February 9, 2011

Tracking vs. Racking for Maximum Solar Power

Save 15 – 20% on whole system based on output performance
Payoff in a 1/3 less time

Abstract

This paper enumerates and compares various methods of flat-plate, one-sun photovoltaic electric (PV) installation with respect to the power production levels they allow over a full year. The comparison assumes a single weather environment (Albuquerque, New Mexico, USA) and 2 kW (2000 Watts) of PV panels. The methods include a flat-roof mounting, fixed angle and adjustable (elevation only) rack mounting and several tracking mechanisms. The goal is to show that while apparently costing extra, the end effect of appropriate tracking for flat-plate PV, when viewed from a fixed power production standpoint, is to actually save sufficient money on the amount of PV necessary to produce any specific amount of yearly power (number of kilowatt-hours, the unit of measurement used in electrical power usage and billing) to produce a significant net savings on the overall system.

Editorial Note

It should be noted that prior to making expenditures on PV or other solar electric generation, typically offering only about 15-18% energy conversion efficiency, the residential/commercial energy user should look into sealing the spaces involved, insulating them to higher ‘R’ (insulation rating) levels and installing a solar thermal collection system to cover domestic hot water and space-heating needs. Thermal conversion systems generally run at very high efficiencies; in the vicinity of 75%. Typically thermal systems cost less than PV electric and produce the form of energy that is in the highest demand for a typical household or commercial facility. Solar thermal collection systems are also among the cleanest energy conversion systems along with natural daylighting, wind and hydro-electric. Although producing perfectly clean energy after production, standard silicon photovoltaic cells require the same manufacturing processes as silicon computer chips both of which require large amounts of electrical and gas energy as well as large volumes of water to produce; and leave behind toxic water and other materials to process afterward. A further consideration for commercial users is the thumb rule that 75% of the electrical energy used during the day is for interior, artificial lighting. Investigation into natural daylighting solutions and low-power LED lighting systems will go a long way to reduce the requirement for solar electrical power.

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Preface

The typical reason for installing solar collectors of any sort is to save money on utilities. That savings arises by not using power from a commercial source, like the local electric company, and replacing it with a less costly, or free, energy source.

Once the decision is made to install a solar electric or thermal power conversion system, the method used to mount the receiver panels in the sun should be the next most important issue. Every household or business has some sort of typical load quota (average yearly power usage), that if met by the solar electric or heat conversion system, would represent that the facility is 100% solar powered. Any chosen approach to sizing and designing the solar generating system should establish what it would take to accomplish that and only then, trim around the edges until the budget and space restrictions are accommodated.

The amount of time that the sun shines on a PV panel, the variation of the angle of incidence of the sun to the panel during that time (zero being perpendicular to the panel surface) and the temperature of the panel affect the amount of energy produced. A 2 kW PV array, using good quality panels, will produce 2 kW of power when it is facing directly at the sun, the sunlight is reaching the panel at an intensity of 1000 Watts per square meter (~10.75 square-feet) and the panel temperature is 25ºC (77ºF). Any other condition will change the amount of power output. Cooler temperatures will increase the output slightly; lower sunlight intensities will reduce the output proportionately. Angles of incidence greater than ten degrees will diminish the output of the flatplate PV panels proportional to the cosine of that angle. The integral (summation from moment to moment) of the power level (incorporating sun intensity, angle and panel temperature) over time produces the actual, usable output; generally measured in kilowatt-hours. An average household will use from five to seven hundred of those per month at a cost of about eight cents each from the grid supplier plus surcharges. Some of the grid-power surcharges are fixed; a monthly charge to be hooked to the grid, for example. Others are based on usage, such as a fuel surcharge. The latter can be reduced with solar power usage, while the former stays in place as long as you remain a grid power subscriber. The advantage to remaining on the grid when able to produce all your power with the sun is that on the occasion when Mother Nature gets depressed, it only costs a few bucks to maintain your energy-based lifestyle through the down-time instead of hunkering down with blankets and a game of Parcheesi (ancient board-game predating television).

Passive Mounting Systems

Face-Up, Flat Mounting

This flat roof mount, by Sunpower Corporation, based in California, does not require any type of attachment to the roof. It is simply laid down, wired and surrounded by a wind deflection fairing at the outer edges to help prevent wind from lifting up the panels.

There are pros and cons to this as with any mounting method. There is very little additional cost over the PV panels and in the middle of summer, this configuration actually performs quite well during midday. Unfortunately the output drops off markedly when the sun is lower in the sky during the early or late part of each day and the rest of the year when the sun stays lower in the sky.

The photovoltaic process creates heat. The temperature of the panels already runs higher due to the lack of convective cooling because the edges are sealed and the heat is trapped below the panels next to the roof. In addition, the higher the heat of PV panels the less power they produce so in the summer, the power output is further limited due to the heat produced by the increase levels of solar energy.

One might think that the heat would be a good thing but most of the heat is generated in the summer when you don't want it, and in the winter, the power output is so low that it doesn't make as much heat as you'd like.

