The Ravina Project

Solar Array Efficiency 06

A Simple Standard

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A Simple Standard

Introduction

It is hard to compare the efficiency of our solar array from day to day. How are we doing from season to season? How does our array stack up against another of a different size across town? If we make a change do things get better or worse? These are interesting questions.

In this document we want to suggest one simple way to evaluate your home array and quite possibly those of other people in your neighbourhood or city.

At the end of the paper we use our new standard to examine the effects of heat, if any, on solar power generation.

How to measure array efficiency

This is a tough assignment.

A calculation for array efficiency is really a calculation of a metric. It's difficult to build a simple metric based upon data that changes from moment to moment. It is much better for simple calculations if the metric is based upon data that is more or less constant.

We know that the total amount of daily sun available to generate power is a variable controlled, for the most part by: weather, sun angles, length of day, air quality, and the size of the array. If we look at these variables we can divide them into two categories. The first category contains variables that change their values on a moment by moment basis all day long. Of the variables we listed above, the weather, air quality and the sun angle fall into this category. The second category contains variables that are more or less constant for the day. In the above list, the variable representing the size of the array does not change moment by moment and may be considered to be a constant over substantially longer periods of time than a day. The last variable from the 'constants' list is the length of day. It varies on a day by day basis but does not change during the course of the day. The day is the same length at sun rise as at sun set.

It seems to us that it might be interesting to build an efficiency metric based upon the two 'constants' in the list above. We can arrange the constants in a calculation where the total amount of power harvested in watt-hours (Wh) is divided by the size of the array in kilowatts (kW) and further divided by the number of minutes in the day. The resulting value is expressed in Watt-hours per minute per kilowatt.

The metric would place our 1500 watt array here at The Ravina Project on a par with a 1,000,000 watt array.

Efficiency based upon length of day and array size

So how does your array stack up when there are 560 minutes or 800 minutes in a day? Hard to know unless one develops a standard that eliminates the differences in the length of day. On January 20th 2007 we generated 6.4 kWh of power. How do we compare that day's output with, let's say, the 8.8 kWh we generated on the May 13th of the same year? Both were sunny days.

We make the calculation by taking the 6400 Wh of power generated on January 20th and dividing it by 1.5 for a total of 4270 Wh. On January 20th there was 572 minutes of sunlight available for power generation here in Toronto. So we divide 4270 by 572 to give a rate of 7.5 Watt-hours per minute per kW of generation capacity.

How does this compare with the May 13th reading? Let's do the math. First the total power generated is 8.8 kWh or 8800 Wh. The size of the array is 1.5 kWh so we firstly divide 8800 by 1.5 which equals 5866.7 Wh. On May 13th there was 883 minutes available to generate power. The resulting power efficiency of the array is 5866.7 divided by 883 equals 6.6 Watt-hours per minute per kW of generation capacity.

We see that the array was working harder for us on January 20th than it was on May 13th even though the May total kWh generated is greater. With this comparison we now can compare apples and oranges by turning the oranges into apples. Suppose my friend has an array of 5000 Watts down the street. How do his numbers compare with mine? How hard is his array working for him? Another way of using this simple efficiency metric is to compare the same array on a day by day or season by season basis. Are there any differences?

New for 2008

In 2008 we will add the daily efficiencies to the daily generation charts and sheets we publish on the WEB site. This allows you, if you have an array of panels at your place, to compare your efficiency each day with ours. Here we try to compare days where the sun has been forceful all day long. There are usually a few days in the month that fall into this category. Since there is a correlation between the maximum amount of sun power generated in a day and the total amount and quality of sun available, we try to compare days that have exceptional sun.

Efficiency and Maximum Daily Temperature

Since we have developed a simple method of looking at the efficiency of our solar array, let's try to use it to analyze our array performance with respect to temperature. We have noticed that during cold days we can get sustained power output in the mid 1200's. On hot days we are lucky to get a sustained output of 1060 watts or so. Will these differences in sustained power output be reflected in any way in changes to the array efficiency?

To help us we can consult our first full year of power generation data. Along with that data we have also made a daily entry for the sun rise and sun set times, calculated the length of day in minutes and recorded the maximum temperature in Centigrade.

Consider the sheet for January 2007.

