The Ravina Project

Solar PV Sustainability

An Examination of Energy Returned on Energy Invested in Monocrystalline PV

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The Ravina Project - Goals

The Ravina Project consists of several projects all proceeding concurrently. If we were to rename our project today we probably would name it, “The Ravina Projects”.

Our project goals page allows our readers to understand the scope and depth of the various areas of inquiry focused totally on the household.

See the Project Goals page on our WEB site at:
www.theravinaproject.org/project_goals.htm

Solar PV Sustainability

Introduction

This paper examines the assumption that the energy returned on energy invested (ERoEI) of solar photovoltaic monocrystalline panels is sustainable over 25 years of usage. We have expanded the paper to both incorporate the phenomenon of curtailment and the RETscreen database of solar generation potential. We use two well known peer reviewed papers to provide us with energy invested amounts. These papers approach the calculation of energy invested from totally different points of view. To complete the effort we use our generation numbers from September 14th 2013 to June 23rd 2016 to evaluate the energy returned part of the ratio. We are shocked to find that it is doubtful that the ERoEI of monocrystalline solar PV is sustainable.

ERoEI

Energy Returned on Energy Invested will be the major concept at the heart of this paper. In simple terms, the energy invested into an energy harvester's lifecycle can be compared to the energy the harvester will produce over its lifetime. The energy returned part of the ratio is very straightforward. Here at The Ravina Project we measure our energy returned from our 2.8 kW solar PV array every day at the end of the generation day. From the papers we have read on the calculation of the ERoEI ratio, the main complexity with the calculation is the energy invested part. Exactly what part of the harvester's: fabrication, transportation, installation, maintenance and recycling energy counts as energy invested? As with many things, when one looks at something closely enough, it gets complicated. The energy invested in solar PV is one of those complex issues

There are two papers we would like to cite in this effort to pin down a value for energy invested. We choose these two papers because they look at the problem from two very different points of view. One is a survey paper which looks at many papers each trying to estimate a good value for energy Invested. The other looks closely at the whole PV lifecycle from solar PV fabrication to end of lifetime retirement. We will use values suggested by both these papers in our calculations below.

Energy Invested Research

Bhandari et al

The first paper is a survey paper which, in our opinion, is a very valuable contribution to a better understanding of energy invested amounts. The paper is entitled, "*Energy payback time (EPBT) and energy return on energy invested (EROI) of solar photovoltaic systems: A systematic review and meta-analysis*" by Khagendra P. Bhandari et al, published in, *Renewable and Sustainable Energy Reviews 47 (2015) pp. 133-141*. On page 137, fig. 2. a survey of the embedded energy in monocrystalline solar panels (like ours) from many different papers has a Mean of 6,225 MJ/m^2 with a standard deviation of 2,883. The authors account for this rather large one sigma value by referring to several papers in their survey which placed the embedded energy value over 10,000 MJ/m^2 and one that placed the value at around 1,708 MJ/m^2. This large difference indicates that the energy invested part of the ERoEI is difficult to calculate however, since it is a survey paper, it gives the reader a good ramp up on this issue. As well, the nice thing about such a review paper is it evaluates many papers allowing the reader to benefit from their collective data.

Using kilowatt-hours rather than megajoules the Mean energy invested value is 6,225/3.6 = **1,729 kWh/m^2**.

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Ferroni & Hopkirk

The second paper we want to draw from is entitled, "*Energy Return on Energy Invested (ERoEI) for photovoltaic solar systems in regions of moderate insolation*" by Ferroni & Hopkirk, published in *Energy Policy 94 (2016) pp. 336-344*. This paper goes to great lengths to reach a definite value for the energy invested in solar PV. Its strength is its in-depth analysis of energy invested as the authors try to get a good understanding of the proper energy invested value. I'd like to quote the paper. It gives a great summation of the processes (and energy inputs) required in the fabrication of solar PV. From page 341 …

> "Whilst a large part of the solar module production industry was located in Europe before 2010 … today almost all European companies have been either closed, have suffered huge losses or have undergone bankruptcies. Leadership has been taken over by Chinese companies who now represent over 70% of the current world production. The main reason for this shift is the high cost of electricity in Europe, and this is very important for the energy intensive solar industry.
>
> The production of PV modules requires a process consisting of approximately 200 steps, starting from crystalline silica mining, upgrading silica sand to metallurgical grade silicon, upgrading metallurgical grade silicon to solar grade silicon. The pulverized metallurgical grade silicon is combined with hydrochloric acid to produce trichlorosilane. This is subjected to a multistage distillation process, referred to commonly as the Siemens process to obtain polysilicon. Solar cells are produced by transforming polysilicon into cylindrical ingots of monocrystalline silicon, which are then shaped and sliced into thin wafers. Next a textured pattern is imparted to the surface of the wafer in order to maximize the absorption of light. The wafer is then doped at a high temperature with phosphorus oxychloride, provided with an anti-reflective coating of silicon nitride and finally printed with a silver paste (lead should be avoided) to facilitate the transport of electrical energy away from the cell. A typical PV module consists of several cells wired together and encapsulated in a protective material, commonly made of ethylene vinyl acetate. To provide structural integrity the encapsulated cells are mounted on a substrate frequently made of polyvinyl fluoride. A transparent cover, commonly hardened glass further protects these components. The entire module is held together in an aluminum frame."

Ferroni & Hopkirk goes into the detail of all aspects of solar PV production, from cradle to grave, as demonstrated by their information dense précis above. They place an energy use upon solar PV production, integration of PV to the grid, labour, faulty equipment and energy invested necessary for the capital. Their assigning a value to faulty panels is noteworthy because our first set of Centennial Solar CS-125 panels was faulty. We did not know until we upgraded our array six years later to new Panasonic panels and realized a huge boost in energy production. Needless to say for this paper we only use the data from our new panels which were installed in September 2013. See http://www.theravinaproject.org/Solar_Data.htm for more detailed information on the jump in solar energy production.

