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Space Solar vs Base Load Ground Solar and Wind Power

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Abstract

This paper attempts direct comparisons between ground-based solar and wind electrical power generation systems and those of Space Solar. Ground solar and wind are the two major popularly proposed replacements for carbon-based energy. Potentially, these could become very large base load electrical power sources due to: 1) their current political recognition as the desired replacement sources and 2) to their widespread availability. However, they have severe physical limitations. For Space Solar, only those aspects that are critical for valid comparisons to the ground based systems are give attention. The focus is primarily on physical comparisons, such as actual areas of land and amounts of equipment required to produce given amounts of base load power.

Focus on Base Load Electricity - Power Units Used

The focus of this analysis is on production of electricity since a) electricity is one of the fundamental ways energy is being used, b) the amount of electricity being used is increasing faster than other kinds of energy, and c) several different methods for creating electricity using non-carbon sources are possible. That is, not all methods require heat engines or burning of carbon fuels. (Note that about 85% of all global energy used is still based on heat engines fired by fossil fuels.)

Electrical units are used as a primary means of comparison for amounts of energy and rates of energy use. Most people have a much better idea of what kilowatts and kilowatt-hours are than Quads (Quadrillion BTU), BBO (Billion barrels of oil), and other such specialized use values. It is important to distinguish between amounts of energy (Gigawatts and Quads) and rates of energy use (Megawatt/hours and Quads/year). When heat (thermal) energy amounts or rates using electrical values such as Gigawatts instead of Quads are noted, what is given is the electrical unit equivalent of the heat or other energy amount or rate without actually converting the real energy into electricity.

Globally about 36.4% of all heat energy is used to generate electricity. Electrical Gigawatt units for heat energy converted into electricity can be used as a metric. When energy is converted from one form to another, very large amounts of energy are lost or "wasted" due to natural thermodynamic inefficiencies that are not in most cases due to human failures. If a representation of an amount of energy (a value) is converted to its equivalent value in another form of energy, no energy is lost.

Base Load Power is a primary (and the largest) component of electrical power supply. When base load power fails, the results can range from serious to catastrophic, and some user installations, such as hospitals, must have their own backup power available. Two primary aspects of Base Load power are: 1) its reliability and 2) its cost (usually less than peak load power per kilowatt-hour). When a source of power like solar or wind is intermittent, its usefulness as a source of base load power is at a very severe disadvantage, compared to a normally continuous source of power such as a hydroelectric generating stations on a large river or nuclear plants for which the reliability and capacity factor has steadily climbed for a generation or more.

Even though dramatic improvements in the efficiency of creating, transforming and moving energy have occurred in the last century, the total demand for energy and electricity has continued to increase. Growth in global energy use is accelerating beyond any improvements in efficiency.

Scale of Heat Energy Conversion into Electricity

Note that for all our fossil, nuclear and biomass sources, much more thermal energy is expended in creating the electricity than the energy of the electrical power that is produced. Conversely, when electricity is used (other than to produce heat), its use is more efficient than direct use of fuel. The use of electricity produced from fuels is not wasteful compared to direct use of heat energy.

It is important to understand just how much energy is "lost" during conversion to electricity. In 2008, the U.S. used about 1361 equivalent Gigawatts of heat plus some mechanical energy to generate an average of about 498 Gigawatts of actual electricity, of which 435 Gigawatts were available for sale (before transmission). During this process, about 864 Gigawatts equivalent of heat energy was lost due to energy conversion. This means that about 36.6% of the original heat or mechanical energy is actually converted into power and about 63.4% was lost. The conversion losses for the U.S. are comparable to those for other countries.[1] Typical conversion factors for photovoltaic solar are 20% converted and 80% "wasted" as heat. Wind power efficiencies are much harder and more complex to estimate.

Scale of Global Energy Use

The sun radiates 174,423,000,000,000,000 watts of energy to the earth's cross-sectional area of about 50.3 million square miles or 174,000 Terawatts (TW = 1 Trillion watts). In space above or near the earth, the available solar energy is about 1.3 kw / m^2.[2] However, due to the atmosphere, the earth's surface only gets an average of 77 % of the energy available in space or 134,000 Terawatts. The rest is absorbed or reflected by the atmosphere. Only those areas of the earth's surface directly facing the sun (at noon in summer) and without clouds would be getting the maximum of approximately 1.0 kw / m^2 of full sun that is possible at the bottom of the atmosphere. All of current human energy production and use amounts to only about 16.4 Terawatts, or about 1 part in 10,000 of the sun's energy hitting the earth. All of earth's wind energy represents about 1.5 % of the sun's energy received by the earth or about 2,600 Terawatts. In contrast, all global photosynthetic plant energy is captured from the sun at a rate of only about 26 Terawatts, less than twice our average global energy needs.

