The True Cost of Solar Electricity
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This report analyzes the cost and prospects for solar electricity. It is my view the the widespread promotion of utility-scale and rooftop solar is a fraud imposed on the taxpayer and utility customers. Solar is not competitive with the best sources for grid electricity. Even if one believes in the evil of CO2 and the danger of global warming, there are better ways to reduce CO2 emissions than solar electricity.

Solar electricity has its place. People who live in a place where the electric grid does not reach may benefit from a solar electricity setup. Typically such a setup consists of solar electric panels along with storage batteries to supply electricity when the sun is not shining. For devices, such as roadside emergency telephones, that are located away from power lines, local solar electricity with storage batteries is often the least expensive source of power.

Heating swimming pools is an excellent application of solar energy that does not involve solar electricity. The pool water is circulated through collectors warmed by the sun.

The solar electricity applications that are intended to supply or displace grid electricity are everywhere. These applications, in the majority of instances, receive a subsidy, direct or indirect, created by the government. Without government subsidies the solar electricity business would be very small.

The problem with solar electricity are that it is too expensive and it is not dependable. The expense is mostly in the initial cost that logically must be paid back from the sale of electricity. The lack of dependability comes from the fact that it only works when the sun is shining. It stops working if a cloud blocks the sun. It stops working at night. One answer is to store the electricity, but storage of electricity is expensive. Batteries are impossibly expensive for anything except short term storage. Pumped storage based on a reversible hydroelectric setup and two reservoirs, is more reasonably priced, but still expensive and dependent on a good mountain site.

Single family home rooftop solar is a fake solution. Yes, sometimes the homeowner can save money, but the money saved is paid by other electricity customers or taxpayers. For example in California the price of electricity for large homes has been made very expensive by legislating reverse quantity discounts. Traditionally, electric utilities charge less per kilowatt hour if you consume more power. The reason is that there is a fixed cost associated with the infrastructure required to supply power. Small users have to pay more per kilowatt hour to pay for the connection. But, in California the more electricity you consume, the more each kilowatt hour costs. For larger homes the marginal cost can be over 40 cents per kilowatt hour, enough to make rooftop solar pay. Rooftop solar is also made profitable for the homeowner by a variety of government subsidies.

Rooftop solar causes the homeowner to use less electricity from the utility. This reduces the utility's revenue and that reduction in revenue is going to reduce economies of scale and cause rates to rise for other users. The utility will not be able to shed generating capacity due to widespread adoption of rooftop solar, because solar is undependable. Further, in some instances, the utility is required to buy excess power generated by the rooftop solar. Sometimes the utility is required to buy back the electricity at the same price it sells electricity, at other times at a reduced price. The utility is often put in the position of paying a higher price for electricity than it can get from other sources. This burden falls on the other customers of the utility.

Rooftop solar is risky because the relationship with the utility company is subject to change. The majority of rooftop solar is sold on long term credit and that can create a problem when the homeowner wants to sell his home and it is necessary to pay off the loan for equipment that the new owner may not want.

How Solar Electricity Works

Solar electricity has two branches: photovoltaic and thermal. Photovoltaic depends on the photoelectric effect. If light strikes certain materials a particle of light (photon) is absorbed and the energy is transferred to an electron that is ejected. If there is a charge barrier between two levels of material and the electron has enough energy it can cross the charge barrier. As electrons continuously cross the barrier under the influence of illumination, charge is separated across the barrier with the side having an excess of electrons becoming negative and the side the electrons are leaving becoming positive. An electrical current can then flow through wires attached to each side of the charge barrier. A solar cell is typically constructed using silicon and semiconductor technology.

Thermal solar energy depends on heating up a working fluid with sunlight, usually water. The fluid turns into a pressurized gas (steam) and drives a turbine connected to a generator. In order to reach high enough temperatures optical intensification of the sunlight is required. This can be accomplished by parabolic mirrors tracking the sun, parabolic troughs tracking the sun, or by a field of flat mirrors tracking the sun such that each mirror shines a spot on a boiler atop a tower. Sometimes an intermediate fluid is use to transfer heat from the optical hot spot to the boiler where water or the working fluid is heated. (Optical intensification can be used with photovoltaic too, but is generally not economic.)

