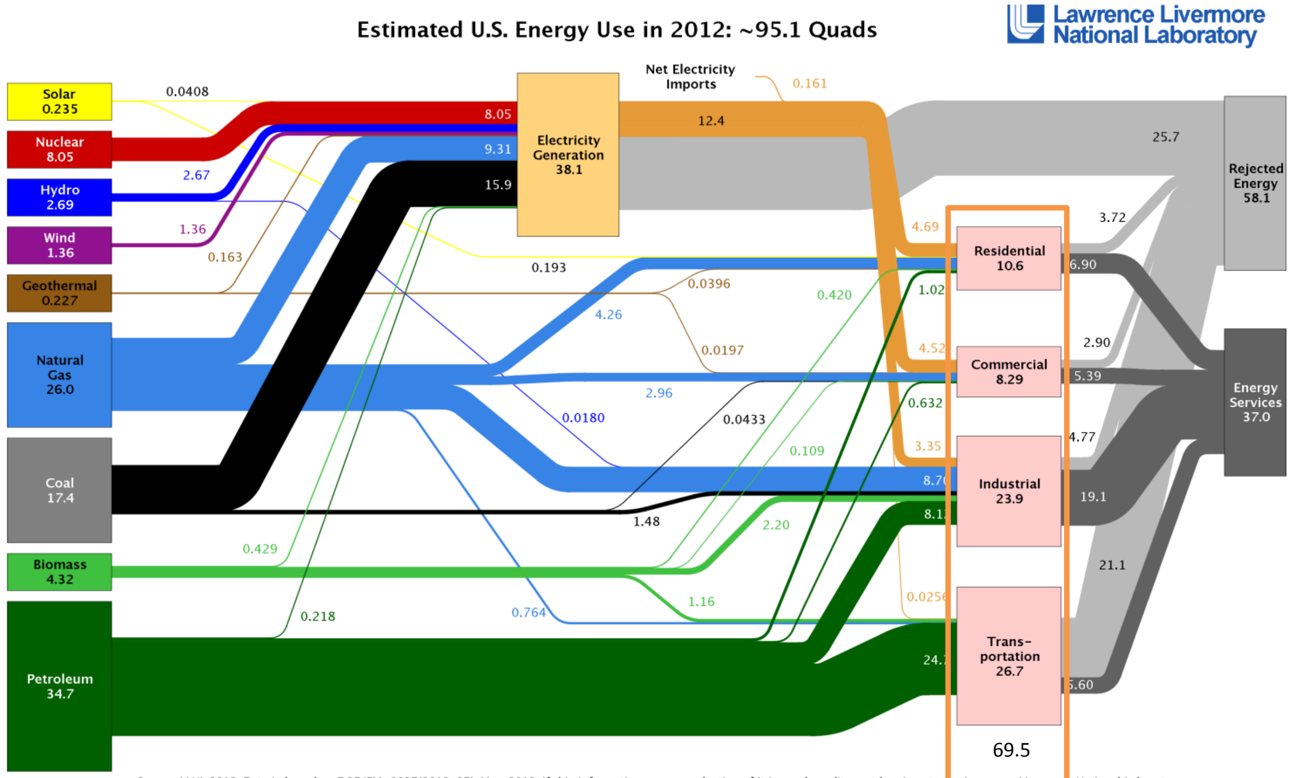
Capture the Sun & Power America With Solar

Is There a Business Case?

Whenever the subject of renewable energy comes up, the conversation usually turns to solar. You hear statements like: “The world receives more energy from the sun in one hour than the global economy uses in one year.”[a] You then ask yourself; “Why can’t we just capture the energy from the sun and solve our energy problem that way?” Why not, indeed?

Let’s suppose that we convert the entire American economy to “all-electric”, and we produce all of the electricity to power it from a solar facility. In other words, we stop burning fossilized carbon and capture the sun. What would this solar plant look like? How much would it cost? We can get a ballpark answer to both of these questions with a few assumptions and some simple calculations.