Their calculation assigned various values to each of the categories of energy input and totaled **2,664 kWh/m^2**.

So here we have the values, one from a survey paper (1,729 kWh/m^2) which looked at many papers on the topic of energy invested and another, a very thorough paper, looking at the fine details of energy invested (2,664 kWh/m^2).

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Energy Returned

We will use our daily data taken from our Outback MX-60 solar charge controller to provide the basis for any energy returned claims we make.

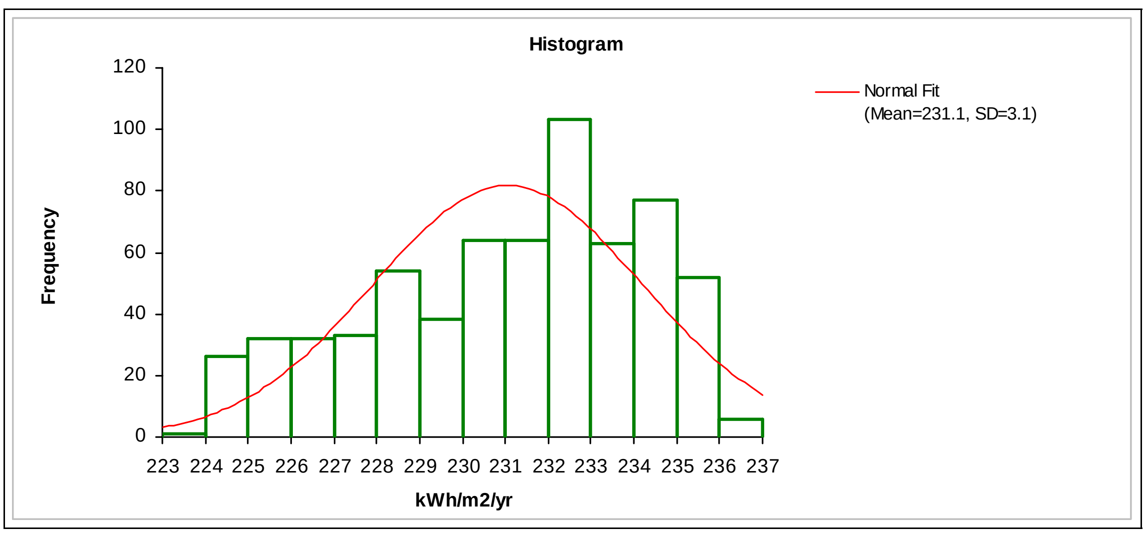
> In order to understand the amount of energy in a kWh the following example will be helpful. A megajoule (MJ) is equal to the approximate kinetic energy of a one megagram (one metric tonne, 2,200 pound) vehicle traveling at 160 km/h (100 mph). A kilowatt-hour (kWh) has 3.6 times more energy in it. Expressed this way one can understand the huge amount of energy contained in a kWh.

Both estimations of energy invested are expressed in kWh per square meter of panel. The energy returned value is based upon an estimation of the amount of energy returned from a square meter of panel over 25 years, the acknowledged lifetime of the panel.

From our data we constructed a series of energy return values each day for 645 days starting September 18, 2014 and ending June 23, 2016.

What method did we follow?

Our new panels were installed on September 17th 2013. We waited 365 days to accumulate the required 365 day daily data. On the next day, September 18th, 2014 we calculated our first value for the number of kWh generated per square meter per year. As each day was added to the list we dropped the earliest day in order to keep the running total 365 days long. The database contains 645 sequential calculations. Each calculation starts with the total 365 day energy harvested divided by 16 square meters to give us the number of kWh per square meter per year. We approached the data in this way rather than taking a 'snapshot' of our data using a representative day for our calculations. Quite frankly we did not know which day was the representative day. Our solution to the problem was to make all the calculations and crunch the statistics. Our method ensures that there is no special date over the 645 days, that is, there is no 'cherry picking' involved.



The graph above, made by our commercial statistics package: Analyse-it, shows the breakout of the daily calculations in a histogram. It gives the reader an idea of the variation in our data and it provides a confidence level that our solar array's performance is consistent.

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Consider the following statistical analysis of the same database.

n	645				
Mean	231.06		Median	231.76	
95% CI	230.81	to 231.30	95.1% CI	231.37	to 232.06
SE	0.124				
			Range	12.9	
Variance	9.92		IQR	5.06	
SD	3.15				
95% CI	2.99	to 3.33	Percentile		
			0th	223.49	(minimum)
CV	1.4%		2.5th	224.53	
			25th	228.56	(1st quartile)
Skewness	-0.45		50th	231.76	(median)
Kurtosis	-0.79		75th	233.62	(3rd quartile)
			97.5th	235.66	
Shapiro-Wilk W	0.95		100th	236.41	(maximum)
p	<0.0001				

As you can see the data are very tight around the Mean. We will use a value of **231.06 kWh/m^2/yr** as our standard generation. Over a 25 year period we will generate 231.06 x 25 = **5,776.5 kWh/m^2**. This is our energy returned number.

ERoEI Calculation

Now we can make the ERoEI calculations using our data.