Fixed or Adjustable Pitch on a Rack

The next step up in efficiency is the use of a mounting frame (rack) that places the panels either at a specific fixed angle or a version that allows periodic adjustments to the elevation (pitch). The placement may be selectable concerning orientation towards south but might depend on the roof-plane orientation. This mounting configuration requires the sun to rise sufficiently to illuminate the panels before any power is made. That will delay power production in the summer mornings and conclude it earlier in the day, but in the winter, it will produce more power than the flat-mounted units because the sun stays in a more confined space. Another benefit over the flat mounts is the ability to make use of convection cooling which will slightly increase the amount of power produced. It should be noted that mounting the panels flat to the roof without a suitable airspace will produce almost the same temperature problems as on a flat surface but proper spacing produces a convective flow under the panels that will keep them at a lower operating temperature and improve output.

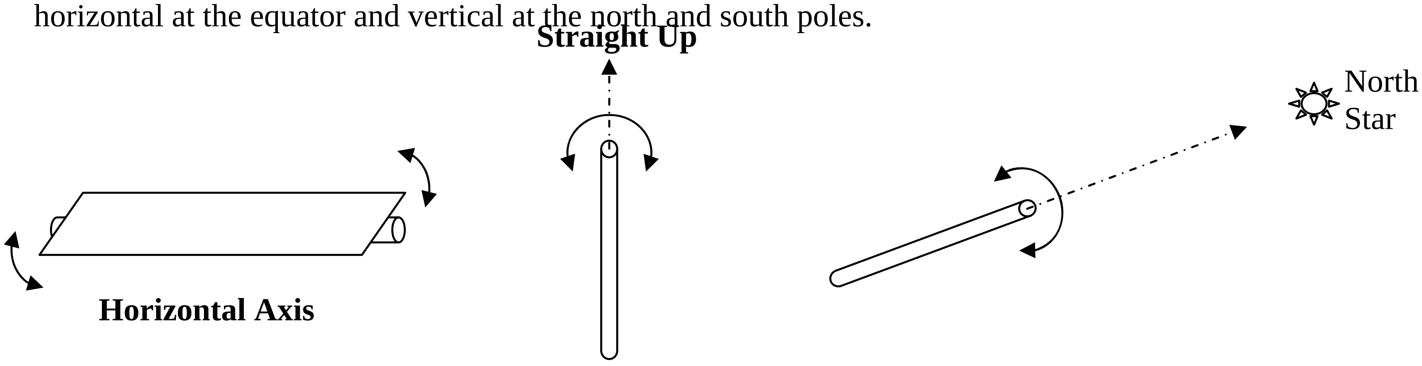
Active Sun Tracking Systems

The real improvements in efficiency come from the use of active sun tracking systems. There are both sun-sensing systems that use a balance of sunlight on two or more photo-receptors to indicate that the array is aligned with the sun or alternatively the lack of light when using a shadow bar sensor. There are also computer-controlled trackers that use the local time, date, time zone, latitude and longitude to compute the position of the sun, then compare it to the known position of the array (using electronic position feedback) and move the tracker motors to align the panels as necessary,

Photo-sensors will work well in full sun or very thin cloud layers, however when thicker clouds present themselves, several things are possible. If the cloud cover is broken, while the sun is covered by one cloud, the edges of the adjacent clouds can be brightly illuminated such that those edges are actually the brightest thing in the sky. As the clouds drift, the sensor, detecting the edge, not the sun, is likely to follow the edge as it passes across the sky in whatever direction the clouds happen to be traveling. At the moment the sun reappears, the sensor usually re-acquires it as the brightest spot and races to adjust itself to the new target, often just in time to have the sun disappear again behind another cloud and light up another edge elsewhere.

Whether a tracker should be driven by a sun-sensor or a computer is a topic of another discussion. The overriding factors will be both the geometry (with respect to the Earth) of the single-axis tracker while two-axis trackers, regardless of the geometry, will point the panels directly at the sun and then the comparative amount of time each type of control keeps the tracker on-sun, no matter how the geometry is configured.

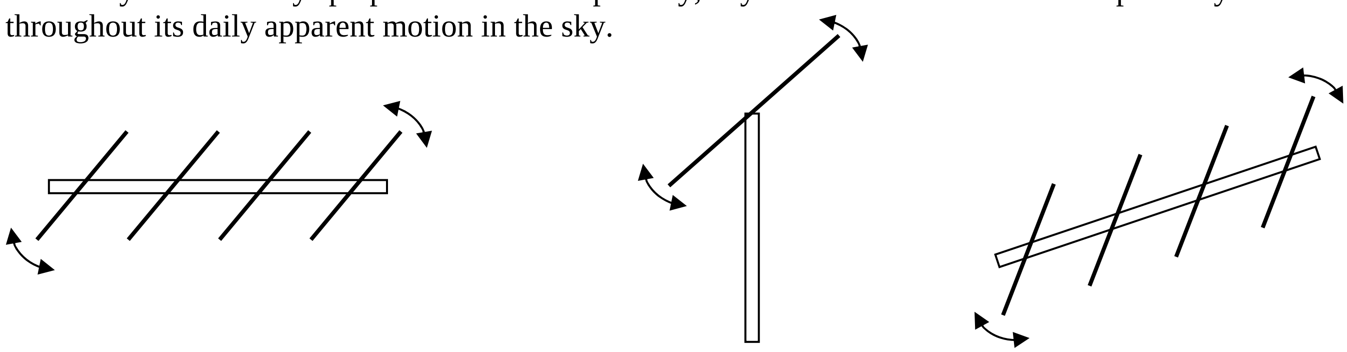
There are three basic geometries for tracking. The geometry of tracking refers to the orientation of the axes of rotation with respect to the ground. A horizontal-axis geometry is one where the primary axis of rotation (the one that is attached to the earth) is level to the ground. A vertical axis is one where the primary axis is perpendicular to the earth's surface and if extended downward, would pass directly through the geometric center of the earth. The third basic geometry is the polar axis which is parallel to the axis of rotation of the earth. The polar axis of rotation changes with latitude, and at the extremes, is horizontal at the equator and vertical at the north and south poles.



