An examination of the economics and practicality of grid scale solar power

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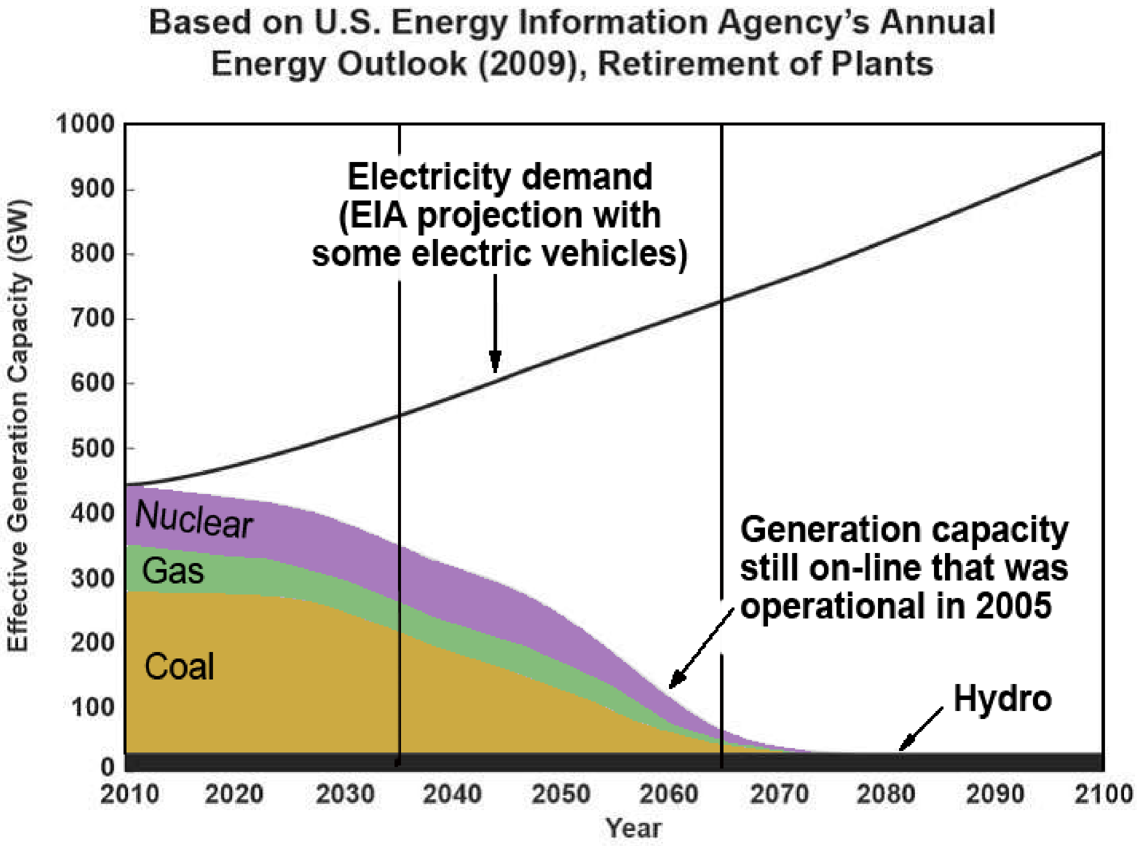
Key Concepts

- By 2060 88% of current on-line utility scale generation capacity will be retired due to plant age and life cycle considerations.
- It requires over 1,000 times more power (energy per unit time) to produce a PV panel than one panel can produce. It requires 3,333 1 m^2 panels at the equator to fabricate one such panel per hour. This is further exacerbated by the DC to AC step up inverter electronics, storage components, electrical interconnecting cables, and land preparation required for utility scale baseload power. Thus a “solar only” generation system cannot be self-sustaining.
- 29.3 billion 1 square meter solar panels are required for 100% solar power in the U.S. based on current demand 24 hours a day, 365 days per year.
- 29.3 billion 1square meter panels would cover 29,333 km2 which equals 7.2 million acres, or almost all of Maryland and Delaware.
- If 1 square meter PV panels were manufactured, installed, and connected at the rate of 1 per second, it would take 929 years to manufacture and deploy 29.3 billion panels.
- The cost of a solar only approach exceeds $15.27 trillion.
- To meet all energy demands for transportation, industrial, and commercial-agriculture would require 176 billion solar panels and 5,574 years to produce.
- Solar photovoltaic cells and panels have a life time of 30 years; 50 years would be extraordinary; thus every square meter of PV surface area would have to be replaced in less than 50 years.

