The Ravina Project

Ambient Heat and Solar PV Power Output

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Introduction

Generally, photovoltaic panels respond to heat by reducing their output even when in full sunlight. The panel manufacturer publishes this information in the panel specifications. These specifications are typically calculated using data gathered in the laboratory. In this paper we will examine this phenomena using our database consisting of 1247 daily observations to get a real world understanding of the effects of ambient heat upon solar PV power output.

The Ravina Solar Efficiency Standard (RSES)

The Ravina Solar Efficiency Standard (RSES) is defined as the total number of Watt-hours generated in a day divided by the number of minutes in that generation day divided by the total size of the collector in kilowatts.

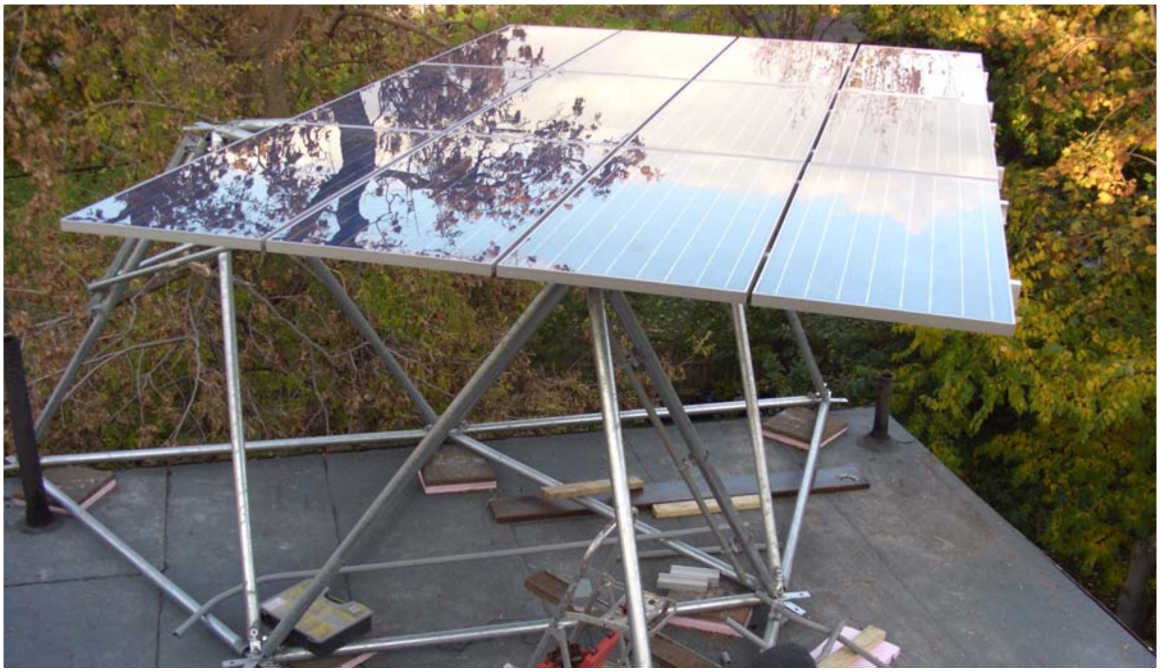
In our paper titled: "The Ravina Project – Solar Array Efficiency 06" available here we introduce and make an argument for a new efficiency standard for solar PV arrays. We won't reproduce the paper here but we take the following points from it:

- Weather and sky conditions are chaotic and hence introduce incredible noise into daily solar energy collection data. Efficiency is extremely difficult to calculate if this noise is taken into account when efficiency calculations are attempted. We ignore the noise.
- The user of solar panels can only control two things, the size of the collector and the angle of the collecting surface to the sun at any time during the day. These two conditions are really static if the collector is not modified either in size or in orientation over the course of a data collection period.
- Generation can only occur when the sun is above the horizon.
- There is a variable / constant parameter that is true for all points on the surface of the earth. The parameter consists of the number of minutes in the day, that is, the number of minutes when the sun is above the horizon. The constant part of this parameter is defined by the fact that at the start of the day and at the end of the same day this number does not change …. it is a constant for that day. Each day is theoretically different so this parameter is a variable over multiple days.
- A combination of the effects of all of the above produces one number, the total energy in kWh collected during the generating day.

Using the points outlined above it is possible to construct an efficiency standard using a combination of the parameters. In order to make all sizes of solar arrays equal for efficiency comparison purposes, the standard size for comparison is a 1 kW array. The length of time in minutes the sun is above the horizon is vital to the amount of energy collected so it is part of the efficiency calculation. And lastly, the total amount of energy collected in Watt-hours provides the starting point for the efficiency calculation.

An efficiency standard is critical to discussing changes in the same array at different times of the year or for that matter the same array at different angles to the sun at the same time of the year. Without a baseline metric for comparison other than brute force generation numbers, there is no method by which arrays can be compared. We know that if generation statistics alone are used to calculate efficiency, the longer days of the year will win out over the shorter days at this latitude. When the length of day is introduced as a leveling factor the short winter days get to be competitive with the long summer days.

Note the support structure here for our solar panels. The panels are very well ventilated. They are approximately 8 feet above the surface of the roof.



Standing under the array, vistas with a distance of a km can be seen in several directions. One of them is also upwind of us, within degrees of the maximum on our Wind Rose for this location at 30m. It's hard to say what that means at 8 to 10 meters, the height of the array given its orientation. I'd bet that the wind vector at 30 m gives wind at 8 m enough push over the panels to confer on average an advantage to panel cooling rates. The array's azimuth is 150 degrees rather than 180 degrees which is normal for arrays at this latitude. Anyway the point is these panels are well ventilated.

Note as well that we are working through batteries and we compensate for the sun's altitude and azimuth at specific times of the day and/or year. The power comes from the array through an Outback MX-60 solar charge controller into our battery pack which operates on a 48 volt DC buss. The pack has about 14.5 kWh of usable energy in it. The power is taken out of the batteries by our Xantrex 4048 inverter/charger to power the household's protected circuits located on a separate panel. When generated power overwhelms the loads provided by the battery and household, the power is sent to the street through our bi-directional utility meter. The Grid becomes our load of last resort. If we lose our connection to the Grid and we are generating excess power then the solar charge controller moderates the power coming from the panels; diminishing the generated power dramatically if required to save the batteries.

Suffice to say that we are using batteries so this setup has systemic loss built into it. We believe that this loss does not interfere with out ability to observe the relationships this paper seeks to demonstrate.

Method

With the efficiency standard we will be using explained, let's turn to the data we have collected here at The Ravina Project and see if we can get a handle on the effects of heat on our generation ability. We will mine our data for interesting relationships.

Panel Specifications

Firstly the solar panel manufacturer produces specification for the effect heat has on the panels.