Thermal solar energy is more expensive than photovoltaic solar electricity, but it has the potential advantage that heat can be stored in an intermediate working fluid, such as a molten salt, for use at a later time or to buffer temporary interruptions in sunlight. Another advantage is that natural gas can be used to fire the boiler when sunlight is absent, allowing for continuous usage or buffering of interruptions. Burning natural gas in thermal solar system is going to be inefficient, with probably less then 35% of the energy in the gas extracted, compared to as much as 60% in a combined cycle gas generating plant. Buffering interruptions in a photovoltaic system is more difficult, because storing electricity is expensive.

Thermal solar is more expensive because it requires a turbine and generator, the same as a fossil fuel plant. In fact the turbine and generator must be much larger due to the low duty cycle of solar, typically 20%. In order to reach high temperatures, necessary for high efficiency, optical intensification is required and that requires tracking the sun on either one or two axis. A grid scale generating system require hundreds of acres of land and thousands of articulated mirror systems. Mass production techniques can reduce costs, but only to a minimum governed by the cost of materials and land. But if solar were ever to become a large part of the grid, much would be thermal solar because of the possibility of storing heat for use at night.

Solar electricity surges. The peak power is 4 or 5 times greater than the average power. Power lines have to be sized to carry the surge but they only deliver the average power. As a result solar oriented power lines are especially expensive.

The advocates of solar tout the low cost of photovoltaic but usually don't point out that large scale adoption of solar requires the use of more dependable thermal solar. Thermal solar generally can store enough heat for one night, so it still requires non-solar backup for cloudy days. The backup can be natural gas fired heaters. Of course natural gas is very cheap and plentiful and can be used to generate electricity in a dedicated plant at a cost far below the cost of thermal solar.

Amortization of an Investment

Since most of the cost of solar is the initial capital cost, it is necessary to spread the cost over the time the generating plant is used in order to allocate a certain capital cost to each year of operation. This is not an exact science. The Energy Information Administration (EIA) uses a 30 year period and a 6.5% interest rate. For coal they use a 9.5% interest rate, apparently on the grounds that the government intends to crush coal for global warming reasons. In this type of analysis the annual cost is the same as the annual payment would be for a 30 year mortgage with the given interest rate. The Excel PMT function can be used to calculate the annual payment or allocation of capital cost. The table below shows the annual payment for different interest rates.

Investment amount	Years amortization	Interest rate percent	Annual Payment	Payback period years	
$1,000,000	30	9.50%	$101,681	9.8	EIA rate for coal
$1,000,000	30	6.50%	$76,577	13.1	EIA rate for other
$1,000,000	30	4.00%	$57,830	17.3	Government guaranteed loan
note: annual payment excel: =PMT(rate, years, amount)					

The row with 4% interest rate is an estimate for a project with a government guaranteed loan. The 4% is 1% above the 30-year treasury bond interest rate. Having this interest rate subsidy cuts the capital cost by about 25%. A 30% tax credit is also available. The two subsidies together amount to a 47.5% reduction. Additional effective subsidies are present in the power purchase agreements, land use concessions, etc.

The payback period is just the initial investment divided by the annual payment. The investment is not actually payed back in that amount of time because interest is ignored. However the payback period provides a simplified method of computing the annual payment or amortization. For the EIA 6.5% case the payback period is 13 years and the annual payment can be computed by taking it as 1/13th of the investment. In this study we will use the 13 year payback to compute the annual capital cost.

Computing the Cost of Solar Electricity

Photovoltaic solar is much cheaper because electricity is generated directly without the need of turbines, generators and optical intensification of sunlight. But, as previously mentioned, the future of solar, if it has a future, is thermal solar.

The cost of a project is measured in terms of the nameplate capacity. If a solar project is 100 megawatts, that means that with perfect sunshine aimed squarely at the collectors, 100 megawatts of power is generated. The average power generated is usually 15% to 25% of the nameplate power. More power is generated in the summer when days are longer and the sun is higher in the sky. (Things are slightly different in the tropics.)