Over the next 50 years, utility companies in the United States must replace approximately 440 Gigawatts (GW) of baseload generation capacity to provide electricity nationwide. Significant electrification of the transportation segment through electric cars and trucks can potentially quadruple the amount of needed power.

This paper explores the system requirements to replace this generation capacity with a photovoltaic only generation scheme. Topics include the definition of peak power demand, time of use issues, reserve power requirements, storage to provide power when there is no sunlight, and the various engineering challenges associated with managing a large area synchronous AC power grid.



This analysis considers the factors involved in dimensioning solar power generating plants. To illustrate the issues involved the example considers the case for supplying the entire electric power needs of the USA from solar energy without the use of fossil fuel, nuclear or other back up. To simplify the calculations, the example considers a single very large hypothetical solar power installation providing all the country's power although in practice, generation would be dispersed in a network of smaller installations throughout the country each one closer to the point of need. Depending on the location of the solar arrays, some modifications or additions to the electricity grid distribution network may be required but these have been ignored for the purposes of this study.

In reality, such a future solar only electricity supply would most likely be generated by a mix of energy sources including several large T&D grid connected solar power installations as well as many domestic installations.

The example used for this study is a conventional solar power plant consisting of a large bank of solar panels, each made up from an array of individual photovoltaic (PV) cells, feeding the electricity grid network during the day. and charging a bank of batteries which will provide the power during the hours of darkness.

The example shown below is a grid connected PV system (batteries not included) which is inactive at night when power is provided by traditional "spinning reserve" of steam driven turbines which make up part of the grid system. An off-grid system like the one considered here also requires a large battery bank to store energy during the day in order to maintain the supply during the night.

Lieberose 71 MegaWatt (electric) Solar Power Plant near Berlin in Germany

Demand Assumptions

Capacity

Sources including the Lawrence Livermore National Laboratory (LLNL), The Department of Energy (DOE), The US Energy Information Agency (EIA) and Index Mundi give estimates of the annual electrical energy demand or consumption in the USA in 2013 ranging from 3,633 to 4,886 Tera Watt Hours (TWh) or 12.4 to 16.7 Quads. A quad is 1.055 X 10^{18} Joules or 1.0^{16} BTU (1 quadrillion BTU.)

The calculations are based on current demand only and do not include future growth. The drive towards the greater use of electric vehicles will increase this demand significantly over and above normal growth and, since most people recharge their batteries at night when the Sun is not shining, this will require a major restructuring of both the generation and storage capacities of the national grid to cope with the increased demand and its changed profile.