Economic and Practical Limitations on Terrestrial Non-Carbon Sources: Relative Diluteness of Solar and Wind

In comparing solar and wind energy, mankind could in theory get all of its energy needs met by intercepting about 0.5% of all the earth's wind energy, or with about 0.01% of its sunlight (assuming no conversion losses), or 0.05% with losses. It is also theoretically possible to extract gold and copper from seawater and common granite rocks, but it is economically impractical to do so. This is due to the diluteness of those elements in seawater and granite. Fortunately, geological forces over hundreds of millions of years have concentrated valuable minerals into ore bodies that are concentrated enough to mine. In the same way, topography concentrates wind energy into certain areas, such as plains and mountain passes, which make those areas valuable for extracting wind energy. Thus, there are large geographic areas where wind power is economically harvestable (such as in the North Sea) and areas where it is not (such as central Texas). With terrestrial solar, there are always certain times (nighttime) when solar will not be available.

Wind and ground solar power have many of the same practical limitations, including their non-dispatchability. That is, they are not always available nor are they capable of being turned on and off rapidly to supply demand as needed. This is due to their intermittent, dilute and unpredictable nature. Note that the example given in this paper is of a photovoltaic solar plant rather than a solar thermal plant, since the former can be used over a wider area than the latter, which needs the very best, cloudless site areas to function efficiently.

Generating Capacity vs. Amount of Energy Generated

The single most confusing issue (to non-energy specialists) relating to alternate energy and electricity production is generating capacity vs. amount generated. When the media report that a wind farm has 1 Gigawatt of capacity (assuming 400 wind turbines of 2.5 Megawatt capacity each, they seem to assume that the capacity also proportionally represents the amount of energy that the wind farm will actually generate. In the real world, all generating systems have a capacity factor (which represents the equivalent fraction of time a generator can produce full-rated power). This factor is always less than 1.0 or 100% for two main reasons: 1) the system is not operating at all times, due to downtime (for repairs or normal servicing) or lack of resources such as wind or sunlight, and/or 2) the system is operating at less than full capacity for all or part of the time.

Area Required to Collect Centralized Ground Solar and Wind Power With Average 20% Capacity Not Considering Storage Losses

To understand wind power sites, three kinds of areas can be considered: the wind resource area, the equipment area, and the swept area (wind intercept area). The equipment area is comparable to the site area of a ground solar plant, while the swept area is comparable to the collector area of a solar plant. Unlike other defined areas for both ground solar and wind, most (97%) of the wind resource area in relatively flat terrain can be used for other purposes.

Wind power requires a wind resource area of about 60 acres per rated Megawatt of installed capacity in good, flat-lying wind sites, so a standard 2.5 Megawatt Turbine would need 150 acres, allowing about 4.3 such turbines per square mile.[3] This would produce about 10.75 Megawatts of rated power per square mile, or about 4.1 Megawatts per square kilometer. Turbines placed too close together will be competing with each other, making each turbine less efficient. An optimum spacing for each wind site can be calculated.

Rated power assumes that the wind is blowing at the best speed for power production, about 14 meters per second; of course, the wind only blows at this speed for a fraction of the time. (Some British sources give values as low as 25 acres per rated Megawatt - these may be for offshore sites.) Turbines can be placed next to farm roads and at the edges of fields, so the total area actually occupied by the wind equipment could be 2 acres per megawatt, or about 3% of the resource area. For wind sites on ridges and in mountain passes, the required wind resource area is at least 10 times smaller, but the area occupied by equipment is about the same.[4]

The swept area or wind intercept area for a 2.5 Megawatt turbine would be about 8000 meters square, with a diameter of about 100 meters (wider than a football field is long) and blade lengths just under 50 meters. Typical hub heights would be from 75 to 100 meters. The proportional swept area per megawatt of rated capacity would thus be about 3000 sq. meters, or 0.74 acres, which is about 41% of the equipment area.

Area Types	Area in Square Meters	Area in Acres	Comparison to Equipment Area	Comparison to Resource Area
Resource area:	243,000 sq. m.	60 acres		100%

Equipment area:	7290 sq. m.	1.8 acres	100%	3% of resource area
Swept area:	3000 sq. m.	0.74 acres	41% of equipment area	1.2% of resource area

Table 1. Areas for a 1 Megawatt Rated Capacity Wind Turbine
(Base Load requires about 4X the given area)

It takes a wind farm resource area of 60,000 acres, 244 square kilometers or about 94 square miles, a site area of 2.8 square miles and a swept area of over 1.15 square miles or about 735 (vertical) acres to produce 1 Gigawatt of maximum rated (installed capacity) intermittent power. To produce 1 Gigawatt of base load power, assuming no storage losses, and assuming a capacity factor of 20%, requires a wind resource area of 300,000 acres or about 470 sq. miles or 1218 sq. kilometers. Actual wind equipment would cover about 14 sq. miles or 36 sq. km, and the total swept area would be about 6 sq. miles.

To compare to solar power, the analysis assumes the best ground-based sun- light strength of 1 kilowatt /m^2, and that the collector area is 1/4 of the site area (to prevent shading of tilted solar arrays). One square kilometer (about 247 acres) of the ideally located solar photovoltaic farm would hold 250,000 square meters (about 61.8 acres) of tilted one-axis tracking photovoltaic panels collecting 250 Megawatts of sunlight at 20% efficiency and at 20% efficiency, producing 50 Megawatts of electrical power when the panels can directly track the sun.