Bhandari et al

Using the Mean value for energy invested from the Bhandari et al paper of 1,729 kWh/m^2 our ERoEI becomes 5,776.5/1,729 = **3.34**. If we subtract one from this ratio to represent the energy used to create the panels, we are left with **2.34** spread over 25 years to be used to energize our civilizations. That ratio expressed in kWhs can be calculated by simply multiplying the energy invested of 1,729 kWh/m^2 by 2.34 which gives 4,045.9 kWh/m^2 to be used by our civilization over a 25 year period. That becomes 161.8 kWh per square meter per year. This is an impressive number. On a daily basis the number becomes an average of 443 Watt-hours per day per square meter of collector injected into our grid to energize our civilization over the course of 25 years.

So to put a bigger picture on these data, each of our 280W panels is 17.1% efficient meaning that under a standard light intensity of 1 kW they produce 171 Watts per square meter of panel surface. In order to get 280 W per panel they need 280/171=1.673 square meters in surface area. A nameplate 150 MW commercial solar power plant would have about 150 MW / 280 Watts = 535,714 panels on its collecting surface for a total collector area of 535,714 x 1.673 m^2 = 896,249 m^2. Using our numbers above, this array, over its lifetime would provide 896,249 x 0.443 kWh/m^2 = 397,038 kWh on average per day over 25 years with an average daily capacity factor of about 397 MWh / (24 hours x 150 MW) x 100% = **11.0%**.

Ferroni & Hopkirk

Using the energy invested number from Ferroni & Hopkirk of 2,664 kWh/m^2 we calculate our ERoEI as: 5776.5/2664 = **2.17**. If we subtract one from this ratio we get **1.17** spread over 25 years to energize our civilization. Like above we calculate this number on a daily basis to be 341 Watt-hours each day placed upon the grid for every square meter of collector over a span of 25

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years. Using this value of 0.341 kWh and the values for a commercial solar PV power plant above, 896,249 x 0.341 kWh/m^{-2} = 305,621 kWh per day over 25 years should be placed upon the grid with an average daily capacity factor of 305 MWh / (24 hours x 150 MW) x 100% = **8.47%**.

Note that the above calculations ignore various losses which can be up to 15%.

Sustainability Cut-off

There have been many efforts at calculating the magic ERoEI ratio that will allow for sustainability of various technologies. There are many who suggest that for all energy harvesters the number is 8. That is, the ERoEI ratio should be at a minimum of 8 before the harvester is considered to be an energy source rather than an energy drain upon the civilization's energy pool. There are others who suggest 5 is correct (Murphy and Hall (2011)) for the minimum sustainable ERoEI ratio.

Maximum Energy Invested for Sustainability

What is the correct energy invested value in order for our array to be sustainable? Since we can't change the energy returned number we can undertake to calculate the energy invested amount to get some kind of top end on the energy invested required to produce one square meter of panel. If the sustainable ERoEI starts at 5 then the absolute maximum energy invested would have to be less than 5776.5/5 = **1,155.3 kWh/m^2**. Similarly, if the ERoEI sustainability cut-off is 8 the maximum energy invested should be no greater than **722.1 kWh/m^2**.

We also would like to draw the reader's attention to a paper we have been made aware of since version one of this paper was written. The paper is entitled, "*Energy Expenditure, economic growth, and minimum EROI of society*" by Florian Fizaine and Victor Court , published in, *Energy Policy 95 (2016) pp. 172-186*. In this paper the authors estimate the energy expenditure as a fraction of GDP for the USA and the world from 1850-2012 and the UK from 1300-2008. They discover that there is a statistical correlation between economic growth and the percentage of GDP expended for energy and further, there seems to be a cut-off of 11% such that a growing economy needs the expenditure for energy to be at or less than 11% of GDP. From an Energy Returned on Investment point of view, their work indicates that, "… *US growth is only possible if its primary energy system has at least a minimum EROI of 11:1*" (from the Highlights section at the start of the paper). That ERoEI ratio is calculated across all generation technologies. The miserable ERoEI of solar PV that we have identified, if true, requires that generators with a much higher ERoEI ratio be deployed to offset solar PV. That is, if larger and larger roll-outs of solar PV occur then to offset the low ERoEI, large rollouts of higher ERoEI generators must occur to keep the energy mix above the minimum of 11:1.

If our solar PV was to meet this 11:1 ratio the energy invested into a square meter of PV panel would have to be no greater than 5776.5/11 = **525.1 kWh/m^2** or **1,837.9 MJ/m^2**.

Minimum Energy Returned for Sustainability

We can also turn this calculation around. Let's accept the energy investment numbers and change our generation numbers to get a calculated ERoEI of 5 or 8.

Using Bhandari et al the minimum energy returned would be either 5 x 1,729 = **8,645 kWh/m^2** over 25 years or 8 x 1,729 = **13,832 kWh/m^2** over 25 years. The yearly energy returned numbers for each of these calculations is **345.8 kWh/m^2/yr** and **553.3 kWh/m^2/yr**. These amounts correspond to yearly average capacity factors of 345.8 / (0.171 x 365 x 24) x 100% = **23.1%** and 553.3 / (0.171 x 365 x 24) x 100% = **36.9**%. Note the 0.171 is our panel nameplate capacity expressed in kW per square meter.

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Using Ferroni & Hopkirk the minimum energy returned to be sustainable will be 5 x 2664 / 25 = **532.8 kWh/m²/yr** and 8 x 2664 / 25 = **852.5 kWh/m²/yr**. These energy returned numbers correspond to yearly average capacity factors of 532.8 / (0.171 x 365 x 24) x 100% = **35.6%** and 852.5 / (0.171 x 365 x 24) x 100% = **56.9**%.