Photovoltaic panels should face south (In the northern hemisphere) and to the extent they are directed off south less power is generated. This is often a problem with rooftop installations. Panels can have a fixed tilt angle, a tilt angle manually adjusted from time to time, single axis tracking with the tilt angle computer controlled, or two axis tracking with the panels always squarely facing the sun. For photovoltaic panels the trend is toward using a fixed angle. If the tilt is equal to the latitude of the site, then the sun will face the panels squarely at local noon on the first day of spring and the first day of fall. The latitude angle gives the maximum average power for a fixed tilt angle. The tilt can be slightly biased to favor winter or summer depending on electrical demand. We assume a fixed tilt of latitude angle in this study. Computer controlled tilt increases power output, but usually the extra cost is not worth the extra power.

Photovoltaic panels have a rated number of watts that they generate. In specifying the wattage, is it assumed that full sunlight with a light energy intensity of 1000 watts per square meter is shining on the panel. By accident, the intensity of full sunlight at sea level with clear sky is very close to 1000 watts per square meter on a surface oriented toward the sun. Commercial panels turn 15-20% of the sun energy into electricity. Because the distance to the sun varies by about 3.4% due to the non-circular shape of the Earth's orbit, the intensity of sunlight varies by about 7%. The Earth is closest to the sun, currently, in January, helping to make winters warmer in he northern hemisphere. The season of closest approach drifts over thousands of years and is partly responsible for the ice ages.

There is a useful publication The *Solar Energy Handbook*. Associated with this handbook is a website with useful computing engines. The online solar irradiance calculator allow one to calculate the total sun energy falling on a 1 square meter plate oriented in different ways during an entire day for each month of the year. This can be done for a variety of locations in the world. The estimates are averages over a number of years and include the effects of weather. For example in Phoenix, AZ, for a fixed plate facing south and tilted at latitude angle, in May, the total irradiance for a day has a factor of 6.74, meaning that 6.74 kilowatt hours of solar energy, in theory, would be collected throughout the day on a one square meter plate. In December it would be 4.92 KWh. In Montpelier, VT, the May figure would be 4.86 KWh in May and 1.26 KWh in December. The average for a year is 3.42 KWh per day in Montpelier and 5.81 in Phoenix. In Calama, Chile, one of the sunniest places in the world, the yearly average is 7.81 KWh, about 15% better than in Phoenix. The amount of electricity generated in Vermont would be only 59% as much as in Phoenix, increasing the cost of solar energy by 70% in Montpelier. The winter generation if about 4 times lower in Vermont.

To find the average number of KWh generated in a day it is only necessary to multiply the nameplate capacity of the plant by the factor given in the solar energy handbook irradiance calculator. This is because the nameplate capacity of the plant assumes 1000 watt irradiance from the sun and the factors given by the online calculator also assume this. To go from the average KWh per day to the number of KWh generate per year multiply by 365.

Example:

Assume a 100 megawatt solar farm in Phoenix, with a factor of 5.81 KWh per nameplate kilowatt, the same as 5.81 megawatt hours per nameplate megawatt. The plant will average 581 megawatt hours per day or 212,065 megawatt hours per year. Assume a construction cost of $1,550,000 per megawatt or $155,000,000. (The EIA estimates $1,510,000 per megawatt for a 150 megawatt plant.) Assume an annual allocation of capital of 1/13th or $11,150,000 per year. The the capital cost of the electricity will be $11,920,000/212,065=$56.2 per megawatt hour or 5.62 cents per kilowatt hour. To this must be added operating cost estimated by the EIA at around 1 cents per KWh for a total of 6.62 cents per KWh for this example. Move to Montpelier and the cost becomes 9.95 cents per KWh. These figures neglect down time when the plant is being maintained or when it has been ordered to curtail electricity production. If we add 0.5 cents for that, or less then 10% downtime, then the range becomes 7.12 to 10.45 cents per KWh in our two examples. Of course these figures are not set in stone. Construction costs vary as do the cost of components, the cost of shipping, the cost of land, the efficiency of management, etc.

Our estimate of 7.12 cents is close to the EIA estimate of 7.37 cents for a plant with a capacity factor of 25%, corresponding to a very sunny place. Since the EIA is known to be biased against coal, it is likely that they are optimistic for renewable energy, both estimates maybe a bit low. The capacity factor in our Phoenix example is 24.2%. Capacity factor is he number of KWh generated per year divided by the number of KWh if the plant generated at full nameplate capacity 24 hours a day.

In summary, we take the cost of utility-scale, photovoltaic solar to be in the range of 7 to 11 cents per KWh, depending on the site.

