Analysis of Solar City Video
Uncovering the Assumptions

Bruce Emerson

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1 Source and Data Provided

In our discussions in GS104 we have considered the question of whether it is possible to replace some or all of our energy use with sustainable (as opposed to renewable) sources of energy. Our guide in this discussion has been the book by David MacKay titled "Sustainability without the Hot Air". Both for England and for the US it appears that it is certainly possible in the sense that there are ways in which we could demonstrably meet our current energy needs though it takes some significant effort. Recently Solar City has put up a short video that asserts that solar energy could meet the power needs of the US with relatively little area dedicated to the task. The actual statement only implies that they are talking about meeting ALL of our energy needs. The map shows three small regions in southern California, Phoenix area, and New Mexico suggesting this is all the real estate that is needed. Here are the core assertions of the video.

1: We can do it
All of the US power needs - "completely power" - can be met with solar PV panels

2: Current Generation from Solar
0.6 percent of our power comes from solar panels (2015).

3: What is the need?
Total need is stated as $4 \cdot 10^6$ GWh.

4: Current efficiency for generation of solar power
The generation of 1 GWh annually from 2.8 acres of solar panels is the stated efficiency.

5: How much area is needed?
These numbers lead to $11.2 \cdot 10^6$ acres which is 0.6 percent of the total area of continental US.

6: Lets do it in 7 years like the moon shot!
No particular description of what it would take relative to current build out rates or material availability.

2 US Energy Use

The Lawrence Livermore National Lab puts out an annual flow chart of the overall energy usage for the US which I have linked so you can find updated information in the future. I have found this flow chart among the most useful tools for general energy discussions like these and I am confident of it's essential correctness. I have checked many of the numbers against other sources and the agreement is consistent. For this discussion the important numbers are the total energy consumption of 97.5 Quads, the total electrical generation of 12.6 Quads, and the solar energy generation of 0.53 Quads.

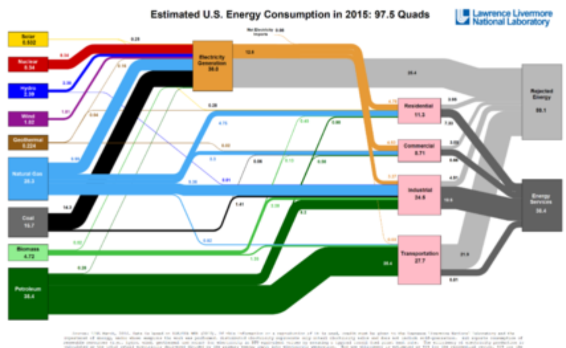

Figure 1: Lawrence Livermore National Labs: US Energy Flow

It bears mentioning at this point that the Solar City video contains a common communication error by confusing power with energy. This is a central concern for the science community which warrants a quick clarification. Energy is what we use to light our homes, run motors, and any other useful task. Energy is the currency of the universe and there are lots of ways to measure it but a common one is kWh (kilowatt-hours). 1 kilowatt-hour is the energy that is used as we run a small space heater or hair dryer continuously for 1 hour. Power is the rate at which we use energy and is usually measured in watts, kW (kilowatts), or even MW or GW (millions and billions of watts). The conceptual confusion is reinforced by the reality that high power objects also tend to use more energy than lower power objects if we overlook the impact of time. It is perhaps useful to notice that a 40 Watt light bulb running all day (lower power, long time) uses the same energy as a 1 kW hair dryer running for 1 hr (higher power, shorter time). Each uses 1 kWh of energy but the hair dryer uses the energy roughly 24x faster.

The next step in sorting out the facts is to make the appropriate conversions so we can compare the numbers on the flow chart to the numbers in the video. To do that we need to be able to express quads in kWh.

1 Quad = $0.3 \cdot 10^1 2$kWh (0.3 billion kWh)
or
1 Quad = $0.3 \cdot 10^6$GWh (0.3 million GWh)

So here's how the numbers on the flow chart convert to more useful units of energy. Note that I have been a little casual with the numbers and have rounded them off a little to preserve clarity without real loss in relevance.

Total Energy: 97.5 Quad = 30 million GWh

Electrical Energy Generated: 12.6 Quad = 4 million GWh

Current Solar Energy: 0.54 Quad = 1/6 million GWh

We can now clarify a couple of assertions in the video. The video is apparently only talking about replacing our current electric power generation capability with solar panels NOT the total energy needs of the country. In rough terms the total energy used in the US is 8 times the electric energy we currently use.