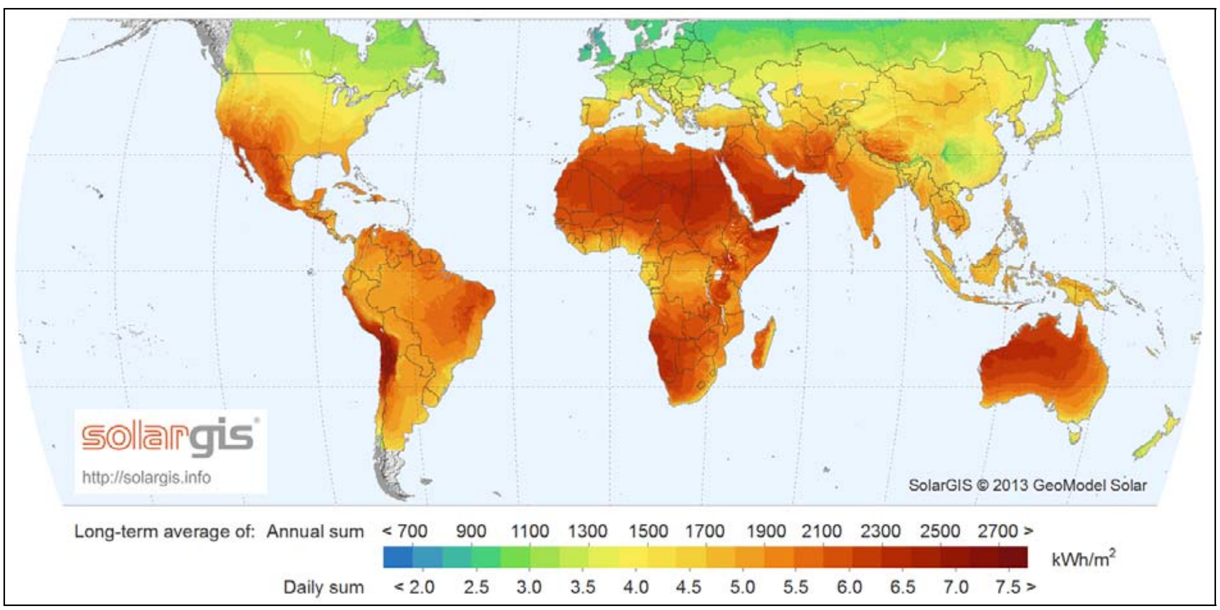
Note that our yearly capacity factor is between 14 and 15% using our sun altitude tracking array.

Looking at Horizontal Irradiance

We can go further in these calculations by trying to characterize the horizontal irradiance required to support these minimum sustainable ERoEI ratios. Let's do a thought experiment. We'll take our array with its mechanism and algorithm and place it in an area with increased irradiance. Our horizontal irradiance here in Toronto is about 1,300 kWh/m² as set out on page 3 of, "*Toronto Police Traffic Services 52 kW PV Installation – Final Report – January 2012*", a report authored by Solar City Partnership.

So to begin the calculation we get 230 kWh/m²/yr with an irradiance of 1,300 kWh/m²/yr which is a ratio of 230/1300= 0.1769. This number is interesting because our panels are 17.1% efficient. The reader will recognize there are thermodynamic entropy issues here but we will ignore them for this paper. Nevertheless, using Bhandari et al to get an energy return of 345.8 kWh/m²/yr and an ERoEI of 5, we need a horizontal irradiance of 345.8/230x1300 = **2,005 kWh/m²/yr**. For an ERoEI of 8 we need **3,127 kWh/m²/yr**. Using Ferroni & Hopkirk to get 532.8 kWh/m²/yr and an ERoEI of 5, we will need an irradiance of **3,011 kWh/m²/yr** and to get an ERoEI of 8 we will need an irradiance of **4,818 kWh/m²/yr**.

Except for the horizontal irradiance of about 2000 the other values seem rather high and are most probably extraterrestrial as judged by the global irradiance map below.



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RETscreen analysis

The RETscreen database is an empirical database consisting of readings from solar panels facing south and tilted at the latitude of the collector. A panel here in Toronto would have a tilt of 43 degrees from horizontal. The amount of energy harvested is expressed as kWh/kW/year, that is, over the course of a year how many kilowatt-hours of energy can be potentially harvested per kilowatt of collector surface. Here in Toronto our potential is between 1,100 and 1,200 kWh per kilowatt per year.

Consider the following Graphic:

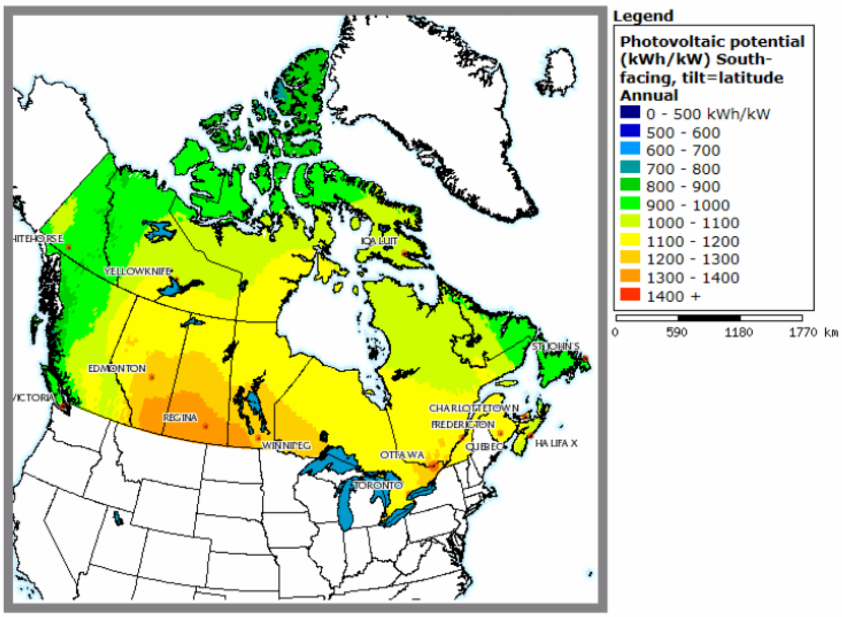
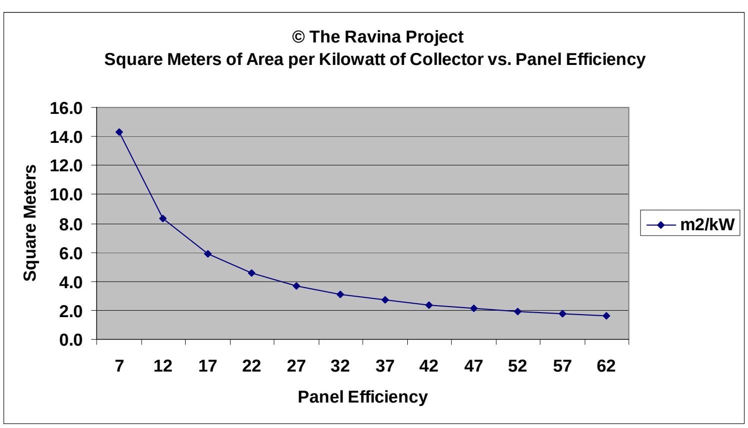