To produce 1 Gigawatt (intermittent) with full sun under the same conditions would thus take 20 square kilometers of site area, and for base load, again assuming no storage losses and an average annual capacity factor of 20%, it would take 100 square kilometers (about 37 square miles of site area), of which 25 sq km would be collector surface and about 75 sq. km. would be spacing to avoid shadowing, power lines and access roads.

Therefore, given a good solar and a good wind (resource area) site of 100 square kilometers each (not counting storage losses), the solar site could produce 1 Gigawatt of base load power, and the wind site could produce 80 Megawatts of base load. (Remember that 25% of the solar site is occupied by equipment compared to only 3% of the wind site). On the other hand, when comparing the equipment-covered areas only, 100 square kilometers covered by solar collectors could get 4 Gigawatts of base load power, while 100 square kilometers covered by wind turbines could get 8.3 Gigawatts of base load power. This indicates that the wind resource is more concentrated than the solar resource in good sites. Of course, such wind sites will require a large amount of maintenance, compared to the solar sites, where the only moving parts are the hinges that track the collector panels slowly once each day from east to west. Solar equipment would require constant cleaning of surfaces.

By way of comparison, in space no site area is required. One hundred percent of the "area" consists of such in-space equipment as collector surfaces, spines and trusses, power generators and transmitters. The mass of the component parts is more important than the area in terms of cost. Some 100 square kilometers of photovoltaic collector in space would generate 26 Gigawatts of dispatchable (able to be directed rapidly on-demand) base load power in space and about 20 Gigawatts on the ground. This assumes the total efficiency after the collector is 75%, with no storage needed and thus with no storage losses.

The following table compares an "energy capture" area of 1 square meter when energy is available for the three systems. Conversion efficiency for all is 20%:

Conversion System - Type Area	Ground Solar - Collector	Space Solar - Collector	Wind - Swept Area
Unconverted Power	1 kw. (max)	1.3 kw. const	1.67 kw. (varies)
Converted Power	200 w. max	260 w.	333 w. (varies)
Capacity Factor	0.2 avg.	0.99 const	0.2 avg.
Average Power	40 w. max	257 w.	66.6 w. avg.

Table 2.

One square meter of swept area has more power in it than 1 square meter of sunlight, but since the swept area is only about 1.2% of the wind resource area, the wind resource is much more dilute per site land area than with solar. The power density per equipment area is more comparable.

The following table compares how much energy can be obtained from available site areas, showing the production limits based on total site area. For Wind, the Site area is the Wind Resource Area and the Collector area is the vertical Swept area.

Avg. Power from 1 sq. Kilometer of Site
Conversion Efficiency = 20%
Ground Solar & Wind Capacity Factor = 20%

Gen. type, supply type, % of entire site	Collector area	Power received	Power generated
Space Solar Base Load (100%)	(site area in space is meaningless)	1,287 MW	257 MW in space

	247 acres		193 MW at ground
Solar - intermittent, 25%	61.8 acres	250 MW	50 MW
Solar - Base Load, 25%	61.8 acres	50 MW	10 MW
Wind - intermittent, 3%	7.4 acres	˜20.5 MW	4.1 MW
Wind - Base Load, 3%	7.4 acres	˜4.1 MW	0.82 MW

Table 3.

The next table shows how much power can be obtained from 1 (composite) square kilometer (of land or air) that is fully occupied by the energy collector equipment. It assumes a share of 2.0 acres of land per megawatt for the wind equipment area and an actual area of 0.74 acres per megawatt for the wind turbine swept area - the area of a vertical circular plane. Efficiency for all systems = 20%. The capacity factor is 20% for Wind and Ground Solar, 99% for Space Solar). Base load amounts assume no storage losses.

Gener- ation Type	Power Supply Type	Area Type	Area of Coll. Equip.	Power Receiv- ed	Power Generated
Space	Base Load	collector	247 acres	1,300 MW	195 (260 in space)
Solar	*inter-mittent*	collector	247 acres	1,000 MW	200 MW
Solar	Base Load	collector	247 acres	1,000 MW	40 MW
Wind	*inter-mittent*	equip area	247 acres	˜ 615 MW	123 MW
Wind	Base Load	equip area	247 acres	˜ 615 MW	24.7 MW
Wind	*inter-mittent*	swept area	247 acres	˜ 1670 MW	334 MW
Wind	Base Load	swept area	247 acres	˜ 1670 MW	83 MW

Table 4. The table clearly shows that with equivalent areas of equipment, space solar produces much more energy per unit area (since it is always available).

Austin, Texas Solar Power Plant as a Model

To take a current example, the city of Austin, Texas is planning to build a 30 Megawatt photovoltaic plant to cost about $250 million on a 300-acre (0.47 sq. mi.) site.[5] This plant is not intended for independent base load use, but instead as a means of replacing periods of primarily gas fired base load power during the day. The plant would produce a total of about 28.9 Megawatts ($8.7 million / MW) covering an area of 267,000 m^2, about 66 acres of active collector area. This amounts to 22% of the site area. The nominal value for collector to site area is 25%. The collectors are to be arranged in panels angled towards the south or south-southwest, probably at an angle of 15 degrees, and using single axis tracking that rotates rows of panels from east to west to track the sun's path.