First we need to know how much electricity our solar power plant must generate. An analysis from the Lawrence Livermore National Laboratory[b] divides the US economy into four sectors – Residential, Commercial, Industrial and Transportation.



Source: LLNL 2013. Data is based on DOE/EIA-0035(2013-05), May, 2013. If this information or a reproduction of it is used, credit must be given to the Lawrence Livermore National Laboratory and the Department of Energy, under whose auspices the work was performed. Distributed electricity represents only retail electricity sales and does not include self-generation. EIA reports consumption of renewable resources (i.e., hydro, wind, geothermal and solar) for electricity in BTU-equivalent values by assuming a typical fossil fuel plant "heat rate." The efficiency of electricity production is calculated as the total retail electricity delivered divided by the primary energy input into electricity generation. End use efficiency is estimated as 65% for the residential and commercial sectors 80% for the industrial sector, and 21% for the transportation sector. Totals may not equal sum of components due to independent rounding. LLNL-MI-410527

Total demand for energy from these sectors (in the box) is about 70 quadrillion BTU's (or "quads") per year. So, our solar power plant must reliably deliver the electric energy equivalent of 70 quads to run the US economy for one year, or $56*10^{12}$ Wh (56 Terawatt hours) of electricity per day[c].

Our solar facility would consist of a photovoltaic (PV) panel and a battery. (There are other forms of solar power, but PV is good for this purpose.) The PV panel would generate enough electricity during the day to power the economy and charge the battery, and the battery would power the economy at night. Our task is to calculate:

1. The size of the PV panel
2. The size of the battery
3. The cost of the whole thing.

The Photovoltaic Panel

Let's assume the following:

1. The PV panel would be spread out in the Southwestern states, because that is the sunniest place in America[d].
2. We build in a 50% safety factor to handle any contingency

If we start with demand of 56 Terawatt hours of electricity per day and add a 50% safety factor, we find that we will then need a system that can produce about 83 TWh/day[e].

The easiest way to estimate the footprint of a solar facility of this size is to look at the operating experience of existing solar power plants. Here are several examples [f].

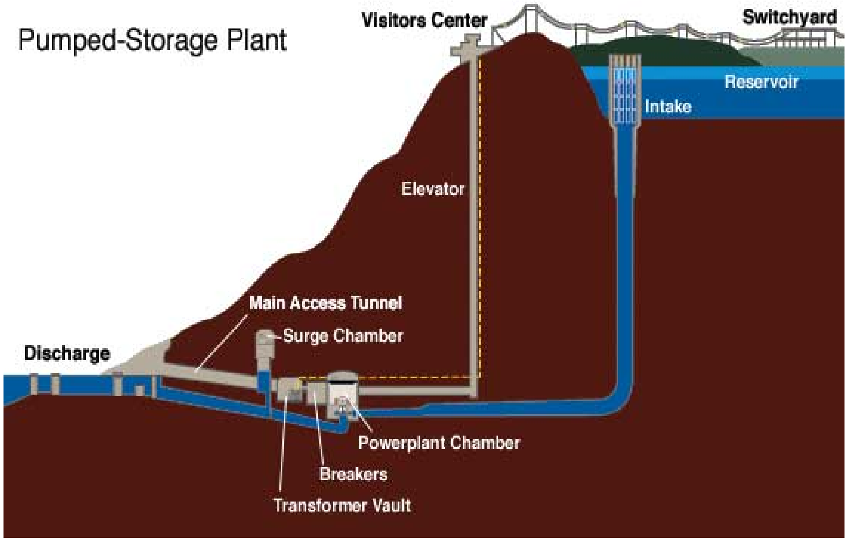
Facility	Location	Electricity Output/sq meter
Nellis	Nevada	150 Wh/day
Beneixama	Spain	160
Serpa	Portugal	90
Solarpark Mühlhausen	Bavaria	68
Kagoshima Nanatsujima	Japan	170

The sample shows that actual output is in the 70-170 Wh/day per square meter range. If we assume 150 Wh/day-sq m for our power plant, then its foot print would be about 210,000 sq mi[g].