Top six power days for the month								
Date	**Sun Rise**	**Sun Set**	**Minutes**	**Efficiency Wh/kW/min**	**Max Temp C**	**Gen Pwr kWh**	**Weather**	**Peak Pwr W**
20-Jan-07	7:42	17:14	572	7.5	-4.6	6.4	br sun	1360
31-Jan-07	7:32	17:29	597	6.1	-3.7	5.5	sun am cld pm	1386
10-Jan-07	7:47	17:02	555	5.9	-2.0	4.9	sun am cld pm	1281
9-Jan-07	7:47	17:01	554	4.9	2.5	4.1	sun am cld pm	1305
2-Jan-07	7:48	16:54	546	4.9	6.6	4.0	sun	1373
4-Jan-07	7:48	16:56	548	4.9	8.3	4.0	sun	1034
		Totals:	**3372**			**28.9**		
		Averages:		**5.7**	**1.2**	**4.8**		
Percent of total monthly power generated by these six days:						**41.3%**		

The efficiency is measured in Watt-hours per minute per kilowatt of array. Notice that the average efficiency for these six days is 5.7 Watt-hours generated per minute. These six days were good days because they represent only one fifth or 20% of the days in the month yet they generate over 40% of the total power for the month. Note the average efficiency of 5.7 Watt-hours per minute and the average daily maximum temperature of 1.2 C.

Consider the sheet for February.

Top six power days for the month								
Date	**Sun Rise**	**Sun Set**	**Minutes**	**Efficiency Wh/kW/min**	**Max Temp C**	**Gen Pwr kWh**	**Weather**	**Peak Pwr W**
23-Feb-07	7:01	18:00	659	8.3	-5.6	8.2	sun cold	1379
24-Feb-07	6:59	18:01	662	7.9	-1.8	7.8	sun	1306
15-Feb-07	7:13	17:49	636	7.9	-8.1	7.5	clear sun cold	1427
18-Feb-07	7:09	17:53	644	7.5	-6.5	7.2	sun sml clds cold	1523
16-Feb-07	7:12	17:50	638	6.9	-4.1	6.6	cld am 9 on sunny	1351
8-Feb-07	7:23	17:40	617	7.0	-3.8	6.5	sun	1379
		Totals:	**3856**			**43.8**		
		Averages:		**7.6**	**-5.0**	**7.3**		
Percent of total monthly power generated by these six days:						**40.7%**		

We see that the average efficiency of the six best days increases to 7.5 watt-hours per minute and the maximum temperature for the days averages at a frosty -5 C. These were good days with one over 8 kWh and two well over 7 kWh. Again as we observed above, these six days contributed about 40% of the power yet represented only about 21% of the days in the month.

Consider the sheet for March.

Top six power days for the month								
Date	**Sun Rise**	**Sun Set**	**Minutes**	**Efficiency Wh/kW/min**	**Max Temp C**	**Gen Pwr kWh**	**Weather**	**Peak Pwr W**
29-Mar-07	6:01	18:42	761	7.9	6.1	9.0	sun	1288
20-Mar-07	6:18	18:31	733	8.1	0.3	8.9	sun	1316
6-Mar-07	6:43	18:14	691	8.5	-10.9	8.8	sun cold	1432
28-Mar-07	6:03	18:41	758	7.4	8.8	8.4	sun no early pm tree shade	1349
11-Mar-07	6:34	18:20	706	7.6	5.5	8.1	sun	1294
9-Mar-07	6:37	18:18	701	7.5	0.5	7.9	pt sun hi hz	1288
		Totals:	**4350**			**51.1**		
		Averages:		**7.8**	**1.7**	**8.5**		
Percent of total monthly power generated by these six days:						**37.9%**		

There is again an increase in the average efficiency from 7.5 in February to 7.8 watt-hours per minute in March. The average temperature rises to 1.7 C. Note that these six days contribute almost 38% percent of the power yet represent slightly more than 19% of the total days in the month. Note the best efficiency recorded occurred on the coldest sunny day.