Horizontal Axis

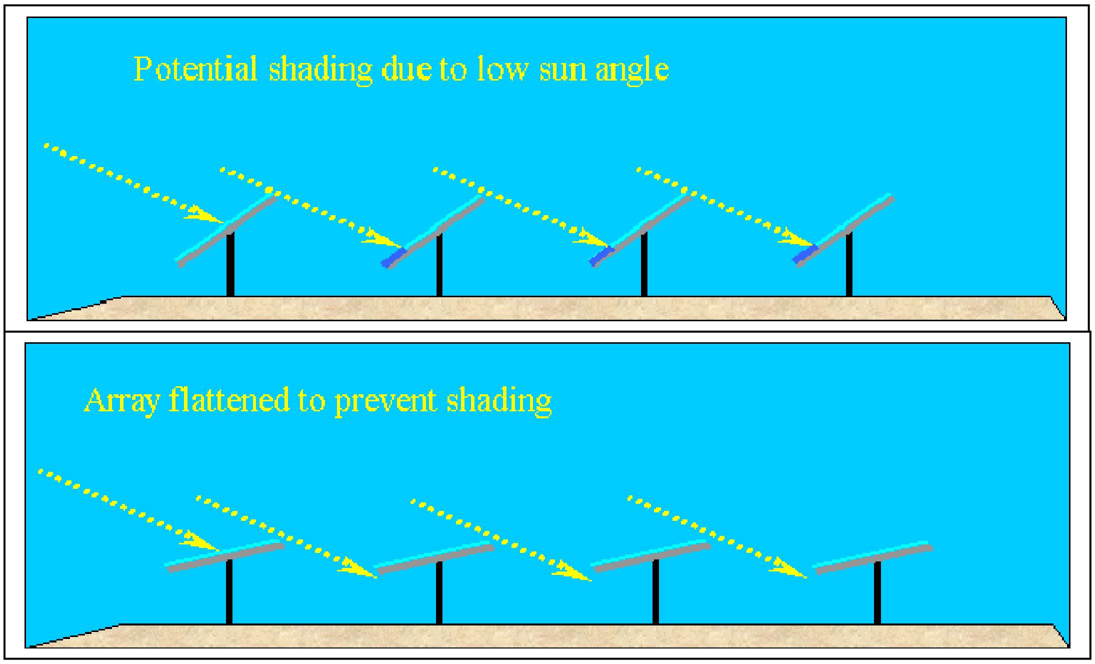
Vertical Axis

Each of these primary axes can have a secondary axis that moves with the primary. Assuming the secondary axis is always perpendicular to the primary, any of these can follow the sun perfectly throughout its daily apparent motion in the sky.



These horizontal-axis trackers are generally arranged in adjacent rows and can be driven individually from east to west (with the axis oriented north-to-south) or can be linked together and driven as a set, much like sun blinds on a window with a central stick to move them. In practice, this configuration of tracker is very cost-effective for large field installations where a single drive motor can move as much as 200 kW worth of panels in multiple, interlinked rows. The only real drawback in is the winter months when the mid-day sun is very low in the sky, the panels produce less power. However, in the winter mornings and afternoons, the ability of the tracker to roll the panels over to a forty-five-degree angle actually produces slightly more power in the mid-morning and afternoon than it does at the sun's highest point. That is a matter of the actual angle that the sun is with respect to the panel, not to the earth. An interesting coincidence with this horizontal geometry, that it shares with the vertical axis variety, is that in the summer, in the mid-afternoon when the air conditioners are going full blast to quell the maximum heat of the day, and even though each is only a single axis and normally can't point directly at the sun, these two trackers have the panels aimed directly at the sun, producing maximum output when it is most needed.

A secondary aspect of the horizontal axis unit is that it will be installed as a two-row system with one kilowatt of panels on each row. This will allow for the single unit comparison of standard motion versus a control method known as 'Back-Tracking' which is a very effective method of preventing adjacent rows from shading each other. Shading a portion of a panel can actually cause the whole panel to stop producing power due to the high resistance of the silicon cells when not energized with sunlight. It is better to have a lower angle of incidence of sunlight on the panel than a higher one when shading is present.