It is worth taking a moment to use these numbers to determine our individual daily energy use since this is often used as a marker for the standard of living in different parts of the world. To do this we need to divide the 30 million GWh among the 320 million citizens in the country and the 365 days in a year.

30 million GWh $= 30 \cdot 10^6 \cdot 10^9 Wh = 30 \cdot 10^{15} Wh$

daily energy use per person $\frac{kWh}{person \cdot day} = \frac{30 \cdot 10^{15} Wh}{320 \cdot 10^6 people \cdot 365 days}$

$= 259 \frac{kWh}{person \cdot day}$

This result is completely consistent with the typically accepted value of 250 kWh/$(p \cdot day)$. Good to know that everything is matching up!

3 Current Solar Generation

The total solar energy generated (0.53 Quads) is roughly 0.6% of the total energy usage of the country though it is important to note that there are number of solar energy technologies that contribute this energy source. Indications are that most of this solar energy generation is now in the form of PV panels though it warrants further investigation to appreciate the details. A common concern for the solar PV industry is the awareness that PV panels generate power during daylight hours peaking in the middle of the day while use rates tend to peak in the evening after sunset. There are strategies for responding to this challenge and others related to the distribution of electric power which are important collateral discussions but not directly relevant to fact checking this video.

4 Current Solar Generation Efficiency

The next key number is what could be described as the efficiency of solar energy generation. This is a complex determination that depends on many factors including solar cell efficiency and weather at the location of the facility to less obvious considerations like the topography of the site, choices about tracking and orientation, and other factors. At the level of this discussion what we want to know is how much energy (GWh) can I generate from some average piece of real estate.

A starting point for all such discussions is to decide what units we will use to compare different examples of solar power. In spite of the fact that we still use acres and square feet to discuss surface area it makes much more sense to use units that allow us to compare data from installations around the world where the metric system is ubiquitous. For that reason I am going to proceed by determining the average power generation capacity (not energy!) for each square m in W/m^2. In these units David MacKay estimates that typical utility scale PV systems in England can generate an average of 22 W/m^2 day in and day out through the year. Just a reminder that this average power output (not energy) assumes that energy is steadily being generated 24/7 throughout the year even though it is really be generated in a much more variable way.

The first check that is worth doing is to look at the average power generation rate given in the video. The data provided is that 2.8 acres generates 1 GWh of energy over a year. Here's how the calculation goes:

$$\text{average power generation} = \frac{1 \cdot 10^9 Wh}{1yr \cdot 2.8acres} \cdot \frac{2.5acres}{10^4 m^2} \cdot \frac{1yr}{8760hrs}$$

$$= 10.2\ \frac{W}{m^2}$$

This seems pretty consistent with the numbers from David MacKay's discussion. Let's do one more quick check. A plausible check is the Topaz Solar Farm which generated 1100 GWh of energy in 2015 from an array with an area of 25 km^2. A quick conversion (1 km^2 = 247 acres) indicates that it takes 5.6 acres to generate 1 GWh. Just looking at our previous result this says that the overall power generation efficiency for this array is around 5 $\frac{W}{m^2}$. All in all it does not seem that the video is being unreasonable in it's assumptions though it is assuming production efficiencies that are about twice what has been currently demonstrated.

5 Area Needed

Looking strictly at the given task of generating 4 million GWh of energy that is our current national use of electric energy the data suggests that this will take between 5 million and 25 million acres depending on which end of the efficiency scale one chooses. The calculation in the video is completely correct for the assumptions they make which leads to 12 million acres. For those who prefer a more global expression of these numbers the range is from 20 billion to 100 billion m^2 ($20 \cdot 10^9$ to $100 \cdot 10^9 m^2$).

Getting a sense of perspective on what this much area means is challenging since we just don't think in these terms very often. I like to use Oregon as a visual reference since it is pretty rectangular. Oregon's area is 255 billion m^2 (63 million acres) so the area being discussed is pretty much 20% of the area of Oregon. It's a little hard to tell from the video but the area shown, which is broken into 3 smaller chunks, does seem to match up pretty well. It's interesting that they choose to break the area up so the isolated pieces seem smaller in the context of the whole United States. Since Oregon is roughly 3% of the total area of the United States the assertion in the video that this area represents just 0.6% of the area of the continuous 48 states is also entirely correct.