The Battery

For the battery we will use technology known as “Pumped Storage”[h].

This method stores energy in the form of potential energy of water, pumped from a lower elevation reservoir to a higher elevation reservoir. In our example, about half of the electric power from our solar facility produced during the day would be used to run the pumps and fill the upper reservoir. Then, at night, the stored water would be released through turbines to produce the electricity that would run the night time economy.



This is proven technology. “Pumped storage hydro (PSH) is the largest-capacity form of grid energy storage available. As of March 2012, the Electric Power Research Institute (EPRI) reports that PSH accounts for more than 99% of bulk electric energy storage capacity worldwide, representing around 127,000 MW”[h]. There are about 50 pumped storage plants with more than 1,000 MW of capacity in operation around the world[i] .

In 2009 the United States had 21,500 MW of pumped storage generating capacity[j]. Many of these plants were built during the 1970’s and have therefore been operating for more than 30 years.

Here are two good examples of pumped hydro electric energy storage in the U.S.:

1. The facility at Ludington, Michigan[k] is built on a bluff overlooking the east shore of Lake Michigan. It was constructed in 1969-73.
2. The Bath County facility[l] is located in the northern corner of Bath County, Virginia, on the southeast side of the Eastern Continental Divide, which forms this

section of the border between Virginia and West Virginia. It was constructed in 1977-85 and is currently the largest pumped storage facility in the world.

Here are the relevant specifications (from this spreadsheet[m]):

	Capacity (MW)	Capital Cost ($2014/W)[n]	Stored Energy (GWh)[o]	Footprint (Acres)
Ludington, MI	1,872	0.98	25.5	1,000
Bath County, VA	3,000	1.40	43.0	820

For the purposes of this analysis, we assumed that the night time energy demand would be about half of the daily demand, or 41 TWh. If we fulfilled this requirement with pumped storage, we would need about 1,000 facilities like Bath County , VA, or about 1,640 like Ludington, MI[p] .

If we assume the average footprint of these facilities to be 1,000 acres, the total footprint would be about 2,600 sq mi[q] for the Ludington option and 1,300 sq mi[r] for the Bath County option.

Note that for the sake of simplicity this analysis does not include a factor for energy losses during the charge/discharge cycle. Overall, the pumping/generating cycle efficiency for these systems is now greater than 80% (MWH, 2009)[s]. Including this factor does not materially change the result.

What Would It Cost?

Assuming today's technology and today's costs, this power system would cost about $70 trillion to build.

The PV Panel

The Energy Information Administration reports that a photovoltaic power plant of 150 MW capacity averaged $3.90/W of capacity in 2012[t]. The capacity of a solar power plant that could generate the required 83 TWh/day of electricity would be about 17 TW[u]. The installed cost of our facility would therefore be $3.90/W times 17 TW or about $66 trillion.

The Battery

If we use the actual construction costs of the two PSH projects above, the Bath County option would cost a total of about $5 trillion and the Ludington option would cost about $3.5 trillion[v].

A few comments

1) Putting the PV power facility in the Southwest makes sense from a solar energy point of view because this is the sunniest part of America. But, this strategy has two problems:
    a. The Southwest, defined as southern CA + the southern tip of NV around Las Vegas + AZ + NM + the panhandles of TX and OK, constitutes about 400,000 sq mi[w]. Our facility would therefore cover about 50% of it!
    b. If a major storm covered most (or worse, all) of this, electrical output would drop dramatically and the whole country would suffer.
2) Putting our PV power plant in the "Southern states", defined as the Southwest + all states east to the Atlantic Ocean, alleviates the storm risk scenario but puts much of the panel in states that are not as “sunny” as the Southwest, and so our PV power facility would have to be larger to account for that. Even without this expansion it would occupy about 22% of it[x].
3) Some people would say that much of the land in these states is “empty”; but others would say that it is wilderness or grazing land or farm land. It’s safe to say that either the Southwestern or the Southern States strategy would provoke some real push-back.
4) PV Panels on houses. There are about 89 million houses in the US[y]. If the owners of every one of them installed 1,000 sq ft (e.g 20 ft by 50 ft) of PV panel on their roof, the total area would be about 3,200 sq mi., a small percentage of the needed area.