Assuming that the optimum tilt for the array is 15 degrees to the south and using single-axis tracking collectors, the average kilowatt-hours per square meter per day for the 30 year period 1961-1990 is 6.4 kwh, when the average maximum obtained is in July with 8.7 kwh and the average minimum is in December with 4.4 kwh. Were the sun to be available directly overhead for 24 hours a day with no clouds, the site would get just under 24 kwh.[6] These figures show that in the winter, the system must rely on 30 Megawatts of gas fired power for an average of 19.6 hours a day, and in July for 15.3 hours a day, for an average of 17.6 hours a day. Thus the capacity factor average for this installation in July is 0.36, for December it is 0.183, and for the year it is 0.266. This is similar to the average capacity factor of 20% often given for various solar sites. Austin is not a good solar site, due to the frequent and prolonged spells of cloudy weather during the fall, winter and spring. Only in the relatively cloudless high summer (usually July through mid-September) can Austin be regarded as a good site.

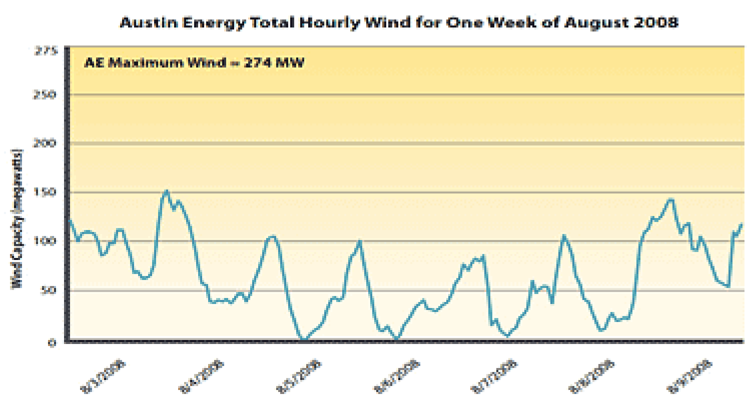
Intermittent Nature of Solar and Wind Forces Require Either Backup Generation or Energy Storage

Since most base load power is provided by fossil sources, the only way to significantly reduce fossil fuel use is to find ways of using wind and solar for base load as well as for peak load use. Clearly, the intermittent nature of these sources is a major obstacle, since base load supply, by its nature, must be continuous.

Ground Solar and Wind present two different types of intermittency. With Solar, users can predict exactly when and for how long they will not have power during the year, as the night-time lengthens and shortens. The approximate curve of available maximum power resulting from the sun's changing elevation, and the type of collector surface, can also be precisely determined. What is not exactly predictable are such factors as clouds, fog and dust that reduce the maximum available power at any given time during the day, although a weather forecast predicting a cloudless day will generally be accurate. For practical reasons, backup or fill-in power must be able to cover the worst-case scenario. For most solar sites in the U.S., the worst case is normally in the winter months and for wind it is in the summer. In addition, concentrating solar, which has a much higher conversion efficiency than photovoltaic, will lose most of its capacity from a thin overcast, since the concentrating reflectors depend on the majority of the light coming directly from the sun's position. A thin overcast creates a sky-full of bright but diffuse light that cannot be concentrated. This is why thermal solar sites are limited to areas with very low cloudiness.

With wind systems, sufficient wind may be available at any time during night or day. However, for any given site, previous records allow a reasonable prediction of wind velocity for a day or two into the future, and can partially predict composite wind patterns over a whole region. Typical good wind site average capacity factors (the actual amount of power generated divided by the maximum power a turbine is rated to generate) are between 20% and 40%. In many areas, available wind power is much greater during the winter months. What is not predictable for wind is the exact amount of power available for a given turbine at a given moment.

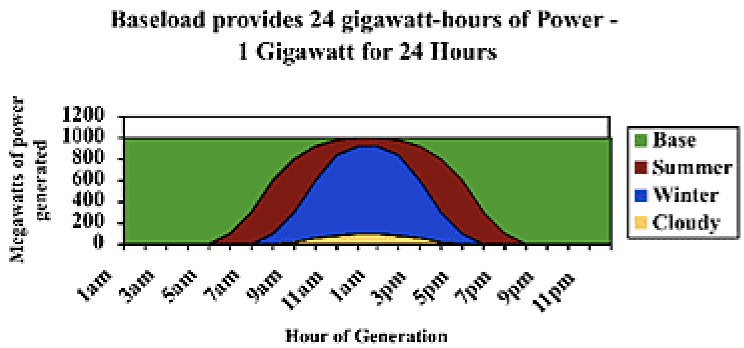
Wind over an entire region can be low to nonexistent, either to co-incidence or to a weather pattern that is affecting the entire region. These "null" periods show up clearly on wind pattern charts, and imply that the alternate dispatchable generating capacity must be about equal to the entire wind generating capacity in each region. In 2008, Austin, Texas had 275 Megawatts of wind generating capacity in western Texas. Graph 1 shows one week during one of the poorest periods for wind, when the capacity factor seems to be averaging about 18% (50 Megawatts out of 275), with 4 periods during the week of essentially no generation at all.