Consider the sheet for April

Top six power days for the month								
Date	**Sun Rise**	**Sun Set**	**Minutes**	**Efficiency Wh/kW/min**	**Max Temp C**	**Gen Pwr kWh**	**Weather**	**Peak Pwr W**
19-Apr-2007	5:25	19:07	822	7.6	11.8	9.4	sun	1545
21-Apr-2007	5:22	19:09	827	7.3	19.5	9.1	sun clr hi ice xtals	1137
22-Apr-2007	5:20	19:11	831	7.1	17.7	8.9	sun hi hz	1123
29-Apr-2007	5:09	19:19	850	6.8	15.7	8.7	sun am cld late pm	1356
20-Apr-2007	5:23	19:08	825	6.4	18.9	7.9	sun	1034
30-Apr-2007	5:08	19:20	852	5.6	17.7	7.2	sun	1139
		Totals:	**5007**			**51.2**		
		Averages:		**6.8**	**16.9**	**8.5**		
Percent of total monthly power generated by these six days:						**41.5%**		

The average efficiency fell from 7.5 to 6.8 watt-hours per minute. There is a dramatic rise in average temperature to 16.9 C. The highest efficiency is attained on the day with the coolest temperature. Note that these six days contribute almost 42% percent of the power yet represent 20% of the total days in the month.

Consider the sheet for May.

Top six power days for the month								
Date	**Sun Rise**	**Sun Set**	**Minutes**	**Efficiency Wh/kW/min**	**Max Temp C**	**Gen Pwr kWh**	**Weather**	**Peak Pwr W**
6-May-2007	5:00	19:27	867	7.1	12.4	9.2	sun	1137
21-May-2007	4:43	19:43	900	6.7	15.3	9.1	sun hi hz contrails	1104
3-May-2007	5:04	19:24	860	7.0	12.9	9.0	sun	1114
29-May-2007	4:37	19:51	914	6.6	19.1	9.0	sun	1057
18-May-2007	4:46	19:40	894	6.6	12.9	8.9	sun	1167
13-May-2007	4:52	19:35	883	6.6	12.5	8.8	sun	1141
		Totals:	**5318**			**54.0**		
		Averages:		**6.8**	**14.2**	**9.0**		
Percent of total monthly power generated by these six days:						**25.1%**		

This chart shows the temperature rising and the efficiency falling. Only two days have efficiencies over 7.0 Watt-hours per minute. Note that these six days contribute about 25% percent of the power yet represent about 19% of the total days in the month. We can account for this by the fact that the median total per day for May was 7.7 kWh of generation. The average was quite a distance away at 6.9 kWh.

Consider the sheet for June.

Top six power days for the month								
Date	**Sun Rise**	**Sun Set**	**Minutes**	**Efficiency Wh/kW/min**	**Max Temp C**	**Gen Pwr kWh**	**Weather**	**Peak Pwr W**
14-Jun-2007	4:32	20:02	930	6.7	20.2	9.4	sun	1078
29-Jun-2007	4:35	20:05	930	6.7	22.0	9.3	pristine sun	1082
22-Jun-2007	4:33	20:05	932	6.7	21.3	9.3	sun pt cld	1400
10-Jun-2007	4:32	20:00	928	6.5	22.2	9.1	sun	1048
9-Jun-2007	4:33	19:59	926	6.4	19.2	8.9	sun	1125
25-Jun-2007	4:34	20:05	930	6.4	27.9	8.9	sun hi mod hz cld pds	1048
		Totals:	**5576**			**54.9**		
		Averages:		**6.6**	**22.1**	**9.2**		
Percent of total monthly power generated by these six days:						**25.1%**		

As the temperature rises the efficiencies continue to drop. The maximum reaches only 6.7 Watt-hours per minute. This is the first month where the average daily maximum temperature is over 20 degrees. The total generated for these six days as a percentage of the monthly total falls again. There are lots of good days during this month like all the other summer months.

Consider the sheet for July.

Top six power days for the month								
Date	**Sun Rise**	**Sun Set**	**Minutes**	**Efficiency Wh/kW/min**	**Max Temp C**	**Gen Pwr kWh**	**Weather**	**Peak Pwr W**
29-Jul-2007	5:00	19:46	885	6.2	24.3	8.2	sun hz	1022
22-Jul-2007	4:53	19:54	901	5.9	24.0	8.0	sun cirrus pt cld	1215
3-Jul-2007	4:38	20:04	926	5.8	22.0	8.0	mod hi hz	1154
21-Jul-2007	4:52	19:54	902	5.8	25.0	7.9	pristine sun pt cld	1234
30-Jul-2007	5:01	19:45	884	5.9	26.1	7.8	sun sml hz	1042
20-Jul-2007	4:51	19:55	904	5.8	23.6	7.8	pristine sun pt cld	1463
		Totals:	**5402**			**47.7**		
		Averages:		**5.9**	**24.2**	**8.0**		
Percent of total monthly power generated by these six days:						**24.7%**		

Continuing with the decline, the efficiencies max out at only 6.2 Watt-hours per minute. The temperature continues to rise. Monthly power percentage is unmoved.