The fourth mounting configuration in the sequence is a vertical axis tracker mechanism. A major difference between this and the horizontal-axis version is that the panels are always canted toward the sun in elevation while following it from east to west. This orientation allows a better balance of maximum angles of incidence on the panel year-round than the horizontal orientation and spends much more time every year with optimum orientation. Although the fixed-angle mounting method shares this balance of angles with the vertical axis mount, the lack of rotation of the fixed mount toward the sun in the morning and evening during summer months drastically reduces the power output during those times.

There are a variety of mounting arrangements for the vertical axis. All provide for the least attachment footprint currently available. In the standard ground-mount version, each 'fence post' is bolted to a small concrete pylon drilled with an auger and filled with concrete. Proper installation can actually allow for the equipment to be removed and the land reclaimed, should the need arise to relocate the equipment. No cutting or digging would be necessary.

An attractive variation of this system places the structure overhead and raised sufficiently to allow for walking room and plantings. The dynamic ground-shading produced by the moving sun and rotating panels provides a gazebo effect that reduces the length of time that any one spot gets direct sun.

This last arrangement is a roof-top testbed where the two front rows are fixed at an angle while the two in back are vertical axis trackers. Though it can be seen that the fixed panels use less room on the roof, the tracking rows will produce a significant amount of additional power output over the year.

A third version of single-axis operation uses the polar mount where the primary axis of rotation is aligned to the North Star (marking the center of Earth's rotation). This variation is a method of mitigating the lack of balanced angle-of-incidence inherent in the horizontal orientation without the need for several vertical masts to mount 4 – 6 kW of panels.

This configuration becomes more and more unwieldy as the latitude climbs toward the North since as the latitude climbs, so does the relative angle of the North Star from the ground but in the mid- and lower-latitudes this solution is a rather good one. The triangular shape allows the array to roll farther over in each direction while keeping the panels from contacting the ground. The frame is fairly simple and requires only an 'A-frame' to support the raised end and a single pivot at the low end.

In this photo, a classic example of the inherent problem with sun-sensing techniques for tracking… it seems all four of the arrays don't agree on where the sun is… though not disastrous from a power production standpoint, it doesn't look right. This is usually a result of electronic imbalances that are the crux of this control system. If two resistors, that are supposed to match, drift apart in their values, the controller reading the resultant value is off by the same amount. Computer-based controllers are not susceptible to this vulnerability and offer a visually aligned field as well as optimum power.

Two-Axis Tracking Platforms

The use of two-axis tracking to keep solar panels exactly perpendicular (in engineering and physics the word ‘normal’ is often used implying perpendicular in two dimensions) is unquestionably the appropriate method for producing the most energy out of any given collector device. The catch is that it is always the most expensive, and unless it is absolutely necessary for some reason, like tracking concentrated or focused solar energy, it is not generally a cost effective solution. The extra expense for the second axis has to be worth it for some reason.

In this case, it is necessary to provide a baseline for comparison in the context of testing, research and this comparison. If all the previous mounting methods use the same type and number of PV panels and a similar set is placed on a two-axis tracker, the latter will provide the best possible output such that at any given moment, the outputs from the other systems can be compared directly to the output of the two-axis system yielding the differences and similarities in output levels under varying circumstances and orientations throughout the day.

There are quite a large number of uses for two-axis trackers. The area of Concentrated Solar Power (CSP) is almost always supported by two-axis tracking mechanisms. There is a sect of single-axis parabolic troughs but they suffer the same negative shift in efficiency when the sun is at a low angle to the trough. The major sub-categories of two-axis application are: Concentrated Photovoltaic (CPV) and Concentrated Solar Thermal (CST); the latter of which can be further broken down into either Reflective systems using mirrors or Refractive systems that generally use some version of Fresnel (*fray-NELL*) lens. (See Appendix A)

A basic two-axis tracker that uses a vertical axis, driven by a small worm drive gearmotor, and an elevation axis driven by a linear actuator, often called a screwjack after the old automotive hand-crank bumper lift jack, which extends and retracts like a long piston to raise and lower the panel with respect to the current azimuth position.

There is a substantial variety of two-axis trackers in operation. Each shares the ability to point directly at the sun throughout each day all year long. The following gallery of trackers is intended only to indicate the range of topics available for discussion concerning energy conversion mechanisms, focusing methods and applications when formulating a structure for a decision on solar/renewable configuration.

Hydrogen Generation for liquid fuel storage – the ultimate goal is to make storable fuel like methanol and diesel fuel out of CO-2 and water – already proven to work… 800 sq-foot parabolic reflector dish with a 40-foot focal length.

25 kW kinematic Stirling Engine Dish – uses vacuum-membrane reflectors to create 115 kW of thermal power to drive a four-cylinder heat-powered engine which drives an AC induction generator.

Two-axis parabolic trough test unit used to characterize the performance of various reflector surfaces and thermal receiver tubes. In practice, these large parabolic troughs are implemented as single-axis trackers oriented with the axis of rotation east-to-west.

A smaller parabolic reflector dish powering a 3 kW free-piston Stirling Heat engine by Infinia Corp. The free-piston version of this thermal electric technology has only one internal moving part. AC power is generated directly using permanent magnets and magnetic induction created by the moving piston.