Figure 4.1: NRCan PV Potential Map of Canada

Note the resulting yearly total is proportional to the power of the collector expressed in kilowatts. It says nothing about the efficiency of the panels in the collector and hence it says nothing about the physical area of a kilowatt of collector. We have been using, up to this point, various parameters that focus on a square meter of panel surface. So to integrate the RETscreen database into this paper we will have to bridge the gap between kWh/kW/yr and kWh/m^2/yr.

Consider the following graphic.



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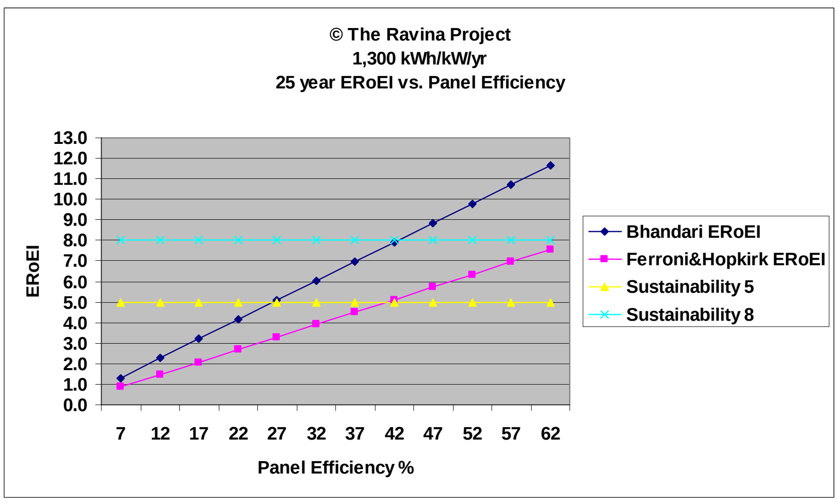
In the graphic above we relate the area in square meters to one kilowatt of harvester at a specific panel efficiency. On the left axis we scale the number of square meters. On the bottom we scale the panel efficiency in steps of 5%. Our panels have an efficiency of 17.1% which means in the laboratory when irradiated with 1000 Watts of light through a standard atmosphere, the panels produce 171 Watts per square meter. So to calculate the surface area required to harvest one kilowatt we need 1000 Watts divided by 171 Watts per square meter equals 5.85 square meters of panel surface. Our 2.8 kW array has an area of about 16 square meters so the calculation works.

We can plug these results into the RETscreen potential values for Toronto. The RETscreen indicates we can generate between 1,100 and 1,200 kWh/kW/yr. A kW of our 17% panels is 5.85 m^2 so we can rewrite the RETscreen estimation as 1,100 kWh/5.85 m^2/year. The kWh/m^2/yr calculation can continue such that 1,100 kWh/5.85 m^2/yr = **188.0** kWh/m^2/yr and 1,200 kWh/5.85 m^2/yr = **205.1** kWh/m^2/yr in a fixed orientation facing south and tilted at latitude.

The calculations above allow us to integrate RETscreen into our discussion of ERoEI because we have a conversion algorithm. Let's look at the highest generation potential in Canada from RETscreen located on the southern Prairies with a return of between 1,300 and 1,400 kWh per kilowatt per year for a fixed array facing south and tilted at latitude. Let's also crunch the energy return over 25 years for each panel efficiency and use the results to calculate new ERoEI ratios using Bhandari et al and Ferroni&Hopkirk.

Consider the following graphic.



At 1,300 kWh/kW/yr the 7% panels need 14.29 m^2 of surface area which returns 1300 kWh/14.29 m^2/yr = 90.97 kWh/m^2/yr. Over 25 years that return is 2,274.3 kWh. Applying the Bhandari et al energy invested value of 1,729 kWh/m^2 the resulting ERoEI is 2274/1729 = **1.3**. Using 42% panels the same calculations return an ERoEI of almost **8.** Similar methodology using Ferroni&Hopkirk's value of 2664 returns the magenta line maxing out as just under **8** with 62% efficient panels.