A couple of things that are worth noting. The first is that if we take current utility scale installations as our model then this estimate of the area needed should be pretty much doubled to 40% of the area of Oregon or a third of the state of Arizona. The second consideration is that if we want to address the overall energy problem we would need to multiply all of these pervious answers by about 8. There are a host of other issues that come up as we think about the overall situation that make it much less simple than just multiplying by 8. It does suggest that the solution to all of our current energy needs would require areas equivalent to something between 1 and 3 "Oregons".

6 Timeline: Possible Moonshot

Finally, the video offers us the current social meme of the 'moonshot' as a model for meeting this goal in 7 years. To address this question we need to develop a few more ideas. One the core confusions about power and energy generation derives from our difficulties in distinguishing clearly between power and energy. The Topaz Solar project mentioned earlier has a capacity of 550 MW or 0.5 GW. What this means is that if it was running at maximum capacity it would generate 1 GWh of energy every 2 hours. The project actually produces 1100 GWh. We can develop a number which allows us to relate these two numbers by dividing the actual energy produced by the maximum capacity of the project.

$$\text{production capacity} = \frac{EnergyProduced}{PowerCapacity} = \frac{1100GWh}{550MW}$$

$$= 2\ \frac{GWh}{MW}$$

It is not at all clear whether this number changes as the density of the solar array increases. All of the current utility scale PV generation facilities show very similar capacity factors. For the purposes of discussion I will use 2 GWh/MW while noting that is easy to imagine the effect of 4 GWh/MW which would be twice as 'efficient'. We need to approach the question of how fast we can build solar power generation this way because the industry data is presented in installed power capacity rather than actual energy generated. What we can now say is that if we need to generate 4 million GWh of energy we will need to have an installed power capacity of 2 million MW.

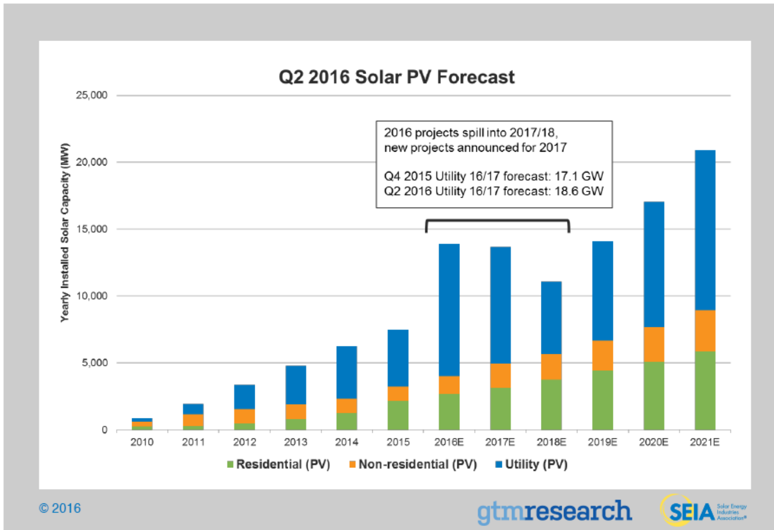

Figure 2: Recent Solar PV Installation

As you can see from the following figure the industry projections for the construction of new PV power projects is about 10,000 MW annually. At this rate it will take 100 years to install 1 million MW of capacity and 200 years to reach 2 million MW of capacity. If you look at the data from before 2016 we were typically installing less than 5,000 MW of capacity annually which would roughly double our numbers above. We would need to build solar PV plants at roughly 30 times our current rate to achieve the offered challenge to create 4 million GWh of energy generation in 7 years. If the energy generation efficiency were to improve to 4 GWh/MW things look a little better but we're still going to have to ramp it way up to meet the challenge. Remember that the discussion here in only about replacing our current electrical needs with solar PV and our total energy needs are 8 times that in round numbers.

Some readers may be worrying about potential growth in our energy needs and I would encourage them to look back at past energy flow charts available from the LLNL. It appears that our energy needs have not grown noticeably for a number of years perhaps because our population have been reasonably stable as well as some inherent gains in efficiency of energy use as people move to more urban environments.

7 Summary

If you have jumped to this part of the discussion looking for 'the answer' here it is in a nutshell. The numbers presented in the video are legitimate and consistent with other sources of data. It is important to remember that what is being discussed is using solar PV installations to meet the current electrical energy needs of the US which are about 1/8th of our total energy needs. What is being suggested is totally possible though the hope to do it in 7 years via some 'moonshot' effort seems very unlikely since it would require a 30 fold increase in our current rate of PV installation.

Please feel free to contact me at bemerson@cocc.edu if you have concerns or questions about this analysis.