CentennialSolar

SPECIFICATIONS OF CRYSTALLINE SOLAR MODULES

Electrical Data
The electrical data applies to standard test conditions (STC):
Irradiance at the module level of 1,000W/m^2 with spectrum AM1.5 and cell temperature of 25^{0}C

Electrical Parameters		CS125	CS130	CS135	CS140
Power (max.)	P_p (watts)	125W	130W	135W	140W
Voltage at maximum power point	V_p (volts)	17.4V	17.6V	17.9V	17.9V
Current at maximum power point	I_p (amps)	7.18A	7.39A	7.54A	7.82A
Open-circuit voltage	V_{oc} (volts)	22.0V	22.0V	22.0V	22.0V
Short-circuit current	I_{sc} (amps)	7.6A	8.0A	8.1A	8.4A

The quoted technical data refers to the usual series cell configuration
All electrical parameters may vary by ±10%
Contact us for warranty details

Our array consists of 12 of the CS125 panels for a total output of 1,500 Watts.

The heat specification is as follows:

Cell temperature coefficients			Limits	
Power	T_K (P_p)	-0.55%/^{0}K	Maximum system voltage	1000V DC
Open-circuit voltage	T_K (V_{oc})	-0.33%/^{0}K	Operating module temperature	-40 to +90^0 C
Short-circuit current	T_K (I_{sc})	+0.05%/^{0}K	Tested wind resistance	Wind speed 192km/h
Certifications: IEC61215				

Note: The specifications are subject to change without notice

The nominal operating cell temperature is 46 C. All measurements taken in the laboratory reference the cells at 25 C. So at 46 C the cell power output is already de-rated by about 9%. So with perfect laboratory sun (through an AM1.5 spectrum) and the cells working at their nominal internal temperature of 46 C the power output of the array is 1,364 Watts. We have seen peak power output of 1800 Watts. Using the same de-rating scale we can calculate in gross terms based upon a delta of 0.55%/K rating that at 1800 Watts output would be 1800 – 1364 = 436 Watts over nominal. The corresponds to the internal temperature of 31.9 % under the nominal which is 31.9% divided by .55% equals 58 C under the nominal of 46 C. The internal temperature of the panels should be somewhere in the neighbourhood of minus 12 C.

You are following this …. Right? All I want to know is how my array performs in heat. The manufacturer's specifications are helpful but not really practical when used to try to answer my question. That is, heat inside the panel is one thing, heat in the air surrounding the panel in another and further the radiative properties of the panels in this installation is still another. This getting complex …

So we will fall back on a simple minded method of plotting the data and looking at the resulting charts to see if we can come up with some trends to show the relationship among the ambient heat represented by the maximum daily temperature and several other categories of data including maximum daily power generation, efficiency and peak daily power.

Data to be Used

The Ravina Project has generation data for three complete years and for 2010 up until the end of May for a grand total of 1247 daily observations. Along with the generation statistics we collect the median and high temperature for the day from the local weather station. We also collect the sun rise / set times for the day so that we can calculate the number of minutes in the day and a short weather report on the sun's availability. If we have overcast all day long we will record the day as **oc**; if the day had no clouds blocking the sun then we record it as **sun**. These are the two extremes. Usually the weather description recorded in the database is somewhere between them.

We will crunch the numbers several different ways to see if it gives us any insights into relationships among: maximum daily ambient temperature in Centigrade, daily amount of energy generated kilowatt-hours and the peak recorded power each day in Watts.

We will use as a tool in this analysis, RSES, the Ravina Solar Efficiency Standard. We propose this standard to allow PV arrays to 'compare notes' if the compared arrays are at the same approximate latitude. For me it sounds reasonable to compare our array efficiency with any other array within 5 degrees of our Latitude whether it be in the northern or southern hemispheres. From our calculations we would not be giving away all that much to an array 5 degrees to our south. Giving up 10 degrees is another story.

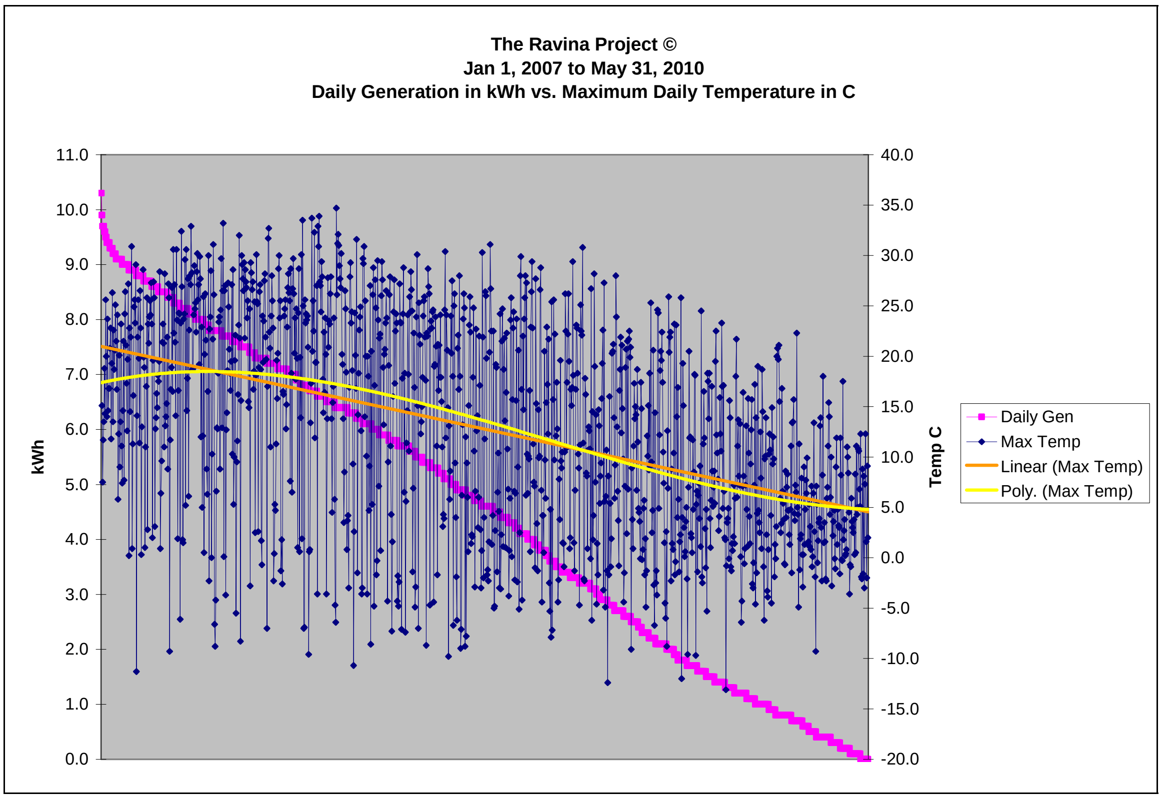
So when compared using an efficiency standard, which is a calculated value, what interesting relationships can be found in the data?

Daily Generation vs. Maximum Daily Temperature in C

Firstly, let's take a look at the relationship between the total daily generation and the maximum temperature for that day. We use the maximum temperature because solar generation is a daylight activity with the maximum period of generation at this latitude grouped around 9 AM to 3 PM which also at this latitude and geographical location usually includes the hottest part of the day. We also have the choice of using average daily temperature or the median. We believe that the maximum daily temperature better describes the ambient thermal environment of the panels.