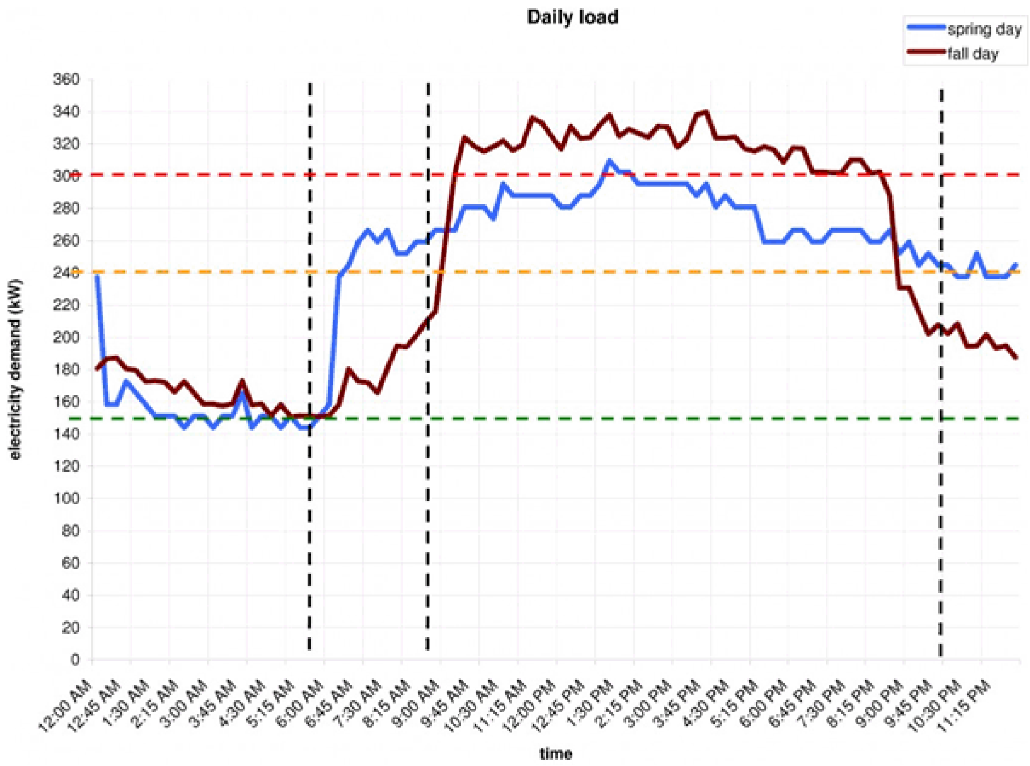
Power

For convenience it is often useful to convert this energy demand into the equivalent average rate of power generation or consumption. This measure assumes constant power generation 24 hours a day, 365 days per year. The power delivered is given by the energy consumed divided by the time, in this case, 1 year or 8,760 hours. Thus the estimates given for average power consumed range from 415 to 535 Giga Watts (GW).

For the purposes of this example an annual energy demand of 3,854 TWh corresponding to a power usage of 440 GW average generation is assumed.

Demand profile

But life is not so simple. The demand is not constant, but varies during the day and also suffers seasonal variations as well as regional variations. There are many published demand profiles reflecting these variations. The profile shown below, compiled by U.C. Berkley, is reasonably representative and offers the possibility of simpler assumptions than some other profiles. It shows that the demand during 12 daylight hours is approximately double the demand during the 12 hours of darkness. This means that 2/3 of the energy is consumed during the day and 1/3 at night.



Source UC Berkley

Assuming that the demand is to be exclusively satisfied by solar power alone, the night time demand would have to be generated by the solar panels during the day.

So with an average (continuous) power demand of 440 GW, the daily energy demand is 24 X 440 = 10,560 GWH.

But all of this energy will have to be captured during the 12 hours of sunlight, that is, in half the time, so that the solar power generation capacity must be 880 GW.

Of the 10,560 GWH of energy produced during the day, two thirds (7,040 GWH) will be used directly by consumers and one third (3,520 GWH) will be used to charge the battery for subsequent discharge to satisfy the consumers during the night.

The corresponding power demand will be 586.7 GW during the day and 293.3 GW during the night.

It is assumed that the daily demand profile matches the timing of the hours of sunlight, but this is not necessarily the case. However it does not significantly affect the conclusions of this study.

In practice, the solar energy captured would be more in the summer and less in the winter so that more solar panels and larger batteries would be needed in the winter and fewer in the summer. An allowance can be made for this but for the purposes of this example, these variations have been ignored.

System Requirements

From the above we can conclude that solar generating power capability of 880 GW and a battery energy capacity of 3,520 GWH will be required to satisfy the demand.

But public utilities always need a plant margin to cover, maintenance, breakdowns, unplanned peak demands and other emergencies and this is typically 20%.

Also there will be a 10% efficiency loss in the inverters necessary to convert the DC solar energy generated by the PV arrays to the AC supply connected to the distribution grid. In addition there will be a further charge-discharge round trip coulombic efficiency loss in the batteries of about 5%. To be generous, let’s say an extra 25% of energy must be generated to cover these two efficiency losses as well as the plant margin.