Graph 1. [7]

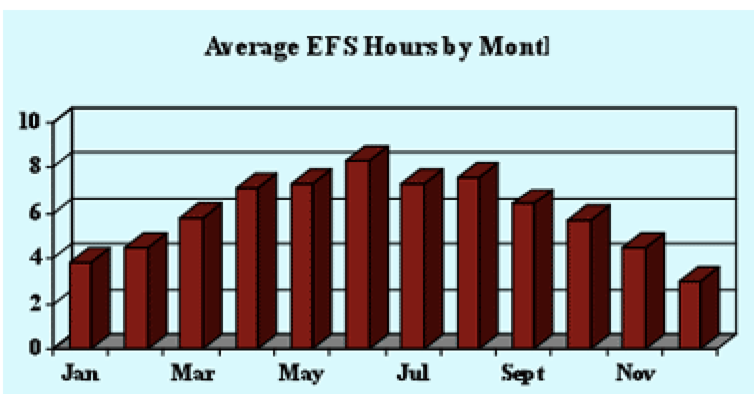
To provide power when wind and sun are not available, users either need backup generating capacity or energy storage with a large amount of extra alternate capacity to fill the storage system during the limited time each day that the sun or wind is available. Backup capacity is virtually certain to be provided by fossil fuel, since that and nuclear are the only sure backups. Storage of electricity that has already been generated is extraordinarily expensive, since the energy form usually has to be converted at least twice, and since very large systems are required to store it. The more compact form in which the energy is stored, such as ultra-compact batteries, the greater the risk when an accident occurs.

Graph 2 shows typical power outputs for 1 Gigawatt base load (such as a nuclear) plant and daytime solar plants during clear summer/winter/cloudy winter days. The total area under each curve represents the number of Megawatt-hours that would be generated by a plant with a 1 Gigawatt-capacity collector that day. It is clear that the blue area representing a clear winter day covers only about 25 percent or less of the total area, indicating why the capacity factor for most solar plants is so low. This is for a non-tracking collector system such as would be installed on a rooftop, and shows the even more severe limitations of "distributed solar" vs. centralized solar systems.



Graph 2.

Graph 3 shows the average number of hours of Effective Full Sun (EFS) in Austin, Texas for a single axis-tracking collector tilted south at 15 degrees. (EFS means the equivalent of steady sunlight at 1 kilowatt/sq. meter. This is related directly to the capacity factor for a solar plant during each month).



Graph 3. [8]

The combination of intermittent power and low power during winter months is what creates the low capacity factors for solar collectors in most areas. Austin usually has week-long cloudy spells during the fall, winter and spring which have a large effect on the factor. The result is a low of 3 EFS hours per day in

December: a capacity factor of 3/24 or 0.125. For 4 months a year the capacity factor is 0.166 or less. The best factor is just for June, with 8 EFS hours a day, or about 0.3. A tracking collector system increases the capacity factor, but has a much larger capital and maintenance cost.

Modeling Base Load Power From Intermittent Alternate Energy Systems

The idea that solar and wind systems have in effect a capacity factor of 100% (that they generated their rated capacity most of the time) is a false impression that the media began giving the public during the 1970's and 80's, and continue to do so, by just not mentioning capacity factors. Since the author knows that wind and sun are not available all the time, he also knows that there has to be a noteworthy difference between generating capacity and power generated. This author was probably one of the first (outside of electrical engineering circles) to define this issue and create a simple way to understand the sizing requirement.

Cost of energy storage is one of the overriding issues for creating base load from intermittent sources. It is painfully obvious how much effort and thinking have gone into attempts to store power and energy for later use. The size of the collector for a stored alternate energy system designed to supply base load power, has to be larger than one designed for daytime use. This can be determined by multiplying by 1) the inverse of the average 24-hour capacity factor for the system, and then by multiplying by 2) the inverse of the efficiency of the storage system. The storage system has to be larger than the demand by the same ratio.

For example, if a given solar system can run at full power for 6 hours a day average, the capacity factor is 25% or 0.25, so the collector has to be 4 times larger. Then, the designer has to account for a battery storage system that can be assumed has 50% recovery efficiency, so the collector actually needs to be 4 times 2 or 6 times larger than the daytime collector size. (A wide variety of battery efficiencies exist depending on the chemistry used. Not a major issue in the past, battery efficiency is now often proprietary information. Verifiable efficiency values for battery storage systems are very difficult to obtain.)

Utility-Scale Energy Storage Requirements for Solar and Wind

Note that the capital cost (and capacity) of any energy storage system depends both on the rate the power can be stored and recovered from storage, and how long (in hours) it can provide full power. The four critical storage factors are: 1) storage efficiency, 2) cost of storage in millions per Gigawatt-hour, 3) the rated capacity in Megawatts or Gigawatts of plant to store and recover power, and 4) the maximum time in hours it takes to recover power at full capacity. Power can be stored at a lower rate for a longer time and still provide the full power recovery capacity required.

Four types of energy storage are serious contenders for utility scale, non-emergency storage, meaning a system that can store and provide a major portion of full power for a city for many hours at a time. They are: 1) Pumped Hydroelectric, 2) Pressurized gas (Compressed Air Energy System), 3) Chemical Batteries, and 4) Molten Salt (for thermal solar only). Each of these types of storage has different benefits and drawbacks.