Our database contains 1247 daily observations from January 1, 2007 to the end of day May 31, 2010.

Consider the following chart containing the complete database.



This chart plots a sorted daily generation number in kWh against the maximum temperature in Centigrade for the day. Looking at this chart several things become clear. As you can see there is a slight rise in the daily temperature right up until the daily generation number hits about 7 kWh. At that point the daily maximum temperatures fall off whist the daily generation numbers increase at a greater rate.

For most of the chart, daily generation numbers increase as the maximum temperature increases. It is only at the highest daily generation numbers that the daily maximum temperature fall off in the third degree polynomial curve fit.

We know from the manufactures specs that the opposite is true, that is, the power output of the panels falls as their temperature increases past 25 degrees C. What's going on here?

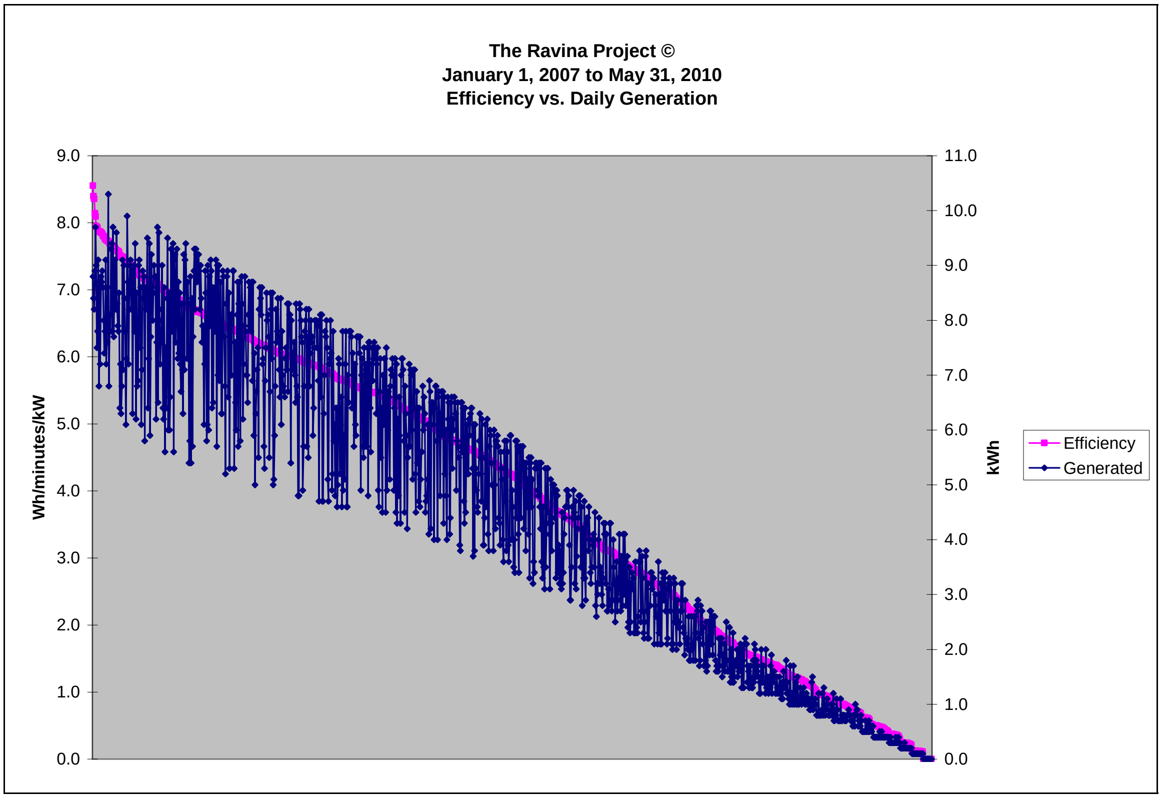
The chart and its confusing implication can be explained. We know that energy production using solar panels is proportional to the amount of time sun shines upon them. At this latitude and over the course of a year, the daily length of time the sun shines upon the panels can vary by about 400 minutes. The shortest day of the year is about 540 minutes and the longest is about 928 minutes. As a consequence the length of day has a huge affect on the total amount of energy harvested on any given day. Also the longest days occur in the Summer time. So it is no surprise that the longest most productive days and the hottest days are correlated when total daily generation is plotted against maximum temperature across the whole database.

We also can understand why a good efficiency standard is really required to compare how well the panels are doing their job at various times of the year and at various daily orientations to the sun. The length of day is a huge and overwhelming statistical signal that hides any other signals we might have in the data. When we use RSES as a metric for comparison we remove this signal and thereby gain access to more subtle information.

One of the signals in the data is just barely visible in the above chart. Notice at the very top end of daily generation numbers that the maximum daily temperature falls off and correlates negatively with daily energy output. We have noticed this phenomenon. It occurs in late April and May when we get pristine sun and cool / cold days. The days are long enough to rival those in the hot summer time but the ambient temperature around the panels is low. We get sustained output of 1250 Watts more or less during these types of days. These days give us our best daily numbers. However, when the data are presented this way this signal does not 'jump' out at you.

Efficiency vs. Daily Generation

Consider the following chart.