Thus the generating power will need to be at least 1,100 GW or 1.1 TW and the battery capacity will need to be 4,400 GWH to allow for the efficiency losses and the plant margin.

What does this mean in practice?

The Available Solar Energy

The actual amount of solar energy impinging on the solar panel depends on several factors.

The solar energy reaching the Earth’s atmosphere, known as the irradiance, is 1,367 W/m^2 normal to the Sun’s rays. By the time it reaches the ground after absorption by the atmosphere it is reduced to 1,000 W/m^2 normal to the Sun’s rays. This corresponds to the energy impinging on a flat plate on the ground when the Sun is directly overhead.

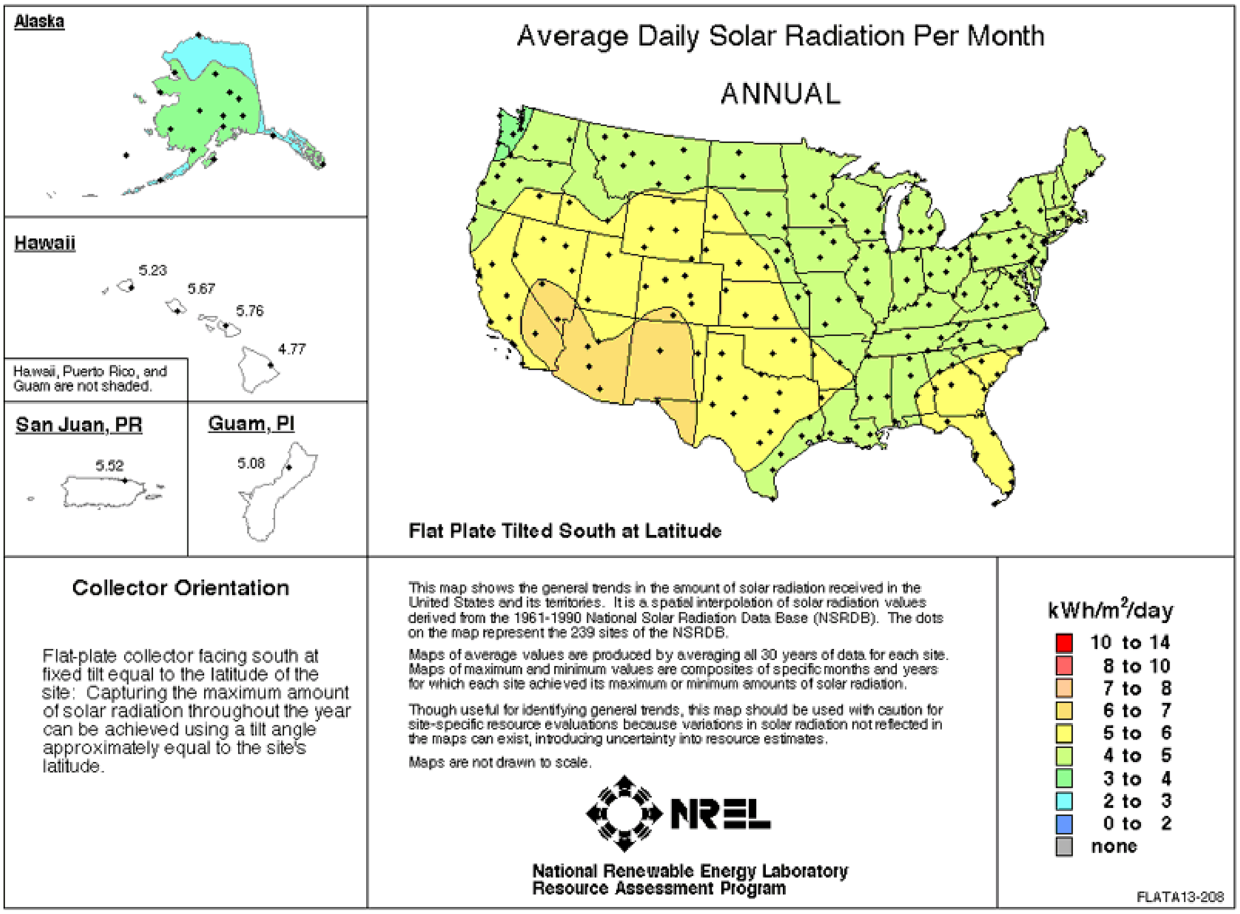
But outside of the tropics, the Sun is never directly overhead and, apart from mid-day, it is never even at its highest point as it appears to move from East to West due to the rotation of the Earth. If the Sun is not directly over the plate, the energy intercepted by the plate will diminish with the actual amount intercepted being proportional to **cosT** times the “normal” incident energy, where T is the angle of deviation of the Sun’s rays from the normal 90° incidence. (See Solar Power – Geometry)