This Solar Furnace uses a reflector heliostat to power a secondary parabolic dish which can create temperatures in excess of 2300 C. for testing materials and hydrogen generation experiments.

The Prospector™ – two-axis solar/weather station for monitoring and logging weather and solar influx and power output data.

Two-axis test trackers for individual PV and concentrator module testing.

← 25 kW PV electric concentrator – 1200 sq-ft uses Fresnel concentrating lenses.

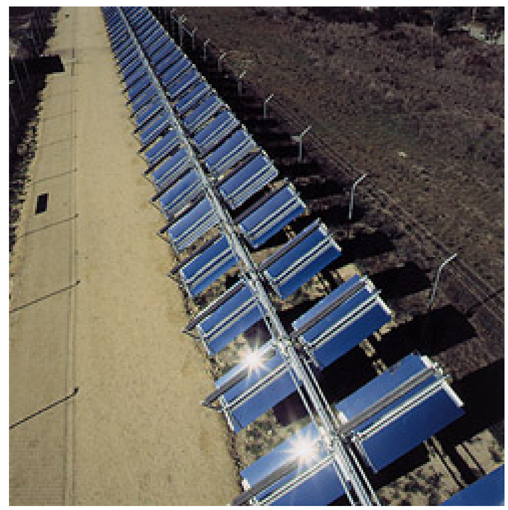
→

Fiberoptic concentrator daylighting – focuses light down fiber and delivers to internal rooms of a building.

Concentrator PV module tracker – uses strip of PV cells at focal point of linear Fresnel lens that produces a line of concentrated light 1 inch by 12 feet. →

Tracking heliostat for a solar telescope – secondary mirror reflects sun image straight down through lenses and filters.

Parabolic reflector concentrators – Concentrated PV receivers – all controlled by a single tracking controller and push rods. →



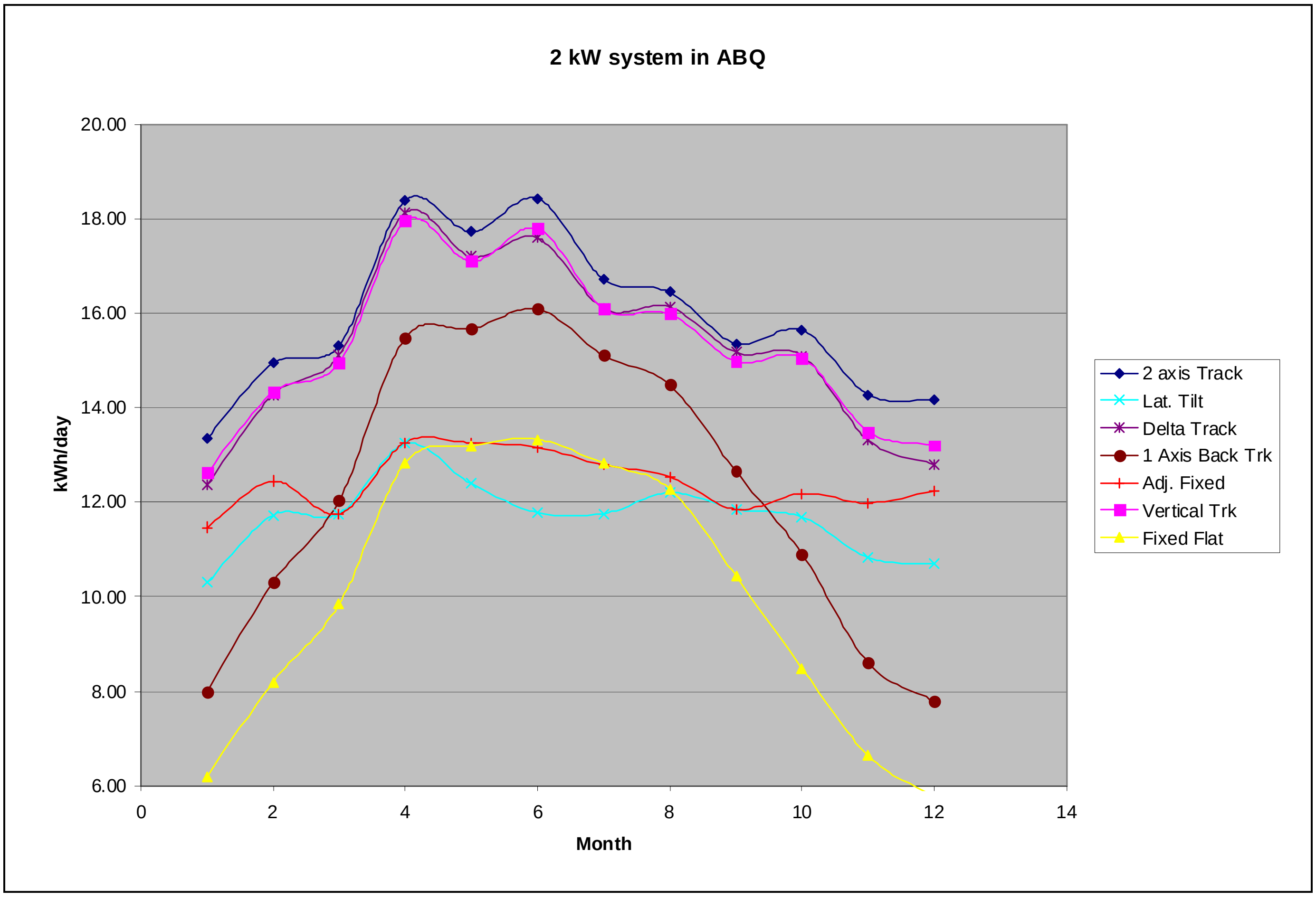
Field of mirrors all focusing to the top of a Central Receiver to make steam and then electricity. The mirror is focused to place an 80 sq-foot beam on the tower at 850 feet yielding a 20-sun concentration from just the one mirror. Most often there are 3-5000 mirror units on a single field.