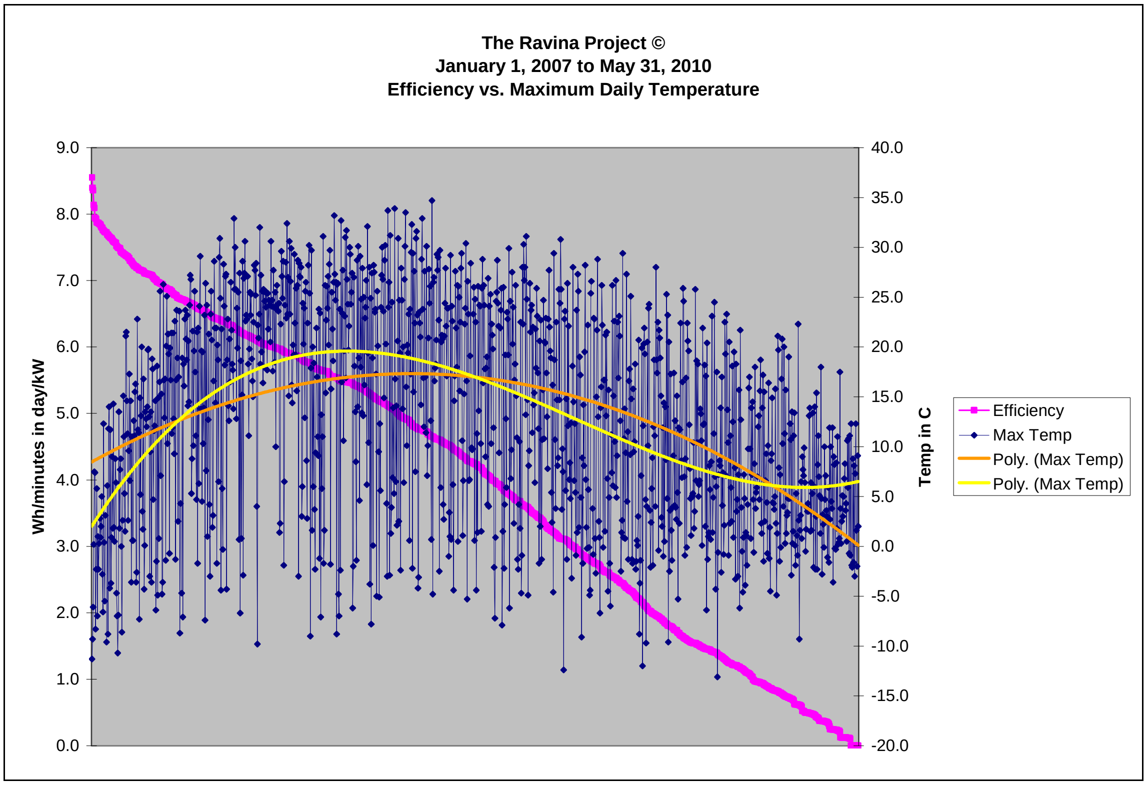


In this chart we plot RSES against daily generation across the whole database of 1247 days. Since the RSES calculation contains the daily generation number in Watt-hours as a starting point we see that they track perfectly across the database. This chart is telling us nothing new from what we would expect from our intuitions. On days when the generation numbers are low, RSES should also have a low value. Low generation numbers are caused by poor generation environments dominated by cloudy weather.

Let's take a look at the data when we eliminate the statistical effects of the length of day.

Efficiency vs. Maximum Daily Temperature

Consider the following chart containing the complete 1247 day database.



Firstly notice that this chart plots the calculated daily RSES number against the recorded maximum daily temperature for each day in our database.

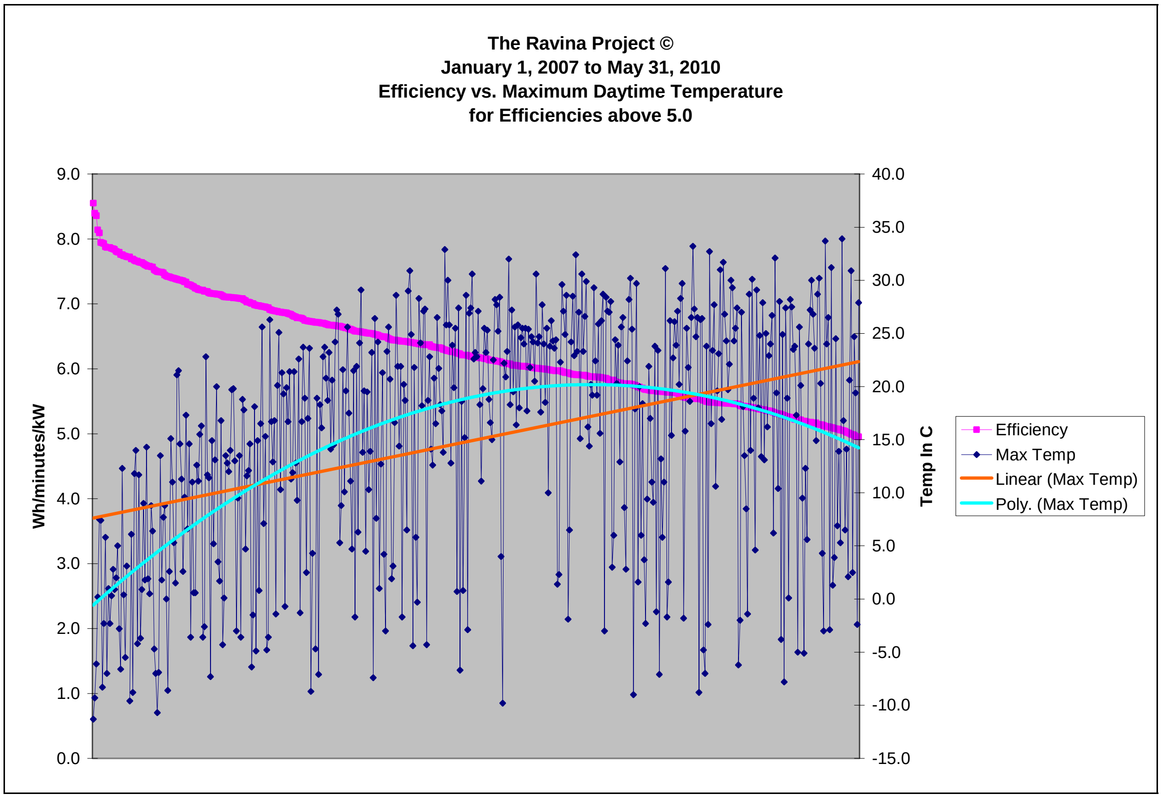
Daily RSES numbers are sorted from smallest to largest going from right to left and plotted against their corresponding daily maximum temperatures in C. The resulting efficiency curve appears to be more or less linear. Daily maximum temperatures on the other hand seem to intuitively fit better to the third order polynomial rather than to the parabola.

Note that at around a RSES of about 5.5 there seems to be a change in the sign of the correlation with temperature. The chart is divided into two distinct parts on the left and right. We know that large RSES values mean good weather for generation and low RSES values mean poor weather. So the right side of the chart can be explained by lots of cloudy days whether they be cold or warm.

The left hand side of the chart where the RSES is above about 5.0 a distinct signal seems to make itself apparent. From about RSES numbers of 5.0 onward and upward the temperature starts to fall. A negative correlation between RSES and Maximum Daily temperature seems to be the case. The curve is dramatic in this area showing the strong effect the maximum daily temperature has upon the efficiency of the array.

Let's examine this region of our database. It contains 505 days where the daily efficiency RSES number is equal or greater than 5.0. As we argued above the larger the efficiency number the better the weather for generation. So these data are dominated by days which have larger percentage of sun during the day.

Consider the following chart.