Then there is no Sun at all during the night.

Finally the angle to the Sun, as well as the number of daylight hours, decreases (In the northern hemisphere) during the winter months as the Earth orbits the Sun.

Taking all of these factors into account, the average of the time varying solar energy received on the ground is called the insolation and figures have been published for the actual insolation at various geographic locations by several sources.

NREL is one such source which publishes a range of charts showing the daily average solar power received during each month of the year, plus yearly averages, for different solar array types and configurations at various locations in the USA. The chart below is typical and has been used, with others in the series, in the calculations which follow.



Hawaii, Puerto Rico, and Guam are not shaded.

Collector Orientation

Flat-plate collector facing south at fixed tilt equal to the latitude of the site: Capturing the maximum amount of solar radiation throughout the year can be achieved using a tilt angle approximately equal to the site's latitude.

This map shows the general trends in the amount of solar radiation received in the United States and its territories. It is a spatial interpolation of solar radiation values derived from the 1961-1990 National Solar Radiation Data Base (NSRDB). The dots on the map represent the 239 sites of the NSRDB.

Maps of average values are produced by averaging all 30 years of data for each site. Maps of maximum and minimum values are composites of specific months and years for which each site achieved its maximum or minimum amounts of solar radiation.

Though useful for identifying general trends, this map should be used with caution for site-specific resource evaluations because variations in solar radiation not reflected in the maps can exist, introducing uncertainty into resource estimates.

Maps are not drawn to scale.

National Renewable Energy Laboratory
Resource Assessment Program

Source NREL

For the purposes of this study, the location chosen for the solar plant is somewhere in the South West, the sunniest part of the country, since this will require the smallest solar array. For a tilted flat plate array, as specified below, the chart shows that the average solar energy intercepted throughout the year by the array is around 6 kWh/m^2/day in the South West. If the plant were to be located in the colder northern states, the energy intercepted would drop by a third to around 4 kWh/m^2/day so that the solar array would have to be about 50% larger to capture the same amount of energy. Other charts in this series show how the insolation decreases during winter months and increases during the summer.

The Solar Array Configuration

Several configurations of solar panels are available.

Fixed Array
The simplest and least expensive solar array is constructed from a series of fixed flat plate collectors all facing south and tilted towards the Sun at an angle corresponding to the latitude of the site.

Tracking Array
The efficiency can be improved by 30% or more by means of tracking systems which ensure that the solar panel is always pointing directly at the Sun. Two axis systems track the apparent changing azimuth and elevation of the Sun as the Earth rotates during the day and continues its year long journey around the Sun. This option is quite complicated and very expensive. See more about Solar Tracking.

The Electrical Energy Captured

From the NREL charts, the annual average insolation (solar energy received) in the South West of the USA is between 5 and 6 kWh/m^2/day for a fixed array tilted towards the Sun and 7 to 8 kWh/m^2/day for steerable two axis solar panels able to track the Sun across the sky, maintaining the Sun's rays as close to normal as possible to the surface of the array. Let us assume 6 kWh/m^2/day for a fixed array and 8 kWh/m^2/day for a two axis tracking array.