Consider the sheet for August.

Top six power days for the month								
Date	**Sun Rise**	**Sun Set**	**Minutes**	**Efficiency Wh/kW/min**	**Max Temp C**	**Gen Pwr kWh**	**Weather**	**Peak Pwr W**
4-Aug-2007	5:07	19:39	872	6.3	25.0	8.3	sun pristine	1074
13-Aug-2007	5:16	19:27	851	6.3	28.2	8.1	pristine sun	1112
8-Aug-2007	5:11	19:34	863	6.3	32.9	8.1	pt cld hot hz	1163
10-Aug-2007	5:13	19:31	858	5.9	25.1	7.6	sun am pt cld pm	1152
28-Aug-2007	5:33	19:03	810	6.2	25.3	7.5	sun hz cld	1042
19-Aug-2007	5:23	19:18	835	6.0	21.3	7.5	cld hz sun	1192
Totals:		Totals:	**5089**			**47.1**		
Averages		Averages:		**6.2**	**26.3**	**7.9**		
Percent of total monthly power generated by these six days:						**25.8%**		

The decline in efficiency seems to have bottomed out at a maximum for the month of 6.3. There is a substantial increase in average daily maximum temperature.

Consider the sheet for September

Top six power days for the month								
Date	**Sun Rise**	**Sun Set**	**Minutes**	**Efficiency Wh/kW/min**	**Max Temp C**	**Gen Pwr kWh**	**Weather**	**Peak Pwr W**
1-Sep-2007	5:38	18:56	798	6.6	21.2	7.9	Pristine Sun	1128
13-Sep-2007	5:51	18:34	763	6.3	19.7	7.2	sun	1117
2-Sep-2007	5:39	18:54	795	6.0	23.9	7.1	Pristine Sun	1076
8-Sep-2007	5:46	18:43	777	6.0	24.4	7.0	Pristine Sun	1076
17-Sep-2007	5:56	18:27	751	6.1	18.5	6.9	Pristine Sun	1137
23-Sep-2007	6:03	18:16	733	6.1	20.1	6.7	Pristine Sun	1077
		Totals:	**4617**			**42.8**		
		Averages:		**6.2**	**21.3**	**7.1**		
Percent of total monthly power generated by these six days:						**26.4%**		

The average daily maximum temperature has declined somewhat over these six days. The maximum efficiency has increased from 6.3 to 6.6 and the average has increased marginally from 6.1 to 6.2 Watt-hours per minute.

Consider the sheet for October

Top six power days for the month								
Date	**Sun Rise**	**Sun Set**	**Minutes**	**Efficiency Wh/kW/min**	**Max Temp C**	**Gen Pwr kWh**	**Weather**	**Peak Pwr W**
21-Oct-2007	6:36	17:27	651	6.0	18.1	5.9	sun hz	1057
22-Oct-2007	6:38	17:25	647	5.9	19.4	5.7	sun pm pt cld	1282
5-Oct-2007	6:17	17:54	696	5.5	21.4	5.7	smog hz sun	969
30-Oct-2007	6:48	17:13	625	5.9	14.9	5.5	sun	1037
1-Oct-2007	6:12	18:01	709	5.1	23.4	5.4	sun br diff	1104
29-Oct-2007	6:46	17:15	629	5.0	13.9	4.7	sun am cld pm	1306
		Totals:	**3957**			**32.9**		
		Averages:		**5.6**	**18.5**	**5.5**		
Percent of total monthly power generated by these six days:						**37.5%**		

October was a dull month with no real pristine sun days. As you can see the six days chosen contributed almost 38% to the total power generation for the month which is the first month over 30% since April. From the month before, October was distinctly different from September with a power maximum at only 5.9 kWh. It's really difficult to see how this month fits into the trend we are seeing with the other months.