Residential rooftop solar installations are much smaller and will tend to cost about $3,500 per kilowatt of nameplate capacity. A 6 kilowatt installation will cost $21,000 and in Phoenix generate 41 KWh per day. This gives a capital cost of 10.7 cents per kWh. In Montpelier the capital cost would be18.19 cents per KWh. If $500 per year is added for operating cost, that is an additional 3.3 cents per KWh, giving 14 cents in Phoenix. In

Montpelier the $500 translates to 5.6 cents per KWh giving a total cost of 23.8 cents per KWh. Of course, roofs facing close to south are not always present and adding and additional tilting mount can cost more. 15-30 cents per KWh is probably a realistic estimate, considering how homeowners can be charged by contractors and lenders.

Solar Thermal
According to EIA estimates solar thermal has almost double the capital cost and 3-1/2 times the operating cost. Further, the capacity factor is usually going to be lower. As a result the cost of electricity is going to be in the range of 15-30 cents per KWh.

Example: Ivanpah solar plant

The Ivanpah plant cost $2.2 billion giving an annual capital cost of 1/13th that amount or $169 million. Nameplate is 377 megawatts. Planned output is 930 million KWh giving a capital cost per KWh of 18.2 cents. The EIA estimate for operation and maintenance for thermal plants adds another 3 cents for 21.2 cents / KWh. This plant has had considerable operational problems and is probably producing at more than 30 cents / KWh.

Comparison: Natural Gas Plants
There are 2 common types of gas plants: 1) single stage turbine 2) combined cycle natural gas plant.

A single stage turbine is similar to an airplane jet engine. A rotating turbine has a compressor section that takes in and compresses air, followed by a combustion chamber where the air is mixed with gas and burned. The hot gas drives the power turbine and then is directed to the exhaust. The rotating shaft of the turbine drives a generator. According to the EIA an advance combustion turbine has a capital cost of $640 per kilowatt for a 237 megawatt unit. The heat rate, or Btu used for each KWh is 8550. That corresponds to extracting 40% of the energy in the fuel (one KWh equals 3420 Btu)

A combined cycle plant uses a gas turbine-generator for the first stage. A second stage uses the hot exhaust of the gas turbine to generate steam and drive a steam turbine, thus extracting more energy from the gas. Sometimes the exhaust from more than one gas turbine may be use to drive the same steam turbine. According to the EIA a 439 megawatt advanced combined cycle plant costs $1013 per kilowatt. The heat rate is 6200 Btu corresponding to an efficiency of 55%. (Higher efficiencies greater than 60% are quoted by some manufacturers.)

Typically combined cycle plants, being more efficient, are used as base load plants and run a high percentage of the time. The EIA uses an 87% capacity factor for combined cycle gas plants.

Single stage turbine plants are less efficient, but the capital cost is cheaper and they can start up much faster, in perhaps 10 minutes, compared to 30 minutes or more for a combined cycle plant. The EIA uses a capacity factor of 30% for these plants.

The table below shows costs for sample plants.

Type	Nameplate Size MW	capacity factor	cost / KW	total cost	KWh per year	capital cost / KWh
Advnced Turbine	237	30%	$640	$151,680,000	622,836,000	0.019
Adv Combined combined cycle	429	87%	$1,013	$434,577,000	3,269,494,800	0.010

	heat rate Btu/KWh	Cost gas / MMBtu	Fuel Cost/KWh	Fixed O&M $year/MW	fixed O&M/ KWh	variable O&M $/KWh	Total cost$/ kwh
Advnced Turbine	9800	$3.51	0.034	$4.60	0.0018	0.0042	0.059
Adv Combined combined cycle	6200	$3.51	0.022	$14.00	0.0018	0.0026	0.036

The single stage turbine comes at a price of 5.9 cents / KWh. The combined cycle at 3.6 cents / KWh. The fuel cost is 3.4 cents and 2.2 cents per KWh.

Does Solar Energy Displace Elements of the Existing Grid?
Demand for electricity in any locality varies by time of day and by season of the year. Demand is lowest in the early morning around 4 AM. Demand is highest in the early evening between 5 PM and 8 PM. In areas with heavy air conditioning, peak demand may be little earlier. The difference in demand, low to high, on average is a less than two to one. Extreme demand often comes on hot days of summer. In California, in summer, the peak demand period is between 3 PM and 6 PM.