Conversion Efficiency

The current generation of mass produced commercial PV cells for converting solar energy into electrical energy have a conversion efficiency of around 15%.

This means that the above fixed array can generate the equivalent of a 24 hour average continuous power output of (6÷24) X 0.15 kW/m^2 during each hour or 37.5 Watts/m^2.

Similarly a two axis tracking array can generate an average of 50 Watts/m^2 during every hour.

During hot sunny days the PV cell output will increase due to the increased solar radiation, but at the same time the cell temperature will also rise causing the cell output power to fall due to the decrease in the conversion efficiency. See (Solar Cell Operating Characteristics).The PV cell output power typically reduces by about 0.5% for every degree Celsius increase in PV cell temperature. The precise output power achieved from the cells depends on the conditions, but to optimize the power output, water cooling is often employed to keep the cell temperature as low as possible.

The calculations in this example assume STC (Standard Test Conditions) PV cell ratings, that is a cell temperature of 25 °C without external cooling. Local conditions may necessitate cooling to get the best out of the solar arrays and this would increase the cost and complexity of the installation.

Energy Lost During Charging

Because of the mismatch during charging between the voltage generated by the PV array and the voltage of the battery being used to store the charge there is a potential energy loss which can be as high as 10% of the captured energy. This loss can normally be reduced to about 1% by using Maximum Power Point Tracking, an electronic technique designed for this purpose.

The Solar Array Dimensions

To generate the system requirements of 1,100 GW, a fixed solar array would have to have an area of 1,100,000,000,000/37.5 sq meters, made up from 29.333 billion, 1 meter square panels, covering an area of 29,333 km^2 or a square with sides of 171.3 km long. This is about the size of Belgium and 50% bigger than Israel, just for the silicon PV cells.

Similarly, using the more expensive tracking array could reduce this area to 22,000 km^2 or a square with sides of 148.3 km.

Solar Array Manufacturing
Note that If 1 square metre PV panels were manufactured at the rate of 1 per second, it would take 930 years to manufacture 29.3 billion panels.

It takes energy to make PV panels, especially the highly efficient, old-school crystalline silicon kind. Even just creating the silicon crystals requires heating rock or sand to around 1,650 °C (3,000 °F), and that’s not counting the creation of the electronics that connect the silicon wafers to the grid, and the mounting hardware that holds the whole thing together. And then there’s the energy used to ship the panels and install them.

To calculate payback, Dutch researcher Alsema reviewed previous energy analyses and did not include the energy that originally went into crystallizing microelectronics scrap. His best estimates of electricity used to make near future, frameless PV were 600 kWh/m^2 for single-crystal silicon modules and 420 kWh/m^2 for multicrystalline silicon. Assuming 12% conversion efficiency (standard conditions) and 1,700 kWh/m2 per year of available sunlight energy (the U.S. average is 1,800), Alsema calculated a payback of about 4 years for current multicrystalline silicon PV systems. Projecting 10 years into the future, he assumes a solar-grade silicon feedstock and 14% efficiency, dropping energy payback to about 2 years.

An often overlooked fact is that solar generation cannot provide enough power (energy per period time) to produce useful quantiles of solar panels. As an example it would require 3,333, 1 m^2 panels located at the equator to provide the necessary energy to fabricate 1 new 1 m^2 panel per hour.

Service Area
The total area covered by the solar array will significantly larger than the area of the panels to allow for installation, maintenance access and periodic cleaning. The space required for the batteries is in addition to this.

Site Location

The example above assumes that the entire solar generating capacity is located in a region with the most advantageous solar conditions. What if the plant were to be located in the cloudier and chillier North East?

From the NREL solar maps, we can see that the average daily solar radiation would be reduced from 6 kWh/m^2/day to 4 kWh/m^2/day. Thus the average electrical power produced by the PV cells with the same efficiency of 15% will reduce from 37.5 W/m2 to 25 W/m^2 and the number of one square meter solar panels required to produce the same electric power would consequently increase by 50% to 44 billion covering an area of 44,000 square kilometers or a square with sides of 210 km. Bigger than Denmark, the Netherlands or Switzerland.