Consider the sheet for November

Top six power days for the month								
Date	**Sun**	**Sun**	**Minutes**	**Efficiency**	**Max**	**Gen Pwr**	**Weather**	**Peak**
	Rise	**Set**		**Wh/kW/min**	**Temp C**	**kWh**		**Pwr W**
23-Nov-2007	7:19	16:48	569	7.1	-3.2	6.1	sun	1244
2-Nov-2007	6:52	17:09	617	6.6	9.7	6.1	sun	1125
18-Nov-2007	7:12	16:52	580	6.7	4.2	5.8	pristine sun	1383
13-Nov-2007	7:06	16:56	589	6.6	9.6	5.8	sun	1088
25-Nov-2007	7:21	16:47	566	5.7	6.3	4.8	sun sml hz	1089
10-Nov-2007	7:02	16:59	597	4.2	5.4	3.8	sun am cld pm	1224
		Totals:	**3518**			**32.4**		
		Averages:		**6.1**	**5.3**	**5.4**		
Percent of total monthly power generated by these six days:						**46.0%**		

Firstly we notice that the six days account for 46% of the total monthly power generation. It looks like these six days were by far the best of the lot for the month. We also notice a bump in the efficiency when the daily maximum temperature is lowest.

Consider the sheet for December.

Top six power days for the month								
Date	**Sun**	**Sun**	**Minutes**	**Efficiency**	**Max**	**Gen Pwr**	**Weather**	**Peak**
	Rise	**Set**		**Wh/kW/min**	**Temp C**	**kWh**		**Pwr W**
12-Dec-2007	7:39	16:42	543	5.8	4.1	4.7	sun pt cld pm	1261
1-Dec-2007	7:28	16:44	556	4.2	-4.1	3.5	sun pt cld	1578
31-Dec-2007	7:48	16:52	544	4.2	1.4	3.4	sun am pt cld oc pm	1106
8-Dec-2007	7:35	16:42	547	4.1	1.6	3.4	sun pt cld	1275
17-Dec-2007	7:42	16:43	541	3.9	-1.7	3.2	sun hz	
5-Dec-2007	7:32	16:43	551	3.8	-5.8	3.1	pt cld am sun pm	1198
		Totals:	**3282**			**21.3**		
		Averages:		**4.3**	**-0.8**	**3.6**		
Percent of total monthly power generated by these six days:						**56.5%**		

This month was a ‘dog’ for power generation. Twenty-two days of the 31 in the month had ‘**oc**’ for ‘overcast’ in the weather report column. Even the best days had ‘**cld**’ for ‘cloud’ in the weather report. The six best days accounted for substantially more than half the power generated in the whole month.