Base load plants run nearly all the time and are usually nuclear, coal or combined cycle natural gas. These plants have the lowest marginal cost of generation. The marginal cost of generation is mostly the cost of fuel for fossil fuel or nuclear plants. As demand increases more plants are bought on line. Ultimately, gas turbines are used. Gas turbines have the lowest capital cost but the highest fuel cost. They can ramp power fast, important for ramping power to handle rapid increases in demand.

Hydro plant usage is more complicated since water is often limited and usage may conflict with water storage requirements. Hydro usually can ramp fast.

Solar is not reliable. Even the sunniest city in the U.S., Yuma, AZ, has 50 cloudy days a year. Keeping the grid able to satisfy demand is always a statistical calculation. If enough things go wrong at the same time the grid will have to curtail delivery. Each grid would have to do its own calculation to decide if any existing resources can be decommissioned when solar is added. However it seems unlikely that his would be significant, especially since solar peaks at noon while demand peaks are late afternoon and early evening. Our assumption is that a fully capable non-solar grid must be maintained even if solar is added to the grid.

Because introducing solar does not displace conventional grid capital investment, solar really competes with the marginal cost, mostly fuel cost, of existing grid elements displaced by solar. The marginal generators are usually natural gas powered and consume 2-3 cents per KWh at current gas prices. Solar can’t come close to 3 cents per KWh exclusive of subsidies. In the best photovoltaic locations it will cost about 7 cents and more in less sunny localities.

Solar Energy Government Subsidies
This is from the Solar Energy Industries Association (SEIA) website and the this publication.

Accelerated depreciation - 5-year depreciation for solar energy equipment. If the 30% investment tax credits claimed only 85% of the property may be depreciated.

Department of Energy Loan Guarantee Program - Guarantees loans for large energy projects.

Solar Investment Tax Credit- A 30% tax credit for solar projects. If the project costs $1 billion, the developers receive a $300 million reduction in income taxes.

State property tax and sales tax exemptions - 38 states offer property tax benefits and 29 states offer sales tax exemptions.

Some eastern states, like New Jersey, have established quotas for solar energy - Solar renewable energy certificates (SREC's) can be purchased to satisfy the requirement. The SREC's must represent solar energy connected to the New Jersey grid. The SREC's sell for about $193 per megawatt hour. As a result solar is subsidized to the extent of 19 cents per KWh, far above the cost of producing solar energy In New Jersey [about 12 cents]. The producer can sell the SREC and the electricity as well as receiving federal subsidies. This foolish program is costing about $400 million per year just for the SREC's.

How Much Money is Wasted on Solar Energy
At the end of 2016 the U.S. had 40 gigawatts of solar capacity. Assuming an average 18% capacity factor this amounts to 63 billion KWh per year. If we assume that the cost of solar (8 cents) is 5 cents above its worth (3 cents) then about $3 billion dollars a year is wasted on supporting this uneconomic source of power. If the entire grid could run on solar, the waste would be 100 times larger, or about 300 billion. That is about $2,500 per year for each household. This is probably an under estimate given that New Jersey alone has $400 million in sales of solar renewable energy certificates. Probably 5 times as much money is wasted on supporting uneconomic wind energy.

The Future of the Electrical Grid

Currently solar and wind energy are being expanded at a reckless rate even though these technologies have negative worth. Natural gas generation is being expanded rapidly because gas is (temporarily) cheap and the regulatory problems with gas are small compared to the alternatives of coal or nuclear. Coal plants are being rapidly decommissioned under a relentless campaign of false propaganda by the Sierra Club's program to demonize coal. That program follows an earlier program of propaganda to demonize nuclear. The Sierra Club also opposes hydro because they oppose dams. They oppose natural gas because they oppose fracking, the reason we have cheap natural gas. One wonders if the real problem is that the Sierra Club is opposed to electricity.

The electrical grid is vulnerable to electromagnetic pulse, either from a solar storm or from a high altitude explosion of a small nuclear weapon over Kansas. There is every reason to suppose that this capability is part of North Korea's plans. Although the grid can be hardened at reasonable cost, very little is being done. Instead billions are being spent on foolish renewable energy projects. A multi-year failure of the grid, due to destruction of capital equipment by electromagnetic pulse, would be catastrophic.