On the other hand, because of the higher PV cell temperatures experienced in the South West, installations would probably require local cooling systems to optimize the power output, whereas installations in the North East would benefit since they could get by without PV cell cooling. Cooling requires additional power to pump and chill water.

The required battery capacity would be largely unaffected by the location, but the cooling requirements could change. In the warmer southern regions forced cooling will most likely be required, but in the milder northern conditions we could expect this requirement to be reduced though probably not eliminated.

The Battery

Storage Requirements and AC Power Grid Engineering Challenges

The battery is no less complicated.

Thomas Edison is reputed to have said “When people get into the battery business they automatically become liars”. That was before he got into the battery business himself. It may not be true today but there’s plenty of room for misunderstanding the battery specifications, particularly with modern Lithium batteries.

Let’s just look at the capacity here. The battery’s capacity is the amount of energy it can hold. Unfortunately this is not all usable energy since it is not advisable to keep the battery at its fully charged level with a 100% state of charge, nor should a Lithium battery be discharged to below 2 Volts.

The most stressful operating state of a battery is when it is fully charged. Lithium batteries in particular are at risk of damage from even slight overcharging and Battery Management Systems (BMS) must provide precise control of the charging process to avoid this.

Lithium batteries also suffer damage at low states of charge (SOC) because the active chemicals in the battery undergo irreversible changes at low voltage affecting both the battery’s life and its safety. See Lithium Battery Failures and SOC.

Thus a Lithium battery should operate between about 20% and 95% state of charge so that its useful capacity will be around 75% of its theoretical or installed “nameplate” capacity. In the example that follows, the capacity is considered to be the usable capacity. Battery manufacturers however usually specify the nameplate battery capacity as its total energy content or theoretical capacity rather than its useful energy content. You need to know this.

Currently, Lithium ion batteries suitable for grid storage are available from several suppliers in 40 foot containers with various energy storage capacities of around 1 MWH and costing $750,000 or more each. They usually include cooling and an electronic converter unit delivering AC power at 480 Volts 50 or 60 Hertz or similar. To store 1 MWH during a charging period of 12 hours, the average charging power must be 1MWH ÷ 12 = 83.33 kW. Similarly the battery must be capable of delivering a power of 83.33 kW during 12 hours of discharge.

These charge – discharge rates assume the full plant margin of 25% is being generated and used.

Under normal circumstances the actual base load charge – discharge power without the plant margin requirement will be 66.67 kW. However these are the average power deliveries and the peak power availability and demand could vary considerably from the averages.

Ai23 Energy Storage System Container

To store 4,400 GWH would need 4.4 million of these 40 foot containers costing or $3.3 trillion. As a quick error check on the numbers calculated above, the total power handling capability of 4.4 million containers each supplying a power requirement 66.67 kW will be 4,400,000 X 66.67 kW = 293.3 GW, matching the requirement outlined in the Demand Profile above.

The standard container exterior dimensions are 12.193 m X 2.438 m giving an area of 29.727 m^2.

For 4.4 million containers, the containers would cover an area of 130.8 million m^2 = 130.8 km^2or a square with sides 11.44 km long; but adequate access space must also be provided, adding substantially to the total.

There could be some cost and space savings if the batteries were installed in a purpose built building, but this could hamper the planned long term battery replacement program. (See Battery Ageing next)

Note: If the manufacturer's specified 1 MWH battery capacity is the installed capacity rather than the usable capacity considered here, one third more, or a total of 5.7 million containerized batteries would be required to store the required 4,400 GWH of energy.

In warm climates, extra battery capacity (and consequent solar generating capacity needed to provide it) will be required to power forced cooling of the battery to slow its ageing process and thus avoid its premature failure.

Battery Ageing

All batteries suffer deterioration with age and their end of life is generally specified as being when the capacity has reduced to 80% of what it was when it was new. For lithium batteries the lifetime is typically between eight and ten years but depends on the usage conditions. Higher temperatures accelerate battery ageing and thus reduce battery life.