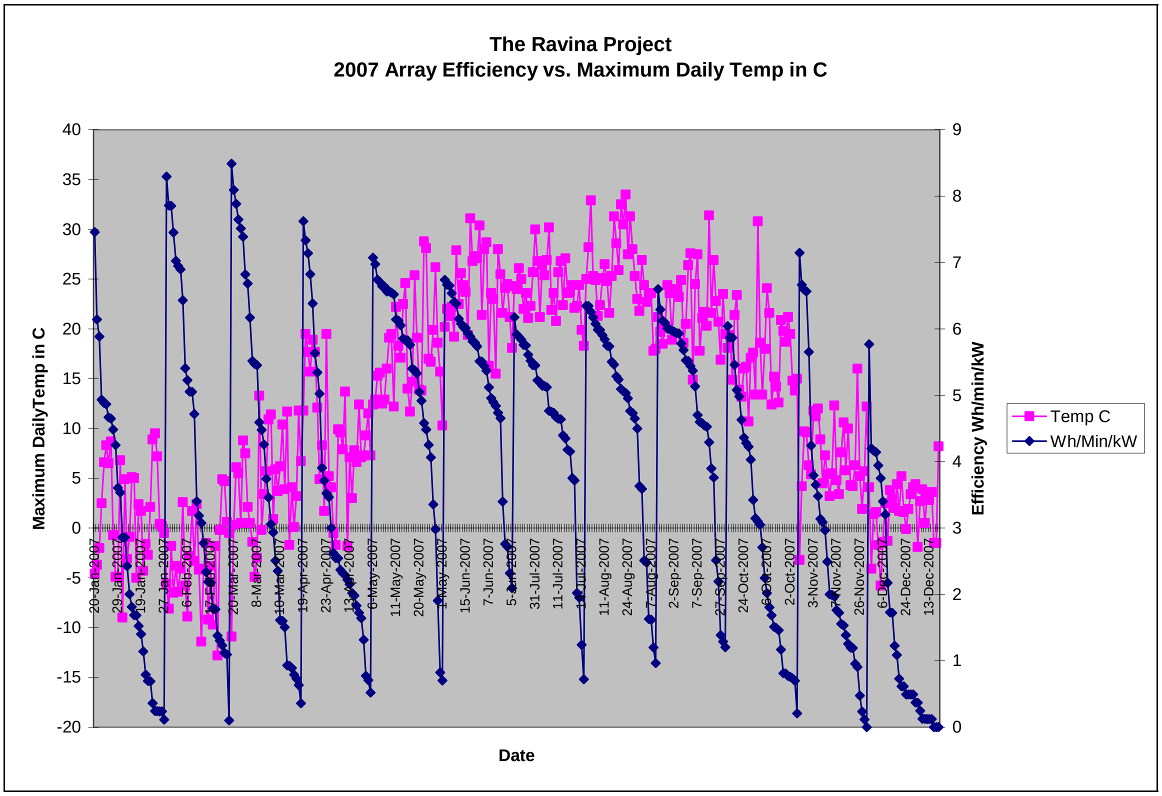
Correlations with heat

Consider the following sheet.

	Average Efficiency	Average Temp		Maximum Efficiency	Maximum Temp
January	**5.7**	**1.2**	January	**7.5**	**-4.6**
February	**7.5**	**-5.0**	February	**7.9**	**-1.8**
March	**7.8**	**1.7**	March	**8.5**	**-10.9**
April	**6.8**	**16.9**	April	**7.6**	**11.8**
May	**6.8**	**15.4**	May	**7.1**	**12.4**
June	**6.5**	**22.5**	June	**6.7**	**22.0**
July	**5.8**	**23.3**	July	**6.2**	**24.3**
August	**6.1**	**27.1**	August	**6.3**	**32.9**
September	**6.2**	**21.1**	September	**6.6**	**21.2**
October	**5.6**	**18.5**	October	**6.0**	**18.1**
November	**6.1**	**5.3**	November	**7.1**	**-3.2**
December	**4.3**	**-0.8**	December	**5.8**	**4.1**
Correlation between average efficiency and average temperature:					**-0.104**
Correlation between maximum efficiency and average temperature:					**-0.508**
Correlation between maximum efficiency and maximum temperature:					**-0.688**
Correlation Without December Values.					
Correlation between average efficiency and average temperature:					**-0.506**
Correlation between maximum efficiency and average temperature:					**-0.803**
Correlation between maximum efficiency and maximum temperature:					**-0.845**

Note the following:

- Average Efficiency is the average for the six chosen days each month,
- Average Temperature is the average daily maximum over the six chosen days each month,
- Maximum Efficiency is the maximum recorded among the six days chosen each month,
- Maximum Temperature is the maximum daily temperature recorded on the day the Maximum Efficiency was recorded.



Consider the graph above.

Power generation data for each month is sorted in descending order. This graph represents the daily efficiency plotted against daily maximum temperature. Note that the highest peaks for efficiency occur in the months which have the coolest daily maximum temperature.

Here are some other statistics for the year.

Average Efficiency for year:	**3.8**	Wh/kW/min
Maximum Efficiency for year:	**8.5**	Wh/kW/min
Median Efficiency for year:	**4.2**	Wh/kW/min
Average Daily Generation:	**4.4**	kWh
Maximum Daily Generation:	**9.4**	kWh
Median Daily Generation:	**4.4**	kWh
Kilowatt hours generated per kilowatt of installed base:	**1069.0**	

Conclusion

Heat has an effect on the generation of solar power to some degree. This stands to reason because the technology used to build solar panels is the same as that used to build transistors. Heat makes it a less efficient conductor for current flow. As the panels get hotter their internal resistance to current flow increases.

Heat seems to be a factor in power generation efficiency. If this is the case then building panels using the present technology and global warming are on a collision course. As the world becomes hotter, our installed base of solar panels using this technology will be come less and less efficient. What ever comes along like MEG will have to account for temperature.

If we discard the data for December the correlation perks up quite a bit.

If you are interested in processing the data we have collected over the year please see the file on the **Raw Data** page:

The Ravina Project 2007 Yearly Solar Data rev xx.XLS.

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

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