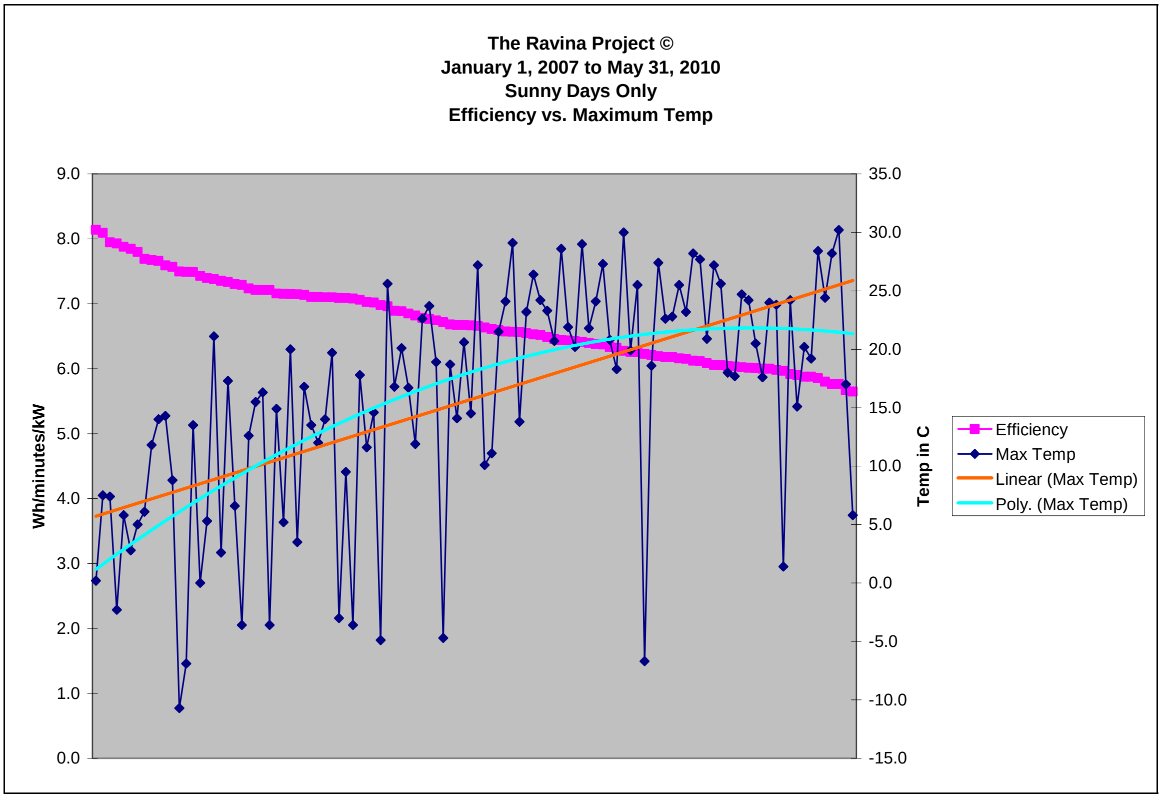


As the curves progress from right to left in the chart the weather becomes less and less a factor as a higher percentage of days have better generation conditions. The relationship between RSES numbers and maximum daytime temperatures becomes apparent as a strongly negative correlation especially when the RSES number gets above 6.0. This transition becomes apparent around the maximum temperature of between 20 and 25 degrees C.

This not unexpected when we think of it. The panel specifications had 25 degrees Centigrade internal temperature as the point where the delta of 0.55%/K change in power output starts.

Clouds can have an effect on the performance of the panels. Can we see the relationship between the ambient temperature fall off and the efficiency of the array if we eliminate the cloudy days?

Consider the following chart plotting 110 sunny days from our database.



Each of these days have been recorded in our records as being sunny days with very few or no clouds. These are not pristine sunny days so there may be contrails, haze, pollution, or barely visible cirrus clouds. In addition, we also know these days are cloud free because the peak power recorded on each of these days is not out of the ordinary for the time of year. We have a section on peak power analysis below. But for now it is suffice to say that we have an observation and meter reading both in agreement that the days recorded in the above chart are sunny days with no shading of the array due to clouds.

We can see quite clearly that there is an increase in the daily RSES number coupled with a dramatic fall in maximum temperature. On sunny days as the ambient temperature falls away from the 20 to 25 degree C range the daily RSES numbers increase their positive slope. The linear curve fit demonstrates the gross relationship but the parabolic fit is more dramatic and to my eye provides a better description of the relationship.

Peak Watts vs. Efficiency

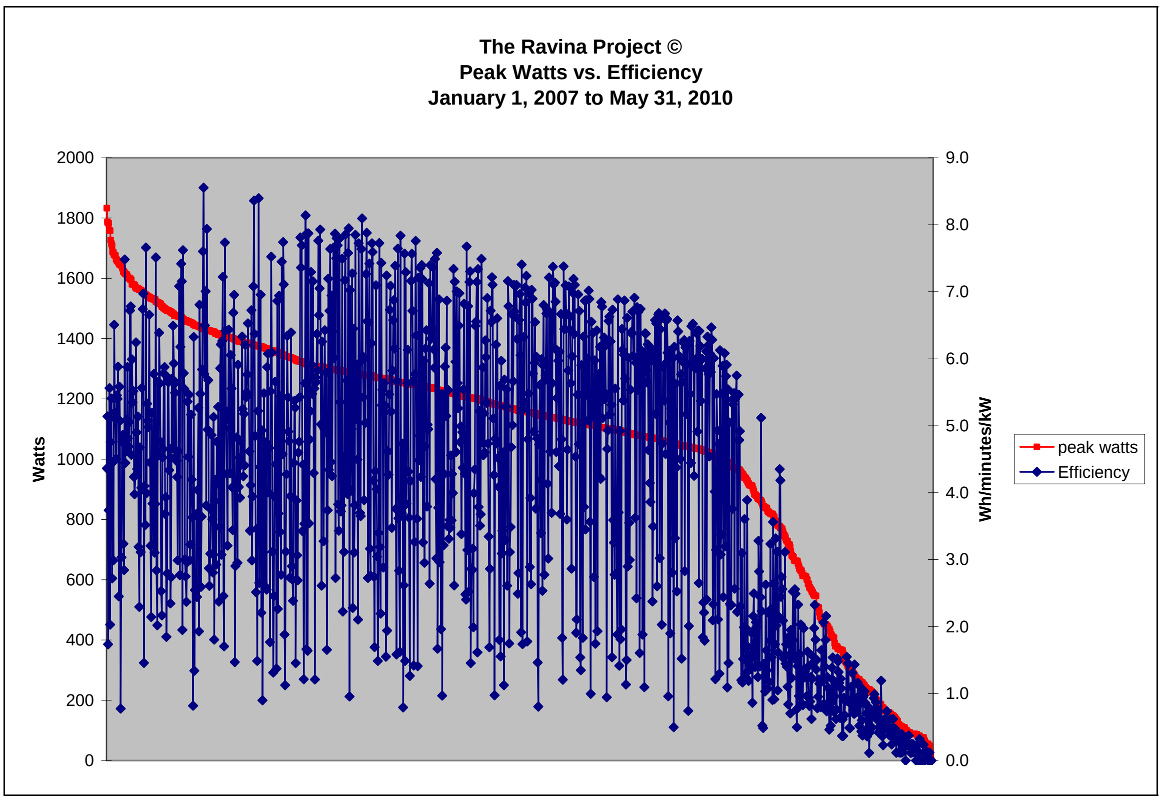
At this latitude, the direct sun can have an interesting effect upon a panel's power output. On a cold day the periodicity of the clouds covering the panels can be very favourable to maximum or peak power recorded on the MX-60 solar charge controller.

On cold days when the array is covered by cloud for just a few minutes the panels cool quickly. When the sun strikes them again, sustained power output surges to exceed the maximum rated power output of the array on a remarkable number of occasions.

It is our observations that in general, peak watt yearly maximums are generated on cloudier days. This naïve observation gives rise to a prediction. The days which have the largest peak Watt records would be the days which have somewhat less efficiency. The rationale for this is that since at times when the panels are covered with clouds they are producing less than maximum power, over the day the RSES value falls.

Can we see evidence of this phenomenon?

Consider the following chart of our complete database of 1247 days.