Additional Construction Costs

Building the solar power plant is not the only cost of capturing the sun.

1) Electrifying the economy. We simply assumed at the beginning that the entire economy has been “electrified”, so that all energy is now supplied in the form of electricity, but this in itself would be an enormous project. By far the largest part of this would involve the electrification of the transport sector. The chart above shows that transportation is the largest user of energy (38%) and that almost all of it comes in the form of petroleum. Electrifying this sector would mean abandoning the internal combustion engine and converting to electricity all cars, buses, trucks (especially tractor-trailers), ships, and the entire railroad network.

2) Re-building and expanding the entire national electrical grid. Today power plants are located close to the user. Major cities, e.g. Chicago, are surrounded by a network of power plants[z]. Our new solar system, however, would locate the power plants where the sun shines the most. So, in theory, much of it would be located in the Southwest, which is the sunniest part of America. This means that the solar-based grid would be much larger than present because it must transport electricity much larger distances, for example, from Arizona to New Jersey.

3) Developing a computer network to control the whole system, the so-called “smart grid”. The solar grid must be able to react to changes in the weather. Suppose we adopt the Southern States strategy. Further suppose that on Monday the Southwest is clear and the Southeast is cloudy. On that day huge amounts of electricity must move generally west to east. Then suppose that on Tuesday the Southwest is cloudy and the Southeast is clear. On that day huge amounts of the electricity must move generally east to west. This will be happening every day as weather systems move across America. The grid and control systems to handle this do not, today, exist.

Compare the “Solarization” of America With Other “Mega-Projects”

America is certainly capable of successfully sustaining large projects over long periods of time that require solutions to major engineering problems. Three examples are:

1. The Manhattan Project. The project to build the first atomic bomb spanned 1942-1946 and cost about $26 billion in 2014 dollars[aa].
2. Project Apollo. The project to put the first man on the moon spanned 1961-1972 and cost about $130 billion in 2014 dollars[bb].
3. The Interstate Highway System. This project was authorized in 1956 and was completed in 1991, 35 years later, at a cost of about $500 billion in 2014 dollars[cc].

These are three very successful projects. What were the keys to their success?[dd]

1. A perceived threat or reward that leads to public acceptance. The Manhattan project and Apollo project were both responses to perceived threats, which compelled policymaker support for these initiatives. The interstate highway system was perceived as an enormous jobs program that would also produce a big jump in economic productivity.
2. A clear goal. Each project had a clear goal – build the bomb, put a man on the moon by end of 1969, build the interstate highway system.
3. Government money that ensures success. All three projects were funded by government. For example, the Manhattan Project consumed about 1% of the federal budget during its life, and Project Apollo consumed about 2% during its life. The Interstate Highway System was self-funded via a gas tax that is now 18.4 cents per gallon[ee]

How does our solar project score on these three success factors?

1. Perceived threat or reward. Climate change and/or exhaustion of fossil fuels. But, does the American public buy in to this? Recent polls suggest that it does not.
2. A clear goal. Electrify the US economy and generate the electricity with a solar-based system. But, whereas the interstate highway system (for example) generated huge benefits to Americans, it is not clear if there are any near-term economic

benefits from, for example, converting transportation from carbon to solar-produced electricity.

3. Government money to ensure success. The government's role in all three projects was to provide the funding. But, given the public's lack of support, the huge amounts of money required, and the fiscal shape in which governments at all levels find themselves, governments today are in no position to fund this entire project.

What To Do?