Below, a single, very large reflector heliostat puts a high-intensity spot on a receiver tower. In practice there is a large

A polar oriented two-axis tracker in India. Polar axis trackers are particularly effective in the tropics due to the very compact solar path north to south. →

A Comparison of Fixed and Moving PV Mounting Methods

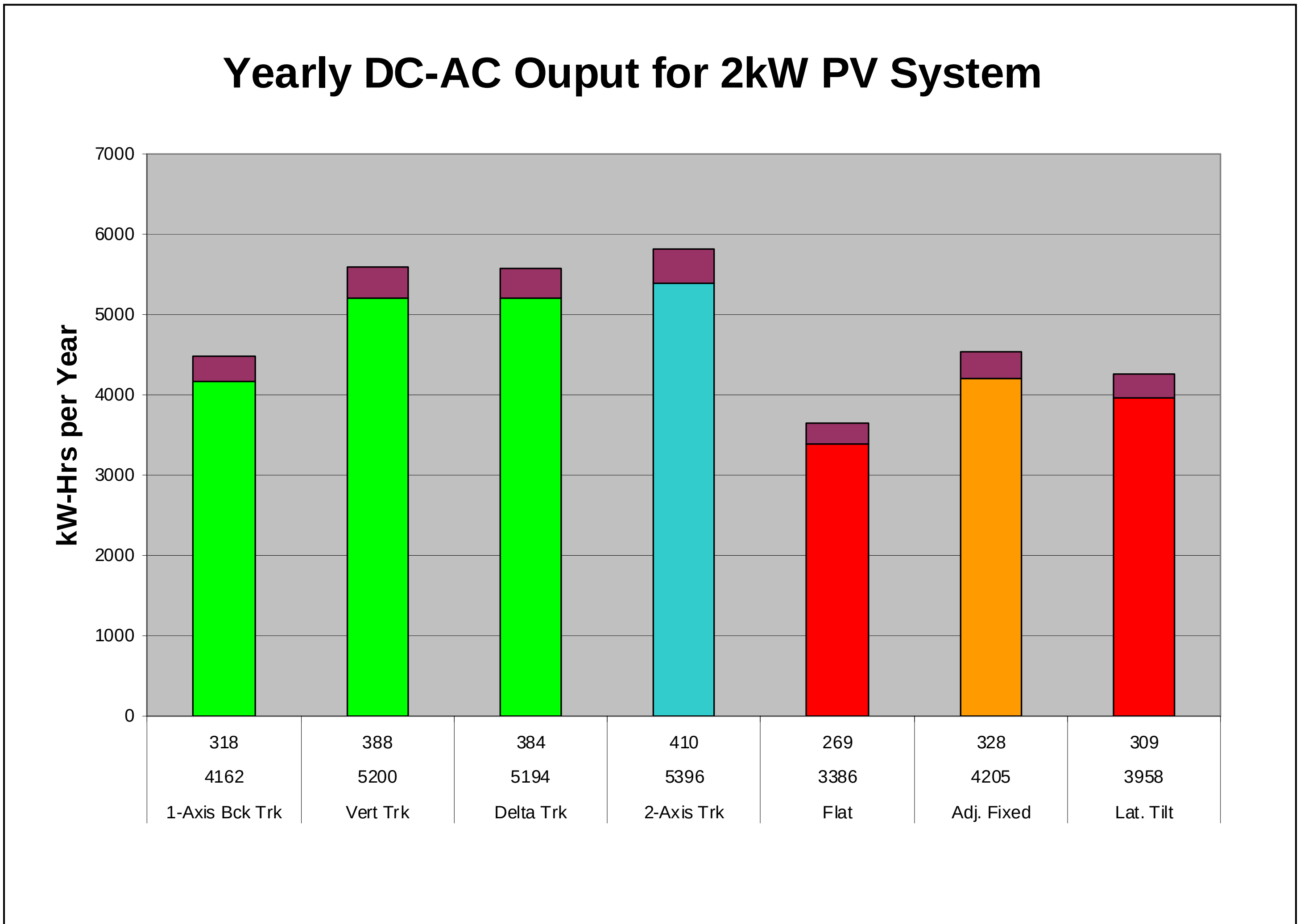
The following graph was generated by a scientist at Sandia National Laboratories – NM from a software simulation package that incorporates real data from a variety of sources concerning PV panel characteristics, weather, average solar levels based on geographical location and many other variables. It then computes the average daily DC and AC output during each month and the effective year-round average daily output for each mounting configuration.