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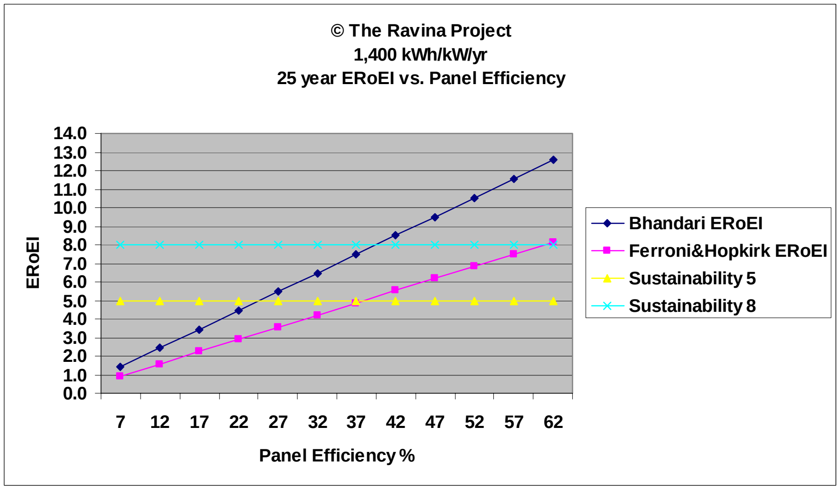
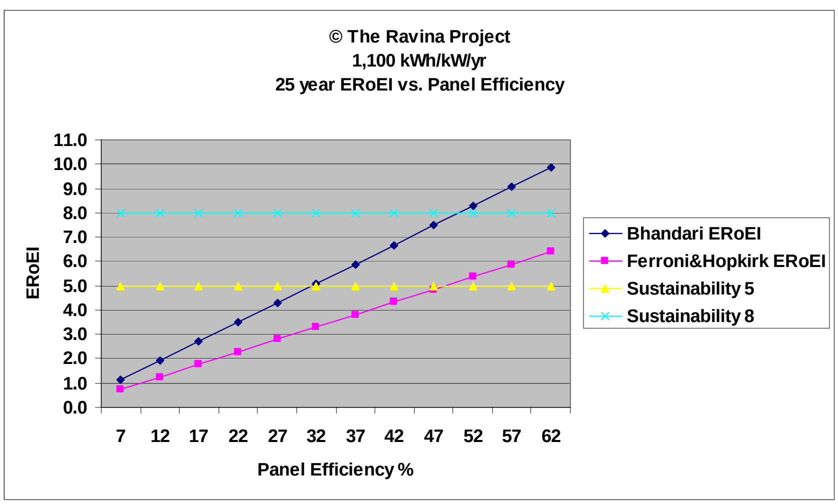
Consider the following graphic.



The only difference between the two graphs is the second uses the high end of the RETscreen potential harvesting value of 1,400 kWh/kW/yr. Note that in the best area for solar energy harvesting even at panel efficiency of 62%, Ferroni&Hopkirk barely makes the sustainability cut-off of 8.

We have also done graphics for our local harvesting potential of between 1,100 and 1,200 kWh/kW/yr.

Consider the following graphics:



This graphic shows the bottom end of Toronto's RETscreen harvesting potential. The following graphic shows the top end.

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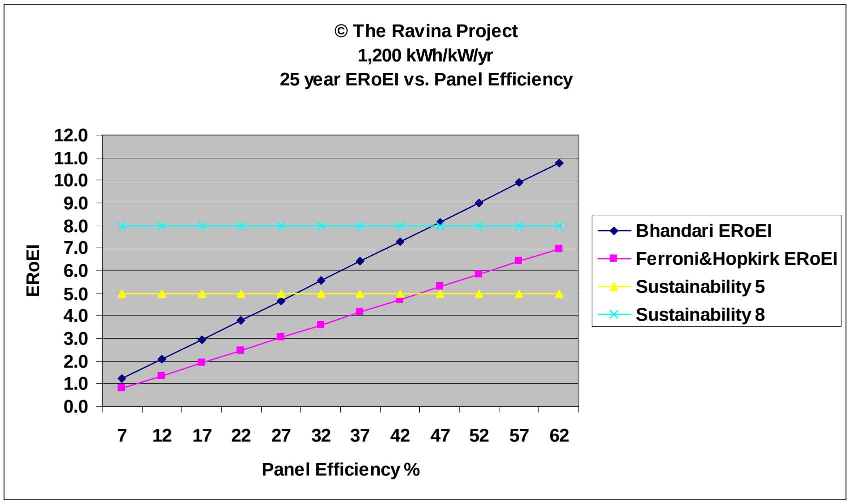

So what does this RETscreen analysis tell us?

- Firstly, we assume that the RETscreen database is a valid database to be used for our argument. At this time of writing we are not aware of any serious critique of it.
- The ERoEI sustainability limit of 8 using Ferroni&Hopkirk is only met at the highest harvesting potential in Canada and only with panels with an efficiency of 62%. So if Ferroni&Hopkirk are correct their energy input values predict there is a significant and troubling possibility that large solar power plants will not harvest enough energy to be sustainable. They will be a negative energy investment.
- The ERoEI sustainability limit of 8 could be met in the best harvesting potential area using the energy input value from Bhandari et al and using panels with an efficiency of about 40%.
- One can understand the importance of discovering a proper energy sustainability value whether it be 5, 8 or 11 as some have proposed (Fizaine&Court 2016). You can see by inspection of the above graphics just how devastating to solar PV a truly verified sustainability number of 11 would be.
- The RETscreen map also shows the potential of using solar PV, wind and storage in combination to energize micro-grids in northern communities. The extended hours of summer sun gives several areas as far north as the northwest coast of Hudson's Bay the same harvesting potential as us here in the extreme south of Canada.
- This analysis further reinforces our contention that solar PV should be used sparingly and should be used where its advantages are leveraged in boutique/niche applications allowing many to participate in modernity through the creation of micro-grids.
- And finally, the whole idea of humanity investing mind-boggling amounts of energy to make solar PV without really having a total and in-depth understanding of the overall energy accounting of solar PV is downright scary in our view. To risk making a bad energy investment during these times where the success of our efforts is measured against the AGW count down clock would be one of the most profoundly risky bets for humanity to make in its history. There will be no time for a 'do over' if we lose the bet.