In order to adopt solar power on a large scale today we must confront four problems associated with the technology.

1. The sun is a relatively low density energy source. Even in a sunny place like Arizona, it delivers only about 200 W/sq m over an average day[ff].
2. Today's PV panels are inefficient at converting this energy to electricity. A typical low-cost PV panel will convert only 15-20% of the sun's energy to electricity.
3. Intermittency. The sun shines for only about half of the 24 hour day, and is often obscured by clouds.
4. Cost. The construction cost of a solar PV facility is about $3.50/W vs about $1.00/W for a gas-fired power plant[gg]. Furthermore, whereas a gas-fired plant produces electricity 24/7 rain or shine, a solar plant produces electricity only during the daylight hours.

The **efficiency of PV panels** continues to improve, and panels with 20% efficiency are coming onto the market[hh], but the theoretical limit of the PV technology in use today is 31%[ii], and getting there has been agonizingly slow. More research is required to improve the efficiency of PV panels and any other technology that converts the sun's energy to electricity.

The **sun's intermittency** issue requires development of grid scale electricity storage systems that are sufficient (in this example) to power the entire economy during the night. Many new technologies are currently under development. As with PV panel efficiency, more research is required to develop these new technologies for electricity storage.

The **capital cost** of PV power plants is falling as the cost of PV panels drops. Today, PV panels cost about $.74/W, one one-hundredth of the cost in 1977[jj]! But the PV panel is only one component of the total cost of a complete solar power plant. The so-called "non-module" costs, e.g. inverters, mounting hardware, labor, permitting and fees, overhead, taxes, installer profit, etc, now make up at least two thirds of the total installed cost[kk]. Further reductions in total cost will require significant reductions in non-module costs. The total cost of a PV power plant today is still about four times the cost of a gas-fired equivalent, and it generates electricity for only half the day.

Finally, as with any energy plan, we must continue to work on energy efficiency. The chart above shows that of the 70 quads of energy supplied to the economy, about 47%[ll] of them are "rejected", i.e. lost. Improving energy efficiency (BTU/$ GDP) is a must, regardless of the way forward.

A Final Comment

The intent of this exercise is to arrive at a ballpark estimate of what it would take to stop fossilized burning carbon and "Capture the Sun". There is obviously a large margin of error, plus or minus, in all of it. One thing is certain. Eventually we *homo sapiens* will consume all of the planet's supply of carbon. Long before that time we must develop an alternative to burning that carbon.

It's a good bet that solar will eventually be a major part of our energy equation. The good news about the sun is that it is:

1. For all practical purposes an inexhaustible source of energy.
2. Free.
3. Available to everyone. No country can seize control of the sun and deny it to others.

But, it is also true that solar power today supplies only about two tenths of one percent of the energy to run the U.S. economy[b]. It is easy to see why when we compare the economics of solar with other options. In the exercise above I estimate the cost of building a system to power today's economy with energy from the sun at about $70 trillion. Doing the same thing with gas-fired technology would cost about $4 trillion[mm], about 6% of the cost of solar.

Remember that this whole exercise has used today's technology and today's costs. Both of these should improve over time, but until they do the business case for a major push into solar does not look good.

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[a] "Solar Energy, A New Day Dawning?", Nature 443, 19-22 (7 September 2006) doi:10.1038/443019a; Published online 6 September 2006

[b] Lawrence Livermore National Laboratory - https://missions.llnl.gov/energy/analysis/energy-informatics

[c] 70×10^{15} BTU/yr = 1.9×10^{14} BTU/day = 56×10^{12} Wh/day = 56 TWh/day

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[d] http://www.currentresults.com/Weather/US/average-annual-state-sunshine.php

[e] PV Panel Capacity
Desired output = 56 TWh/day
50% safety factor raises this to 83 TWh/day