This plot illustrates the predicted kilowatt-hours of energy (the part one uses and pays for) produced by a 2 kW PV system on average per day by the month for a full year for each of seven different mounting solutions. Of the seven, the 2-Axis tracking system, which is the only one that keeps the panels pointed directly at the sun all day, represents the maximum amount of energy that can be produced by those particular panels.

With this performance established for each mounting solution, a comparison of the methods can be approached from the standpoint of ‘Target Annual Production’. It can be seen here that different methods are better sometimes but not others. Trying to size a PV array based on one time of year or on the maximum output of the panels results in either too little or too much PV, and with the trade-offs seen in some of the methods from winter to summer it can make it difficult to quantify. The reason to take this different approach is to establish a reference goal that will illustrate the financial impact of less efficient mounting methods.

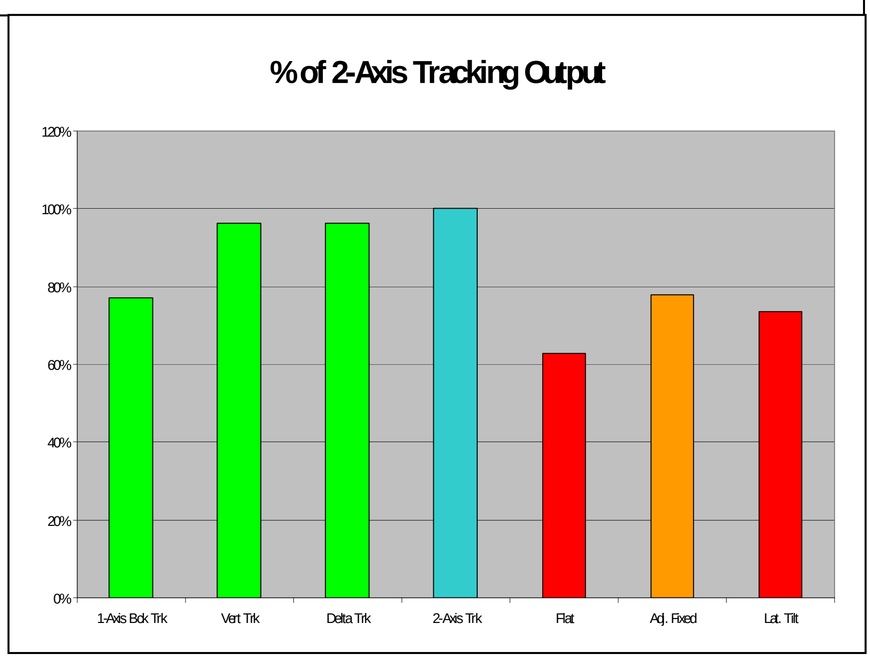
The first step in the comparison is to use the average daily output for each system year-round and sum it up to a grand total for the annual yield. This bar graph indicates the DC-AC energy output. The dark-colored portions at the top represent the losses associated with the conversion from DC to AC using an inverter. The colored portions represent the net AC energy produced from single-axis tracking (Green), 2-axis tracking (Blue), fixed (Red) and adjustable (Orange).



Using the full available power offered by a precision, two-axis tracker as a reference, this comparison shows the relative output of the other six basic mounting methods.

The results fall into three categories of output levels:

- Fixed flat mounting providing just over 60% of available power
- Single-axis horizontal tracking, adjustable and fixed racks all hovering in the 75-78% range
- Single-axis vertical- and polar-mounted units that offer over 95% of the available power.



It would clearly be the case that if two-axis trackers were free, there would be no more logical option than to use one. The fact that anything able to raise the panels off the flat ground will cost money is the source of much aggravation in the solar industry… to the point of trying to leave out any support at all such as the Powerlight system that lays flat on the roof. However, even Powerlight adds a proprietary non-adhesive backing to the panels that helps keep them from lifting off the surface in the wind so there is still some money that is spent over and above the price of panels and inverter.

The mounting method has an affect on quite a few different aspects of the total system cost and net, long-term value. Whether they are all taken into consideration is the fundamental value-category selection mechanism for trade-off decision-making.

The cost of the installed system includes the dedicated space required, the allowable multi-use value such as covers for gathering areas, parking lots or water retention ponds, and the production output of the system. The net system value has several components that range from liquid to strategic to lifestyle. The liquid component is the actual cost minus direct, upfront savings through rebates or special grants. The strategic is both savings due to production output that is used instead of commercial sources and revenue that might be available through the sale of renewable energy credits.

The lifestyle, clearly more subjective, can be composed of just knowing you're using solar energy rather than fossil, and it can involve changes to your routine depending on your usage of the energy. Getting energy when you need it rather than waiting all day for the shower water to warm up can significantly change the daily schedule when the decision to use renewable energy has been made to the point of commitment. Having a system that reaches around and grabs sunlight as soon as it is available in the morning is more convenient… and yes, more expensive.