Our Data vs. RETscreen

One of the secondary reasons for including an analysis of ERoEI using RETscreen is to counter critical and probably justified remarks that our database is unique, compiled using one site only and can't really be used to make any inferences about Canadian ERoEI in general. As the calculations show above, RETscreen indicates the potential solar generation here in Toronto to be between 1,100 and 1,200 kWh/kW/yr which translates to about 188 to 205 kWh/m2/yr. Our actual data used in this paper over 645 days is about **231 kWh/m2/yr**. If we calculate the

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potential for our 17.1% panels on a fixed array tilted at latitude, in the best solar potential in Canada of 1,400 kWh/kW/yr we get 1,400 kWh/kW/yr divided by (1000 Watts divided by 171 Watts) = **238 kWh/m2/yr**. Our energy returned data is very generous in this paper reflecting the best potential in Canada. That is, our actual data is as good as it gets in Canada for fixed angle/azimuth arrays.

Tracking Arrays, RETscreen and ERoEI

Since our data has been generated by one-axis tracker let's explore the value of tracking arrays in general. Note this part of the paper draws upon the theoretical and practical work we completed in 2007 and 2008, very early in this project. These papers provides the theoretical underpinning for all our solar work and the algorithms we use to program our array's time of day orientation to the sun. See our WEB site www.theravinaproject.org/project_papers.htm and download the 2007 paper entitled, "*The Ravina Project – Solar Project Theory and Practice 14*" for the theoretical piece of the analysis and the 2008 paper entitled, "*The Ravina Project – Solar Array Aperture Analysis 21 – Calculating the -3.0 dB Beam Width*", for the practical work to verify our theoretical work.

What do tracking arrays do? They, in essence, virtually increase the efficiency of the panels that make up the array but only in certain circumstances. In cloudy and diffuse sun, panel efficiency rules no matter what their orientation although we have shown that in such conditions laying the array flat increases the power harvest by a very modest 2-4%. The reason for this phenomenon of course is that flat panels look at the whole sky and accept photons from every direction. When tilted, the panels look at neighbouring houses and trees which are not known for emitting useful photons. On sunny or partly sunny days the orientation augments the panel efficiency. To illustrate this point let's use our own data. As we have seen from RETscreen our 17.1% Panasonics arrayed as 10, 280 Watt panels should harvest between 188.0 and 205.1 kWh/m^2/yr if on a fixed array facing south and tilted at latitude. We in fact harvest about 231 kWh/m^2/yr which is 12.6% to 22.9% over expected. The tracking array makes our panels seem like we have a set of fixed panels in the range of 29.7% (17.1+12.6) to 40.0% (17.1+22.9).

So how do we get these numbers? What algorithm do we follow on a daily bases? Everything you need to know is contained in the papers we referenced above. But for sake of brevity the algorithm boils down to this: maximize the area of the shadow cast by the array. From our data and theoretical analysis the size of the shadow is proportional to the virtual size of the array from the sun's point of view. That is, photons hitting the array are traveling in parallel with each other. To maximize the area of the shadow, the array must be oriented in such a way that it intercepts the maximum number of photons. One might think that this analysis is intuitive however, most technology that intimately interacts with electromagnetism does not have such a simple algorithm for maximizing the power of a received signal.

Our array tracks on one axis but there are two axis trackers available. Simple calculations show that they would, at a minimum, provide twice the boost that our array provides. Why not more than that? Well it's because we compensate for nasty azimuths by laying the array flat. When the array is flat the sun's power is determined entirely by the sun's elevation above the horizon. When the sun is 30 degrees above the horizon it falls upon a flat plate with half its power. We have found, in technical terms, that the power roll-off of the sun is proportional to the cosine of the offset angle from Normal (Normal occurring when the sun is directly overhead on a flat panel). Thirty degrees above the horizon means the sun is 60 degrees offset. Cosine 60 degrees is 0.5 or ½. Another reason is the fact that we do compensate for the sun's elevation, that is, our one axis compensation is identical to one of the axes of a two axis tracker. And finally the sun's daily pathway through the sky during the 90 days of winter time are virtually identical with the sun rising already at the half power point caused by azimuth on a fixed array facing south. See the graphic below.