[f] Power Plant Footprint
Nellis Powerplant (Nevada) = 30 GWh/yr on 140 acres = 150 Wh/day per sq meter,
http://en.wikipedia.org/wiki/Nellis_Solar_Power_Plant
Beneixama (Spain) = 30 GWh/yr on 500,000 sq m = 160 Wh/day per sq meter,
http://www.solarserver.com/solarmagazin/solar-report_0109_e.html
Serpa (Portugal) = 20 GWh/yr on 600,000 sq m = 90 Wh/day per sq meter,
http://www.withouthotair.com/c6/page_48.shtml p48
Solarpark Mühlhausen (Bavaria) = 17,000 kWh/day on 25 hectacre = 68 Wh/day per sq meter,
http://www.withouthotair.com/c6/page_48.shtml p41
Kagoshima Nanatsujima (Japan) = 22,000 households @ 3,600 kWh/household on 1.3 million sq m = 170 Wh/day-sq m
http://global.kyocera.com/news/2013/1101_nnms.html

[g] Required output = 83 TWh/day so this divided by 150 Wh/day-sq m = 210,000 sq mi

[h] http://en.wikipedia.org/wiki/Pumped-storage_hydroelectricity

[i] http://en.wikipedia.org/wiki/List_of_pumped-storage_hydroelectric_power_stations

[j] http://en.wikipedia.org/wiki/Hydroelectric_power_in_the_United_States#Pumped_storage

[k] http://www.consumersenergy.com/content.aspx?id=6985

Ludington Pumped Storage Plant, Ludington, MI

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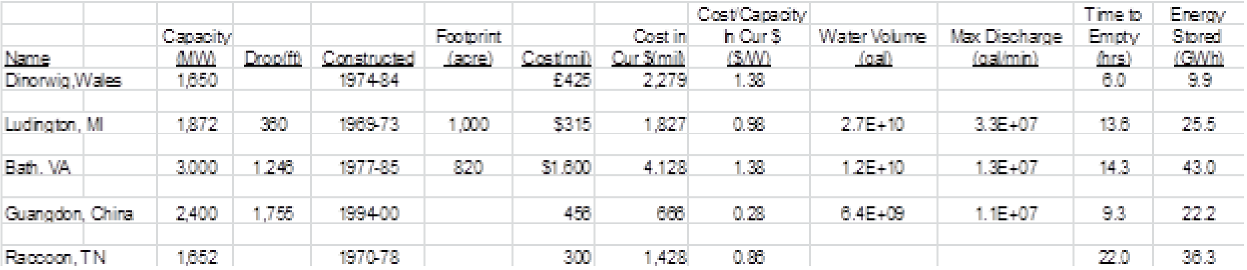
[l] http://en.wikipedia.org/wiki/Bath_County_Pumped_Storage_Station

[m] Some examples of pumped storage facilities. All can be found in Wikipedia:



Name	Capacity (MW)	Drop(ft)	Constructed	Footprint (acre)	Cost(mil)	Cost in Cur $(mil)	Cost/Capacity in Cur $ ($/W)	Water Volume (gal)	Max Discharge (gal/min)	Time to Empty (hrs)	Energy Stored (GWh)
Dinorwig,Wales	1,650		1974-84		£425	2,279	1.38			6.0	9.9
Ludington, MI	1,872	360	1969-73	1,000	$315	1,827	0.98	2.7E+10	3.3E+07	13.6	25.5
Bath, VA	3,000	1,246	1977-85	820	$1,600	4,128	1.38	1.2E+10	1.3E+07	14.3	43.0
Guangdon, China	2,400	1,755	1994-00		456	666	0.28	6.4E+09	1.1E+07	9.3	22.2
Raccoon, TN	1,652		1970-78		300	1,428	0.86			22.0	36.3

[n] The equation here is Capital Cost at time of construction x adjustment for inflation ÷ Capacity
For Bath = $1,600 mil x 2.6 ÷ 3,000 MW = $1.38 /W (inflation adjustment is for the period 1981 – 2014)
For Ludington = $315 mil x 5.8 ÷ 1,872 MW = $0.98 /W (inflation adjustment is for the period 1971 – 2014)
For inflation adjustment use this site: http://www.usinflationcalculator.com/

