these limitations, solar energy has the potential to play an essential, leading role in the global energy system by mid-century. The next section explains why. Sections 3–5 then consider the three main potential barriers to its playing that role: the reliance of current solar technologies on rare elements, the intermittency of the solar resource, and the high cost of current solar technologies. The conclusion that emerges is that cost is the most serious of these barriers.

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Section 6 compares alternative approaches to reducing the cost of solar electricity and argues that resources should be shifted from supporting deployment of current technologies to supporting research and development aimed at producing superior new, less expensive technologies that do not use rare materials, as well at developing the economical storage solutions that would be necessary to operate electric power systems dominated by solar generation. Section 7 outlines some of the shortcomings of current deployment support policies, particularly in the United States, and argues that there is little or no economic justification for the widespread use of more generous subsidies for residential-scale solar generation than for larger plants. Section 8 briefly summarizes the main conclusions.

While the focus here is on grid-connected solar electricity generation, it is worth noting that even though the electricity generated by small-scale PV facilities has very high costs, it often has even higher value in developing nations when used in such applications as providing lighting or charging mobile phones. In addition, in developing nations that currently rely on imported oil to generate electricity but that have substantial hydro potential, PV may play a role in an efficient strategy to displace oil. (On both these points, see Rose et al (2015).) Finally, the use of solar energy to heat water directly is a mature technology widely deployed in regions with a favorable mix of high insolation, high prices for natural gas and electricity, and, in some areas, significant subsidies (Maurano et al, 2015).

2. Solar's potential

Solar energy's potential long-term importance ultimately derives from the profound long-term threat posed by global climate change. The emission of carbon dioxide (CO_2) from combustion of fossil fuels is by far the largest source of the greenhouse gases that are driving climate change. Because CO_2 remains in the atmosphere for centuries, slowing the rise in its atmospheric concentration will require an absolute reduction in global emissions. To do this while providing the energy services necessary to accommodate a growing world population with rising living standards, the ratio of CO_2 emissions to global energy use must be substantially reduced.

About two-thirds of CO_2 emissions from fossil fuel combustion are associated with electricity generation, heating, and transportation (International Energy Agency, IEA, 2014a, p. 11). Several energy sources can be used to generate electricity with minimal CO_2 emissions, and electricity can be used to provide heat and transportation. The most plausible way to reduce global CO_2 emissions is thus to increase the role of scalable, very low carbon technologies – wind, solar, hydro, and nuclear – in electricity generation and to increase the use of electricity in transportation and heating.

The International Energy Agency (IEA) recently modeled several scenarios of this sort (International Energy Agency, IEA, 2014b). In these scenarios, in response to the risks of climate change, global energy-related CO_2 emissions were cut to less than half of 2011 levels by 2050 at least cost. In perhaps the most interesting scenario, growth of nuclear power was constrained by non-economic factors, and, of less importance, carbon capture and storage was unavailable. In that scenario, global demand for electricity nonetheless rose by 79% between 2011 and 2050. Wind, hydro, and solar supplied 66% of 2050 generation, with solar alone supplying 27%. This would require increasing solar generation by a factor of more than 50 from its 2013 level (MIT Energy Initiative, MITEI, 2015, ch. 1) If expansion of hydro facilities were to be limited for environmental reasons, as is already the case in the United States and many other nations, solar energy would need to play an even greater role in electricity generation in order to obtain the assumed emissions reductions.

While one can quarrel with the particular results of this study and the many assumptions on which it rests, its basic message seems indisputable: it is hard to see how global CO_2 emissions can be substantially reduced by mid-century without stifling economic growth unless solar electricity generation is *dramatically* increased. The potentially enormous environmental importance of such a scale-up would seem to imply that public policies toward solar technology should focus on enabling it to occur at politically bearable costs. The rest of this essay accordingly adopts that long-term perspective.

The solar resource is enormous, and its scale is not a barrier to the sort of expansion modeled by the IEA. (While the wind resource is also substantial, it is dwarfed by the solar resource (Jacobson and Delucchi, 2011).) Using current PV technology, solar plants covering only about 0.6% of the land area of the continental United States and experiencing average U.S. insolation over the course of a year could produce all the electricity the nation currently consumes. This is about 83% of the land area currently devoted to the production of corn for ethanol, which contributes only about 7% of the energy in U.S. gasoline (MIT Energy Initiative, MITEI, 2015, ch. 1). Land is relatively more abundant (and accordingly relatively less costly) in the United States than in some other nations, particularly in the E.U., but it is difficult to imagine that scarcity of land would be a significant constraint on expansion of solar generation except, possibly, at very high levels of penetration.

The geographic distribution of the solar resource is not a barrier to massive expansion of solar generation either. Globally, the solar resource is broadly distributed, with insolation varying by less than a factor of three among densely populated areas. Among nations for which data exist, average insolation varies across a much smaller percentage range than 2011 GDP per capita, and there is a weak negative correlation between these quantities. Poorer nations are not disadvantaged in their access to the solar resource (MIT Energy Initiative, MITEI, 2015, ch. 1).

3. Use of rare elements

It is important to ask whether the dramatic scale-up in the IEA scenario just discussed is physically and economically plausible. Capital and labor can be expected to be available in elastic supply over the relatively long period involved, so the major potential barrier would be sharply rising costs or effective unavailability of materials that are not earth-abundant or that do not exist in deposits with sufficiently high concentration to make their extraction possible at reasonable cost.

Current concentrated solar power (CSP or solar thermal) technology, in which the sun's energy is used to heat a fluid that in turn is used to produce steam to drive a turbine connected to a generator, accounted for about 3% of solar generating capacity at the end of 2013 (REN21, 2014). This technology does not use any rare materials and so should encounter no materials-related barriers to scaling up substantially without sharp cost increases.

Today's dominant PV technology, first deployed (on a U.S. satellite) in 1958, is based on crystalline Silicon (c-Si) wafers. Silicon is one of the most abundant elements in the Earth's crust, but current c-Si technologies require silver for electrodes. About 10% of global silver production is currently used in PV modules. While silver production can no doubt be expanded, reducing the per-module use of silver (perhaps by substituting copper or some other abundant element) would likely be necessary to enable massive expansion of c-Si capacity at costs around today's levels. This is clearly a promising area for applied research, and such research is ongoing.

About 10% of current global PV sales is accounted for by several thin-film technologies, notably cadmium-telluride (CdTe), that use relatively rare elements. Tellurium is roughly as abundant as platinum in the Earth's crust, and it is produced exclusively as a by-product of the production of other metals. It is unlikely that production of CdTe solar cells could be scaled up by a factor of 50, certainly not without dramatic increases in the cost of Tellurium. Similar problems of this sort affect other commercial thin-film technologies that use gallium, indium, and selenium. However, there are emerging thin-film PV technologies use