For high power applications, the required battery capacity is usually specified as sufficient to cover the end of life performance. This means that the capacity when new must be 25% higher in order to meet the end of life requirements. Since the calculation above already includes a plant margin factor, there is some leeway here, but in any case it would be prudent to adopt another 10% margin to avoid end of life failures. See more about Battery Life (and Death)

The biggest problem however comes from the finite life of the battery, since the entire installation will have to be replaced every 8 to 10 years.

Battery Recycling

Unlike the situation with lead acid batteries, there are currently very few recycling plants able to recycle Lithium batteries to extract the useful chemicals. In any case, taking a Lithium Cobalt cell as an example, the Lithium content in the $LiCoO_2$ cathode material is only 7% by weight. Lithium is between 20 and 100 times more abundant in the Earth's crust in terms of the number of atoms than Lead and Nickel, so that the demand for recycling is less. See Battery Chemistries.

Note that if these 44 million containerized batteries were manufactured in China, it would take 587 round trips of twenty days each way on the largest container ships to deliver them to the USA.

Energy Return on Energy Invested

A "solar only" baseload power generation system can never be sustainable. It requires more power to produce the solid state semi-conductor based PV panels than they can produce. Whereas a solar panel can pay back the energy invested in it to produce it in 2 to 4 years, it cannot produce enough power to operate solar panel production equipment, let alone the ground preparation heavy machinery necessary to place and interconnect the panels. Power =

energy per period time. It takes a minimum of 500 kWh to fabricate a 1 square meter solar panel.

We must address the concept that has acquired a central role in evaluating our energy future. This is energy return on energy invested, or EROEI.

Adapted from "The Energy Trap" by Thomas Murphy, Ph.D, UCSD

In order to utilize energy, we must exert some energy to secure the source and prepare it for use. In order to burn wood in our fireplace, we (or someone) must chop down a tree, cut it into logs, and split the large logs. To drive our gasoline-powered car, we must expend energy finding the oil, drilling and possibly pumping the oil, then refining and distributing the gasoline. To collect solar energy, we must invest energy to fabricate the solar panels and associated electronics. The result is expressed as a ratio of energy-out:energy-in. Anything less than the break-even ratio of 1:1 means that the source provides no net energy (a drain, in fact), and is not worth pursuing for energy purposes—unless the form/convenience of that specific energy is otherwise unavailable.

In its early days, oil frequently yielded an EROEI in excess of 100:1, meaning that 1% or less of the energy contained in a barrel of oil had to be expended to deliver that barrel of oil. Not a bad bargain. Oil production today more typically has an EROEI around 20:1, while tar sands and oil shale tend to be about 5:1 and 3:1, respectively. By contrast, it is debatable whether corn ethanol exceeds break-even: it may optimistically be as high as 1.4:1. Switching from conventional oil to corn ethanol would be like switching from a diet of bacon, eggs, and butter to a desperate survival diet of shoe leather and tree bark. Other approaches to biofuels, like sugar cane ethanol, can have EROEI as high as 8:1.

To round out the introduction, coal typically has an EROEI around 50–85:1, and natural gas tends to come in around 20–40:1, though falling below the lower end of this range as the easy fields are depleted. Meanwhile, solar photovoltaics are estimated to require 3–4 years' worth of energy output to fabricate, including the frames and associated electronics systems. Assuming a 30–40 year lifetime, this translates into an EROEI around 10:1. This does not include batteries and/or other storage components.

See more about Solar Power

About the author, Barrie Lawson:

Barrie graduated from Birmingham University with a degree in Electrical and Electronic Engineering in 1964. Since then he as has worked at Director level in many branches of the electronics industry including military electronics, telecommunications, computers, automotive and consumer electronics. During the last 10 years he has been involved in the battery business, originally as Chairman of MPower Batteries, a custom battery pack making company in Scotland which he helped to found and later in China where he set up a similar business. He is currently Chairman of CHE EVC, another battery startup company pioneering some interesting new technologies. In his spare time he writes and maintains the Electropaedia web site, a comprehensive knowledge base about batteries and energy sources.