[o] The equation here is Capacity x Time to Empty Upper Reservoir
For Bath = 3,000 MW x 14.3 hours = 43.0 GWh
For Ludington = 1,872 MW x 13.6 hours = 25.5 GWh

[p] The equation here is Demand ÷ Stored Energy
For Bath = 41 TWh ÷ 43.0 GWh = 953 or about 1,000 "Bath-like" facilities

[q] 1,640 x 1,000 acres x 0.0016 sq mi/acre = 2,600 sq mi

[r] 1,000 x 820 acres x 0.0016 sq mi/acre = 1,300 sq mi

[s] http://www.hydro.org/wp-content/uploads/2012/07/NHA_PumpedStorage_071212b1.pdf

[t] http://www.eia.gov/forecasts/capitalcost/ - Table 1. The estimate of $3.90 comes from the EIA's estimate of "Overnight Capital Cost" of a 150MW capacity photovoltaic power plant.

[u] http://www.nrel.gov/analysis/tech_cap_factor.html
According to this chart, the capacity factor for solar power plants installed so far in the U.S. is about 20%. Therefore, the Capacity of a solar plant to power America would be = electricity demand/day ÷ 24 hrs/day ÷ 20% capacity factor
= 83 TWh/day ÷ 24 h/day ÷ 0.2 = 17 TW

[v] Capacity of pumped storage = night time demand ÷ 12 hrs = 41 TWh ÷ 12 h = 3.4 TW
Capital cost for Bath = $1.40/W, so Bath option CapEx = 3.4 TW x $1.40 ≈ $4.8 trillion
Capital cost for Ludington = $0.98/W, so Ludington option CapEx = 3.4 TW x $0.98 ≈ $3.3 trillion

[w] An estimate from Google Maps

[x] NV+AZ+NM+TX+OK+LA+MS+AL+GA+SC+FL ≈ 1 million sq mi according to Wikipedia

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[y] US Census Bureau http://www.census.gov/prod/2013pubs/acsbr11-20.pdf

[z] http://www.eia.gov/state/maps.cfm

[aa] http://en.wikipedia.org/wiki/Manhattan_Project

[bb] http://en.wikipedia.org/wiki/Project_Apollo#Program_cost

[cc] http://en.wikipedia.org/wiki/Interstate_Highway_System

[dd] Analysis in this section is based on this article by Deborah D. Stine, PhD, now at Carnegie Mellon University: http://www.fas.org/sgp/crs/misc/RL34645.pdf

[ee] http://en.wikipedia.org/wiki/Interstate_Highway_System#Toll_Interstate_Highways

[ff] MacKay, Sustainable Energy Without the Hot Air, p46

[gg] U.S. Energy Information Administration, Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants", April 12, 2013, http://www.eia.gov/forecasts/capitalcost/, Table 1

[hh] http://www.reuters.com/article/2011/06/20/idUS110444863620110620

[ii] Shockley-Queisser limit. http://en.wikipedia.org/wiki/Shockley%E2%80%93Queisser_limit

[jj] http://www.economist.com/news/21566414-alternative-energy-will-no-longer-be-alternative-sunny-uplands

[kk] http://emp.lbl.gov/sites/all/files/LBNL-5919e.pdf, graph on p14

[ll] From the chart on page 1:
Total energy to drive the U.S. economy (in the box) = 69.5 quads
Total energy input = total energy output
Total energy output = rejected energy + energy services = 32.5 quads + 37.0 quads
Therefore rejected energy = 32.5 / 69.5 = 46.8%

[mm] 83 TWh/day required to run the economy
Assume the capacity factor for these gas-fired plants = 90%
Then capacity = 83 ÷ 24 ÷ 0.9 = 3.8 TW
Cost to build = 3.8 TW x $1/W ≈ $ 4 trillion