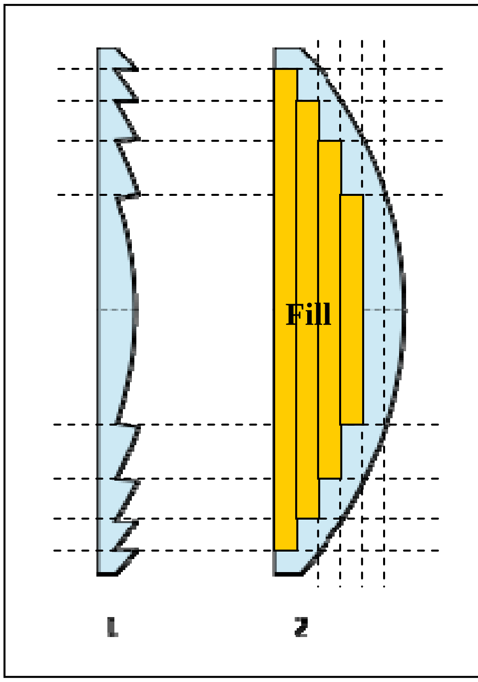
The percentage of power recovered is mostly constant for any given tracking or mounting method regardless of size, but the value gained is subject to the finite number of mechanical solutions available and the size ranges they cover. There is a trade off in smaller systems that does not always support the upgrade to motion. It is still useful to investigate the possibility.

The bottom line is that the production output is what pays off a system so that a return on investment can be realized… putting in an anemic system that wheezes its way through life putting out only two-thirds of the available potential increases the payoff duration by 50%, often out-distancing the longevity of the PV panels which are considered to have a life of between 20 and 30 years.

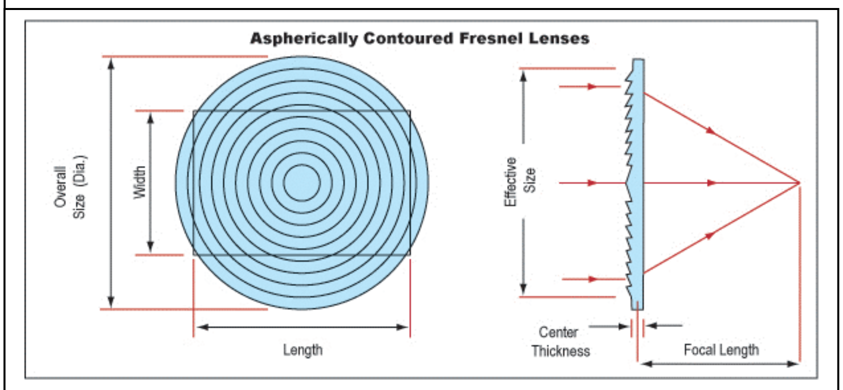
The perspective that will clarify this is that for any amount of PV panels, a proper tracking system will save 1/3 on PV costs, which can include some savings on inverters as well, while putting out the same amount of power (in kW-hours). The savings is greater than the differential price of the tracking mechanism and will pay itself off sooner.

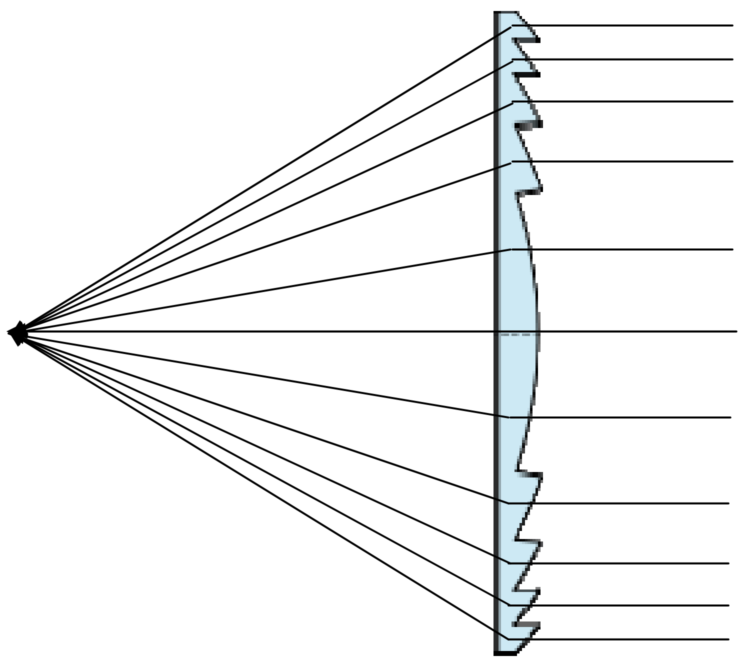
Appendix A

Fresnel Lens



The Fresnel (*fray-NELL*) lens is an approximation of a single convex refraction lens. It is conceptually created by slicing the full lens concentrically and discarding 'fill' areas while collapsing the remainder to a more compact section.





The Fresnel lens, developed by French physicist Augustin-Jean Fresnel for lighthouses, actually is a reversible lens. If a light source is placed at the focal point, the rays will emanate from the other side as a directed beam, giving the lighthouse its penetration into the night and foul weather.

When energized from the other side by columnar light such as that from the sun, the rays are focused to a spot of concentrated light proportional to the focal length.