A 2005 government-sponsored climate change paper gives estimates for some energy storage costs, suggesting that pumped hydro storage would cost between 10-45 dollars per kwh. This translates into an average of about $25,000 per Megawatt-hour and $25 Million per Gigawatt-hour. A storage plant that needs to store 26 Gigawatt-hours (just 1 day's power supply) would thus cost about 650 Million dollars to build (estimated range from $260 Million to $1.1 Billion dollars).

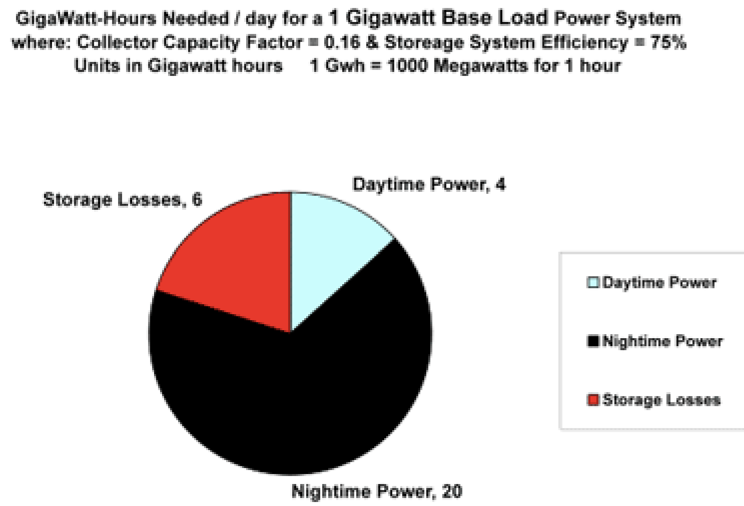
This same report indicated that compressed gas storage (where the storage volume already exists) could cost as little as 1/10 the cost of pumped hydro storage, while Battery storage systems could cost up to 5 times more than pumped hydro storage.[9] Thus, it is clear that capital construction costs for a energy storage system sized to match a primary energy generation facility are comparable to the capital needed for the generating facility. Another source gives storage capital costs for Wind at about $1.8 Billion per GW.[10]

Requirements for 1 Gigawatt of Base Load Power Output Assuming Storage with Losses and Worst-Case Conditions

To keep a storage example very simple, assume a city needs an average of 1 Gigawatt of base load power. (This is comparable to what Austin,Texas uses). That city will need 24-Gigawatt-hours of power each day. Assume that the city wants to run (as an extreme case of trying to use an environmentally purist methodology) entirely on ground based solar and wind. Using a worst-case scenario method, it can be assumed that the capacity factor for both types is 0.16. In other words, during 16 percent of the time (about 4 hours a day on an average day), the city's utility needs to gather all of the energy required for those 4 hours and also for the 20 hours when it will not be gathering any energy. (In Austin, the average mid-winter day during December and January provides only about 3 hours of full sunlight, and the period with about 4 hours or less of full sunlight per day lasts almost half the year).[11] Conversely, the summer is the worst time for wind energy. The energy collection system (solar, wind or a combination) needs to be at least 6 times larger than a system that produces 1 Gigawatt with full solar or wind energy input, in order to collect the 24 Giga-watt hours in just 4 hours.

Assuming the storage system (such as pumped hydro) has an efficiency of 75%, if the city stores exactly 20 Gigawatt-hours, it only gets back 16. (Note that in the very best solar sites, use of thermal collectors and thermal storage could remove this additional requirement). This means that the city must store 30% more or 26

Gigawatt-hours to get back the 20, suggesting that the collector for this site also must be sized to collect 4 + 20 + 6 = 30 Gigawatt-hours or 7.5 times larger than a daytime only collector. This is shown in Graph 4 below. These values also assume average winter conditions, and do not cover the week-long cloudy periods which are quite frequent.



Graph 4.

Power Collected	Power Stored	Collector Capacity Ratio
4 GWH	0 GW hours direct use	1 GW
20 GWH	20 GW hours night use	5 GW
6 GWH	6 GW hrs to cover storage losses	1.5 GW
30 collected	26 GW hours stored T	7.5 GW

Table 5.

Note that 7.5 Gigawatts of collector capacity is about equal to the entire installed capacity of Texas wind turbines at the end of 2008, which, if they were all 2.5 Megawatts, in size, would represent 3000 turbines, covering 450,000 acres, just to produce 1 Gigawatt of base load power.

Taking the cost of the proposed Austin Solar Plant ($8.7 million / MW), or 8.7 billion / GW, as a model of current ground solar costs, it can be shown that to provide base load power with ground solar and using no fossil fuel (thus requiring a collector 7.5 times larger) will cost about $65 Billion per Gigawatt, plus the cost of the massive energy storage system. This is about 30 times higher than costs for existing base load plants and assumes that there are no long cloudy periods (that you get some sunlight every day). This cost level seems unaffordable.