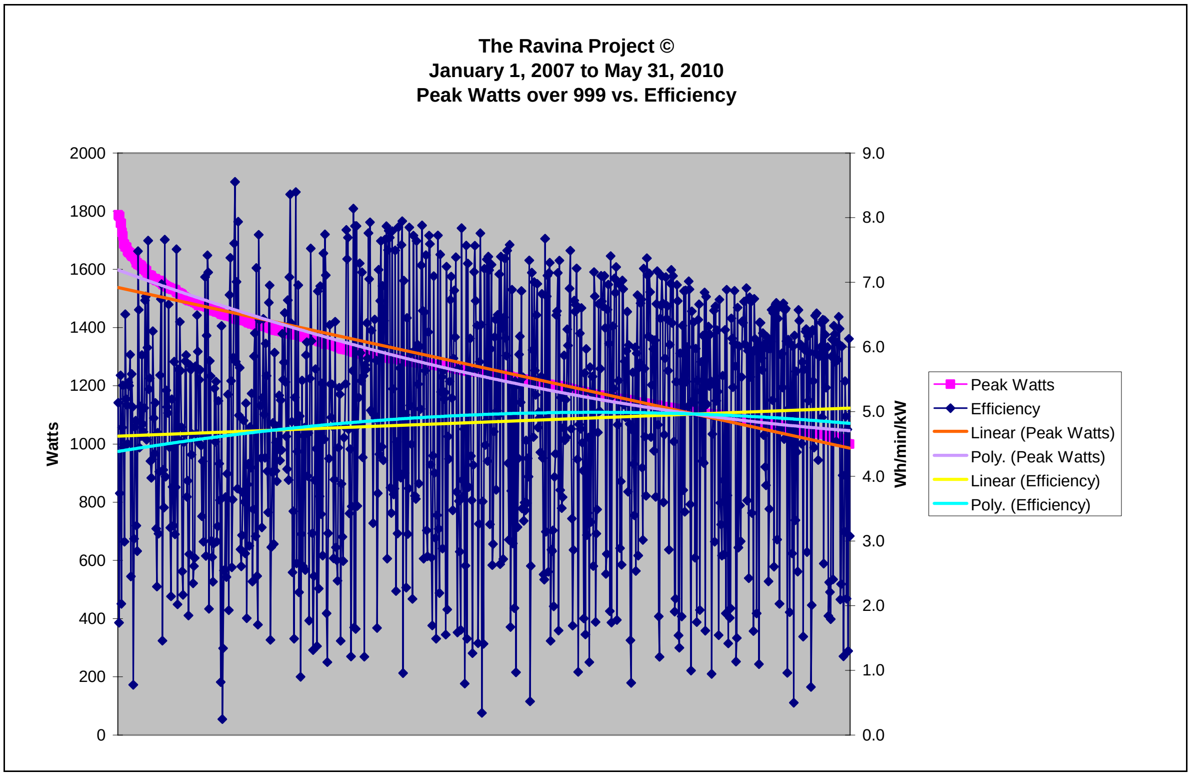
When I first saw this chart I had no clue what I was looking at. What happens at a peak power of 1000 W? What is the reason why efficiency should get hammered when the daily peak power is below 1000 watts?

This chart looks like two different charts.

The first one contains days that are above 1000 watts peak power the other one has days with less.

However, can we demonstrate that days with high peak power are days with less efficiency?

Consider the following chart plotting daily observations over 929 days.



To make this chart, days with peak Watts over 999 were selected from the whole database. They were sorted and placed on the chart. For each of these days the RSES number was plotted.

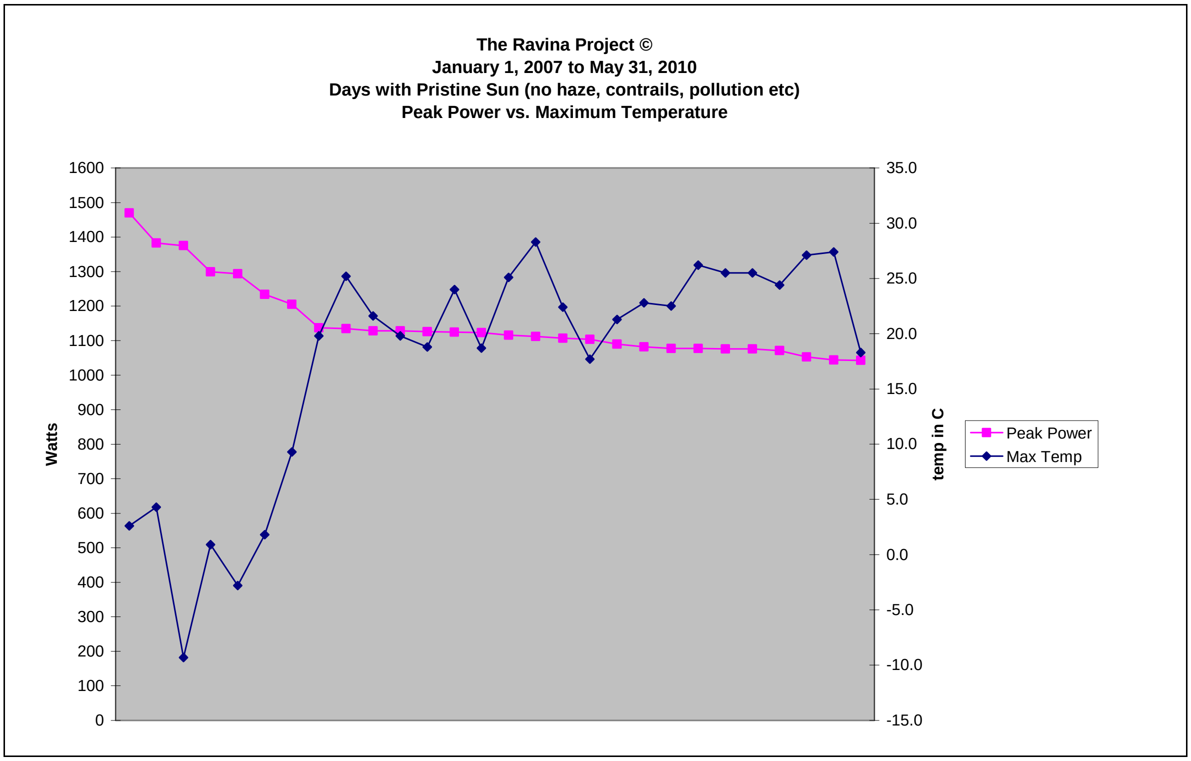
Here in this chart we can see quite clearly that as the peak power reaches upper levels the efficiency falls off. The linear curve fit gives an indication of the relationship and the parabolic curve fit gives it a little more emphasis.

The peak watts increase, sometimes rapidly in comparison to efficiency, but the interesting observation is the declining efficiencies when daily peak power rapidly increases. We see this phenomenon in our observations.