Ground-Based and Space Based Energy Supplies - Primary Comparisons of Ground Based Alternates

A common media misconception from some who have reported on space solar issues has been the idea that there is 8 times more sunshine in space than on the ground, implying to the public that the sun is 8 times brighter in space. It is important when dealing with media to be very clear about the differences between the energy density of solar on the ground and in space. Sunshine in space is only 30% stronger than on the ground at noon under a clear sky at midsummer. The best obtainable surface value for sunlight is about 1 kilowatt/m^2 of thermal energy. In space at the earth's average distance from the sun: anywhere along its orbit, sunlight produces about 1.3 kilowatt/m^2 of thermal energy. The solar output never varies more than about 1/10 of 1% and so is known as the "solar constant." (There is a larger annual variation in what the earth receives since the earth's orbit is not a perfect circle).

The 8 times more sunlight in space fallacy comes from the fact that a square meter of solar panel in space, exposed to raw sunlight for 24 hours a day, will generate approximately 8 times more solar power than the same square meter on the ground in 24 hours on average, due to night-time darkness, atmospheric absorption, clouds, fog, haze, dust, low sun angle, and storage losses.

To see how much energy can be received in space, a quick scale-up reveals that areas of the collector facing the sun get the following amounts of power from the sun:

Collector Area	Power Received Per Area (rate)	Energy Received Per Day
1 square meter	1.3 kilowatt/m^2	31.2 kilowatt-hours/day
10 x 10 meters (100 m^2)	130 kw/m^2	3120 kw-hrs/day
100 x 100 meters (10,000 m^2)	13,000 kw/m^2	312,000 kw-hrs/day
1 square kilometer (1 million m^2)	1.3 gw/km^2	31.2 gw-hrs/day

Table 6.

The analysis assumes that the power satellite collector modules are using photovoltaic film rated at exactly 20% efficiency, which means that a square kilometer collector will produce 0.26 Gigawatts of power at the collectors. (We will also assume such film exists by the time satellite construction begins). The author draws on the efficiency chain from his 1998 paper which shows conservatively that about 75% of that electricity (0.195 Gigawatts) would reach the electrical grid as usable AC power.[12] Rounding that figure to 0.2 Gigawatts allows an easy calculation: 5 square kilometers of collector film surface are required in space to provide for 1 Gigawatt of base load AC power, or 24 Gigawatt-hours per day, on the ground.

Arguments in Favor of Space Solar Compared to Ground Solar and Wind

The massive advantage Space Solar has over ground solar and wind is the almost constant availability of 30% stronger sunlight in Geostationary or Geosynchronous Earth Orbit, which totally removes the requirement for storage of any kind. Thus, Space Solar is ideal for use as a base load power source. Power beams from a small number of spare satellites can be very rapidly switched from one receiving antenna to another during the very brief eclipses of satellites during the Equinox periods to cover scheduled or emergency power needs.

SSP has one characteristic advantage over nuclear: it is very dispatchable and is also a much faster form of "spinning reserve." The original concept of "spinning reserve" was of an extra generator running with water turning it at full speed, but where no power was being generated or transmitted. Such a generator can be switched to generating and transmitting mode very quickly. It would be too expensive to continuously power a generator like this with fossil fuels, and as a result, the delay in starting gas fired combustion, for example, is much greater than with a real "spinning reserve." (Batteries can cover part of this startup-lag requirement without using up too much energy). Reactors take much longer to bring on line, and cannot be used to cover wind and solar. Normally, reactors are not operated in start and stop mode, thus they are not dispatchable.

Space solar is much more efficient in land use and materials use than ground solar, which will of necessity need to cover huge areas (100,000 square miles or more) of land with the hot black surfaces of solar panels. Space solar energy receivers will cover much smaller areas with relatively sparse arrays of what are effectively like wire TV antennas, since the solar panels themselves are in space (where they belong!). This lets about 80% of the sunlight reach the ground and the area under the array can either be left as wild or used for farmland.

Another Point of View: Results from the Garrett Paper Support SSP

University of Utah physicist Tim Garrett published a 2009 paper[13] that gives strong indirect support to SSP. In an article based more on physics than economics, Garrett suggests that energy conservation will have little effect in the long run, and that the globe currently needs to replace and/or add about 300 Gigawatt-equivalents of new non-carbon energy sources each year in order to stabilize current greenhouse gas levels. This rate of construction would not, however, reduce the current rate of greenhouse gas production. With current global demand at 16.4 Terawatts, and about 14 Terawatts of this energy coming from carbon fuel, he estimates it would take 46 years to eliminate all the existing carbon energy production, that is, if we could build an additional 300 equivalent Gigawatts (0.3 Terawatts per year) of carbon-free energy plants to cover new energy demands for both fuel and power.

Nuclear power can only cover part of the 300 Gigawatts per year needed, since there is not an unlimited amount of uranium. If we had cheap access to space, SSP would be the way to provide an unlimited amount of energy, since there is no fuel to deplete. Trying to generate that much energy using ground solar and wind means the globe would have to add 1200 Gigawatts per year of solar and wind capacity (assuming a capacity factor of 25%, yielding an average of 300 Gigawatts) along with either the power storage needed to make it available as electricity when needed, or the equipment to create non-carbon fuels out of the majority of it. Assuming that the capital cost of building the ground wind and solar equipment is about $10 Billion per Gigawatt, and that the storage and conversion equipment would be about the same, the annual global cost to meet this "red queen's race" would be about 24 Trillion dollars a year, of which the annual US share would be at least $5 Trillion/yr.

If nuclear reactor parts could be mass-produced and the reactor construction standardized as France does to keep the capital cost at $2 billion/Gigawatt, the global annual cost would be 2.4 Trillion and the US share would be about 500 Billion/yr. Building re-usable rockets and a system for constructing and implementing SSP operations in space would probably cost much less than what the U.S. would spend on nuclear or ground solar during a single year. In addition, SSP represents the only source of power that we can keep adding to at this rate without causing any environmental degradation or massive use and depletion of physical resources to build the many millions of tons of ground solar and wind equipment required.

Perception and Comparisons of Alternate Power Costs Between Surface and Space Generation Locations

One energy web site reports that electricity costs in the U.S. averaged 10.64 cents per kwh in 2007, based on EIA figures. The lowest average cost for a whole state was in Idaho at 6.35 cents and the highest was in Hawaii at 24.13 cents. The industrial Northeast and California averaged around 15 cents and Texas was at 12.4 cents.[14] Estimated capital costs vary wildly. Official and Media estimates of alternate energy costs tend to be lower than the actual costs at the time of construction.

The approximate mass of a 1 Gigawatt powersat has been estimated at no less than 2,500 tons. [15] Using the assumed $10 million per ton cost of the Ariane V payloads, and assuming (only for this comparison) that the Ariane was scaled up to a true HLV size with the same launch cost per ton, this would put the current (uneconomic) cost for launching a single powersat to LEO at no less than 25 Billion dollars per Gigawatt, or $25,000 per installed kilowatt. This estimate does not include any of the other costs in space and on the surface, which might total about 5 billion for building the satellite collectors and the ground receiving antenna, for a grand total of $30 billion per Gigawatt. Existing types of fossil plants have a capital cost about $1-2 Billion/GW and new nuclear plants are estimated to cost about $2-5 Billion/GW, depending on the laws of the country in which the plant is built.

The cost of the planned intermittent Austin Solar Plant was previously used as a model of one intended to provide base load power with ground solar and using zero fossil fuel. This showed that such a plant would cost about $65 Billion per Gigawatt, plus the cost of a massive energy storage system ($5 Billion for 26 Gigawatt-hours storage), totaling about $70 Billion per Gigawatt. This shows that space solar costs are already comparable now to any non-intermittent ground solar or wind plants proposed to produce base load power without any significant fossil fuel backup, such as those that some local governments may soon support due to political pressures.

Ignoring the fabrication costs of the SSP components and receivers (rectennas) on the ground, which are probably in this price range already, and assuming that ion or plasma tugs can get the SSP payloads from LEO up to GEO for a fraction of current launch costs, it is clear, again, that the LEO launch cost is the critical and reducible part of the investment. This also means that bringing launch costs down by a factor of just 5 will make space solar competitive with the intermittent non-carbon energy systems. Bringing earth-to-space transport costs down by another factor of 10 would make them directly competitive with existing non-intermittent base load generating systems. There is no economic law that says it is impossible to get surface-to-orbit prices down by a factor of 50. Many such economic "laws" proclaimed in the past by notable people have been forgotten by the public. Trips on use-once and then throw-away airplanes would be just as expensive as use-once rockets are now.

Right now, gas fired generation is the only real way to complement the large numbers of wind and solar installations generating energy about 25% of the time each year, since the gas reserve can be brought on-line relatively quickly. When SSP comes available, it will be an ideal method of backing up the wind and ground solar, since its power can be switched to a given rectenna very rapidly, protecting the existing investments in ground solar and wind. The extra SSP power does not have to be wasted, since a plant next to a spare rectenna could be brought to service powering some interruptible process, such as conversion of energy to synthetic fuel, when the power is not otherwise needed.

Conclusions

Maintaining a sufficient national and global energy supply in the face of declining fossil fuel reserves is critical to controlling global warming, maintaining economic security, and assuring international security and stability. Like any "Titanic," there comes a point when steering hard to the left is too late and a crash (or collapse) is inevitable. Having a means of predicting or detecting when we are approaching such a crisis point can be useful, a service which this paper hopes to provide.

Clearly, the world needs to find a source of base load electricity that can be proven to be large enough to fill the energy and electrical generation gap and also replace much of the energy currently used as vehicle fuel. The Garrett paper underscores the sheer immensity of this task. The next-generation energy source must be installed without using up unacceptably large amounts of material resources and land; it must be made available at an affordable cost when compared to other energy sources. Installation of that source must start with the current generation. In the absence of near term fusion power, and as long as politics and safety concerns prevent the widespread use of nuclear fission power with reprocessing of nuclear fuel, the only energy system that can be currently proven to have such characteristics is Space Solar Power, initially implemented using power satellites in Geosynchronous Earth Orbit. Reducing costs of launching payloads into Low Earth Orbit is an essential prerequisite and first-step for building such an energy system.

ADDITIONAL RESOURCES

For download: Facing the Numbers (DOC, 360 KB).

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