A dropping efficiency indicates that for some period of the generating day the array was not producing power at the maximum output. The biggest impediment to power generation are clouds. But interestingly enough as clouds increase, the panel's temperature returns or approaches ambient temperature moderated by airflow over both sides of the collecting surface. We see on a regular basis sustained power at 1250 Watts and then clouds for a few minutes drops it to 600 Watts and then when the sun comes out again, the charge controller registers between 200 and 250 watts more power to about 1450 or so. This power slowly returns to the sustained power as the internal temperature of the panels increases and reaches equilibrium with the ambient air temperature. You can see in the chart above, peak power can go 20% over the rated power if the panel is cool enough and it is hit with very intense insolation through a pristine sky.

Maximum Daily Temperature vs. Peak Power

Consider the following chart of 28 daily observations.

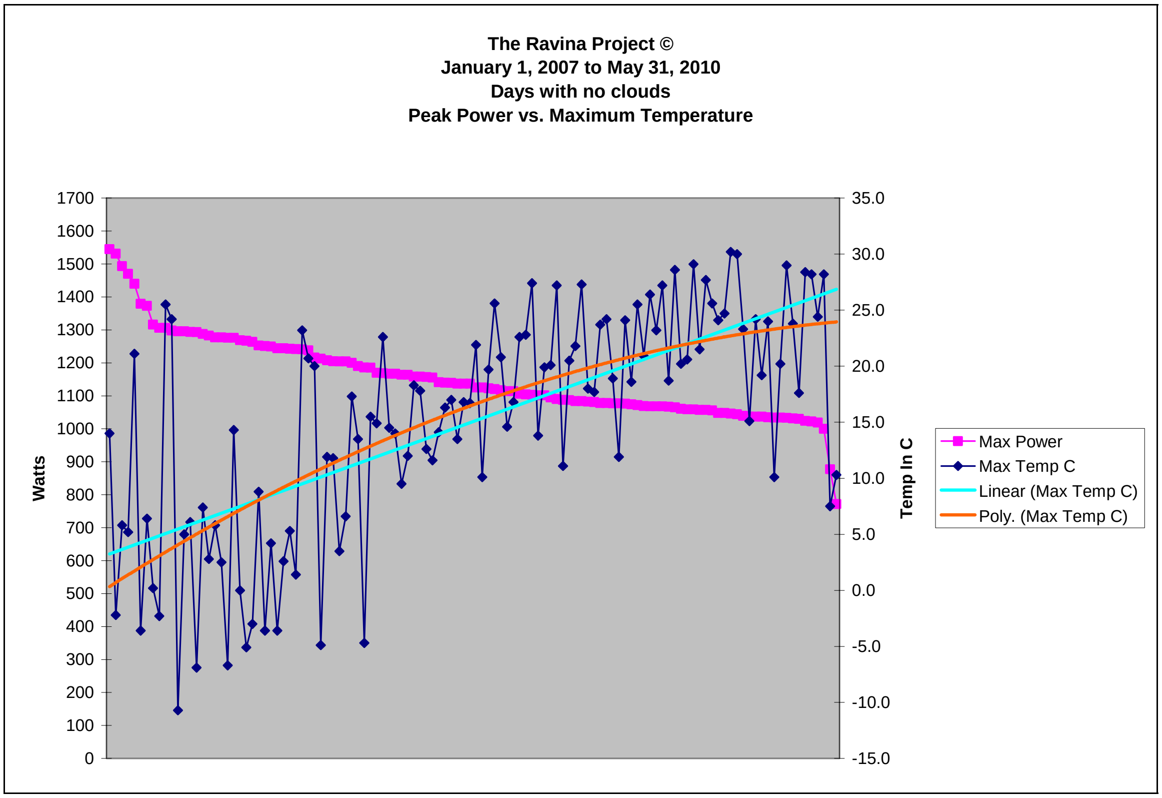


We label a day with 'pristine' sun as a 'sun' day plus extremely good sun. To determine the sun is pristine, we test it. We raise our hand to the sun to block it out. We examine the colour of sky immediately surrounding the sun. If the colour is darker blue like a dark 'robins egg' blue then we say the sun is in a pristine condition. The sun as well must maintain this condition for most of the day which means observations in the am and pm. Pristine days are few but much appreciated.

On cloudless days the peak power is also the peak sustained power. There are no other phenomena which would separate these values. Therefore, since these days are cloudless it is the ambient air temperature that drives the panels to a maximum sustained power of about 300 watts over their normal range.

Can we see this phenomenon using data from days that are recorded as sunny with no clouds? These days may have haze, contrails or air pollution. A check of the sun on these kinds of days reveals a white / light blue patch around the sun when it is viewed whilst being blocked off.

Consider the following graph of 118 daily observations.

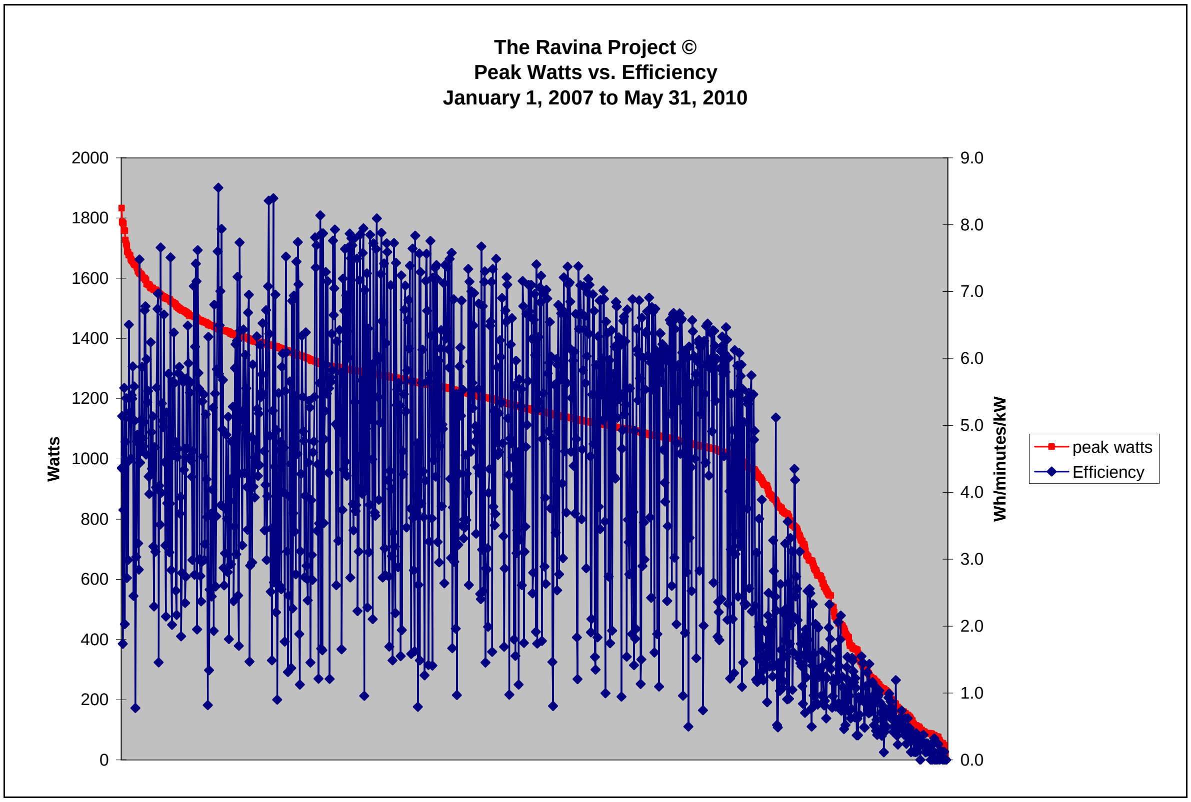


Days were selected which were recorded as ‘sun’ days. This group of days were sorted according to their peak power recorded for that day. The maximum daily temperature for each of those days is also plotted on this graph.

In both the above charts something happens around 20 degrees C ambient daily maximum temperature. From our point of view this is as clean a sun measurement as we can get when demonstrating the relationship between Maximum Temperatures and Peak power.

Peak Watts vs. Efficiency Part 2

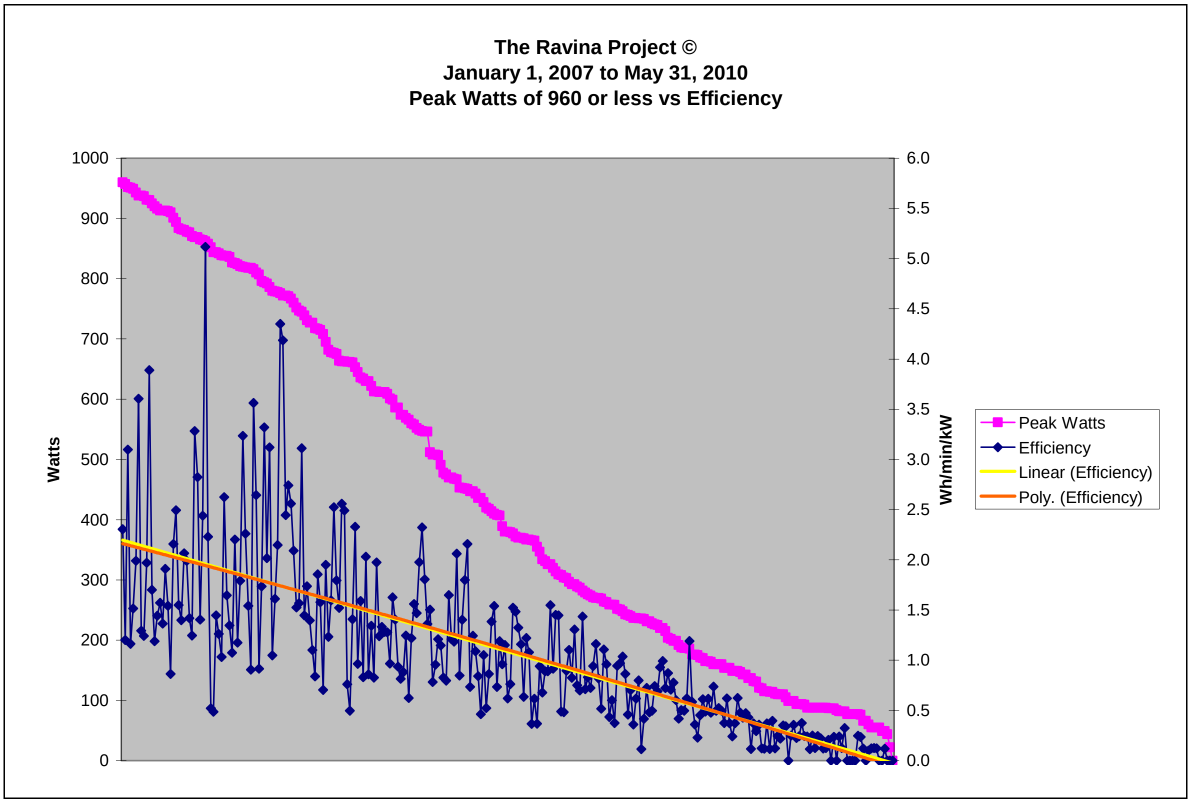
Getting back to that precipitous fall off of efficiency below 1000 watts peak power.



Let us look closer at the graph using only the days which have 960 peak power Watts or less.

Consider the following graph of 289 daily observations.

We have isolated the days which have a peak power recorded of 960 or less and plotted them against efficiency. We hope to get a better look at the dramatic fall off in efficiency



We can eliminate haze, heat, contrails, pollution and the like. The key is that the efficiency falls off dramatically. We know of only one phenomenon that tanks efficiency and that is clouds. But these are not partly cloudy days. On a seemingly cloudy day all you need is one shot of pure sunshine lasting just a few seconds during the main generating times of the day to set the peak power meter to 1200 Watts or more. When you have days where the peak power is so low, the sun has not broken through the cloud at all during the day. The best you might get is a bright diffuse which on this array registers at about 500 to 700 Watts during the peak generating times around 11:00 AM sun time plus or minus a few hours.

Looking at the graph, we don't see any efficiency number over 3 until the peak watts get over 750 and that is bright diffuse. There only 6 days which have efficiencies over 3.5 on the whole chart.

So that explains the huge fall off in efficiency when the peak power falls under about 1000 Watts. When the data is sorted the days with overwhelming cloud are grouped together at the bottom of the sort. Since any kind of direct sun on the array will produce peak power of greater than 1000 Watts, all the days have at best diffuse sun conditions.

Conclusions

Ventilation

One of the interesting observations of this exercise is the real world effects heat has on the performance of solar PV arrays. To look at the manufacturer's specifications on heat is one thing but to see it working in a real installation is another. Heat affects performance and at this installation the difference in sustained power output between noon on a sunny, cold, winter's day and the same sun time on a hot summer's day is 200 Watts. Our panels are very well ventilated so the heat effects you see in our data are best case. On roofs where panels are placed within 10 cm or so of the roof surface, heat buildup will be an issue

Global Warming

Global Warming will bring about elevated temperatures on average for the whole globe but in certain areas the increase in heat will be several degrees during heat waves. At the end of this century the hot areas of the American south west will be substantially hotter than they were in the 1980s. Keep this thought in mind. There have been proposals to place monster PV arrays in the deserts of the world and integrating them with long range DC based transmission lines into each continental grid. Global Warming will play a role in an escalated de-rating of these PV arrays due to heat as the years progress. Any up front design and cost/benefit analysis should take this thermal de-rating into consideration when planning for a 25 year or more life time of the PV installation.

Using heat radiation coating for panel undersides

There are some nano based coatings that can be used to increase the efficiency of heat transfer from solid bodies to air. These coatings using zinc oxide can increase the thermodynamic coupling between the solid underside of a PV array and the air. From what is understood at the time of writing this coating is inexpensive to produce and apply. It would be interesting to do a side-by-side test over several years with two identical arrays, one with such underside coatings and the other without and see if there are any benefits accrued by such coatings.

Data

Our data in CSV format can be found at: http://www.theravinaproject.org/raw_data.htm

"If we knew what we were doing, it would not be called research."
- A. Einstein

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