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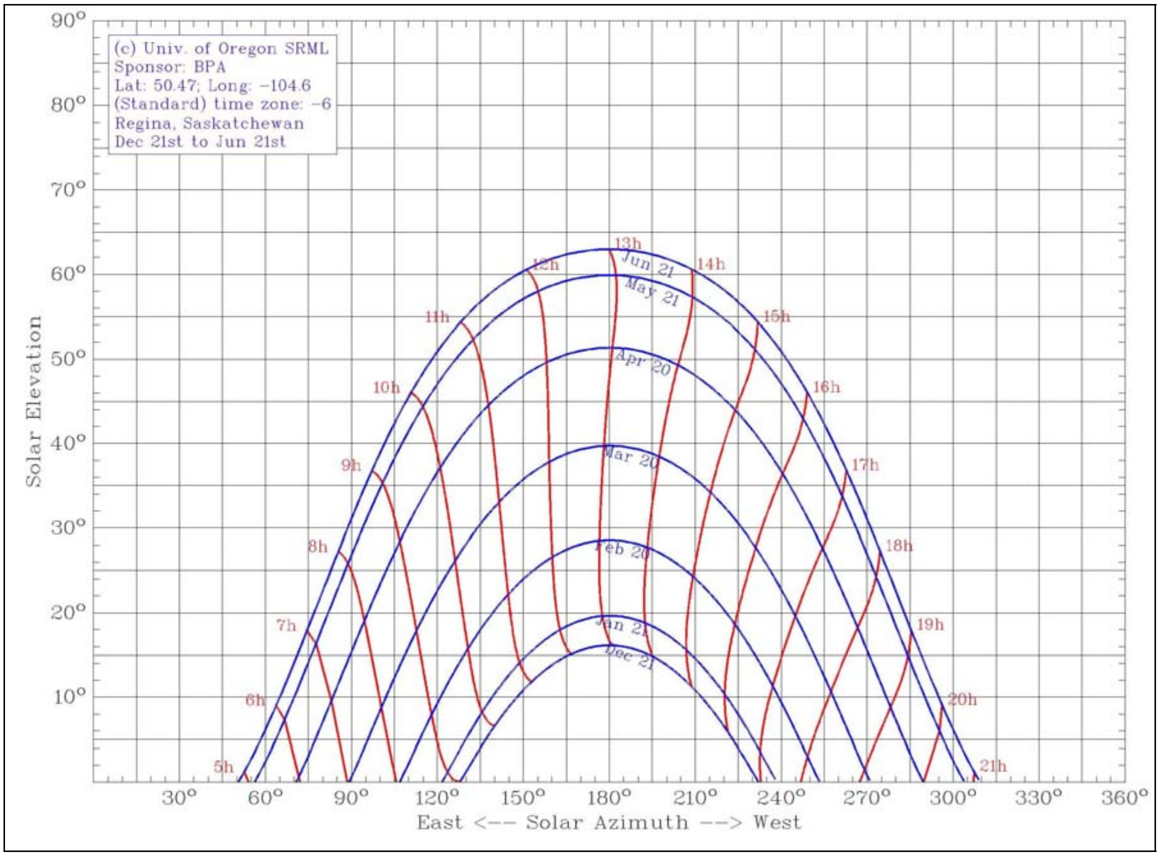
A two axis tracker needs to be in a special location with excellent views of the horizon from the northeast through the south to the northwest. Why northeast and northwest? It's because the sun rises and sets north of the east – west line through the solar array.

The sun chart below demonstrates this phenomenon.

Consider the following sun chart courtesy of the University of Oregon for Regina, Saskatchewan in the heart of the maximum sun energy harvesting potential in Canada as evidenced by the RETscreen map of Canada above. The other 6 months from June through December are a 'mirror image' of these angles and dates.



Along the bottom the sun's azimuth is represented with south at 180 degrees. On the left side the sun's elevation above the horizon is represented in degrees such that zero degrees means the sun's rays are horizontal with the earth's surface and 90 degrees or Normal such that the sun is directly overhead. The blue curved lines represent the sun's pathway through the sky on the dates also in blue. The magenta curved lines represent the local standard time when the sun reaches a particular location in its journey across the sky. As you can see the sun rises and sets north of the east-west line, that is, it rises at an angle on the azimuth less then 90 degrees (directly east) and sets at an azimuth greater than 270 degrees. It has this track through the sky in Regina from March 20th to about September 20th.

Let's double our effective panel efficiency percentage boost calculated from our data to be 12.6 and 22.9 to 25.2 and 45.8 to give our effective panel efficiency of between (17.1+25.2) 42.3 and (17.1+45.8) 62.9. Now you can see why we included panel efficiencies up to 62%. They will get marginally higher as solar PV technology improves but the important part here is to give you, dear reader, a good concept of panel efficiencies, the boost given by sun tracking arrays and their effect upon ERoEI.

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Curtailment

Curtailment occurs with any generator when the energy being produced cannot for some reason be used. This is a brutal situation for those who have invested in solar systems only to be forced to 'throw away' perfectly good energy. There are three situations discussed below where curtailment is an issue. We will discuss each in light of ERoEI. Finally we will look closely at our data to more accurately attempt a calculation of a new ERoEI for us with curtailment taken into account.

Curtailment and Heat

Here in Ontario, Canada the Feed In Tariff program allows the public to invest in solar PV systems up to a maximum of 10 KW. This program is called the Micro-FIT program. The clean energy so produced is purchased by the utility at a premium rate via 20 year contracts. In this way anybody with the means can become a private clean energy entrepreneur.

Note though, that the power purchase agreement between the Micro-FIT generators and the utility specifies that the maximum power output to the Grid must be capped at 10 kW. This does not mean that the size of the solar array is capped at 10 kW. It does mean that the array can be any size but the utility supplied electronics that connect the solar system to the Grid caps the maximum power delivered to the Grid at 10 kW.

On a clear day during the best generation months here at 43 degrees Latitude, the best sun occurs between 10 AM and 2 PM sun (standard) time. Since the best months are also the hottest months, heat plays a role in increasing resistance to current flow inside the panels. By the way the internal temperature of panels can be greater than 50 degrees Centigrade (our measurements) even though their power output specifications are quantified in a lab at an internal temperature of 25 C. So on a hot summertime day with a pristine sun our modern 2.8 kW of 17.1% efficient (at 25 C) panels generate about 2,500 Watts continuously plus or minus 100 Watts. We have more than enough data in our databases to support this claim but presenting it here would be 'overkill' in our view. All that is required for this argument is that on hot summertime days the panels do not produce their peak rated power. Any solar PV user if they look at their production meters on hot, cloudless summer days knows about this fact. For those who are reading this for the first time, your panels are probably working just fine. Resistance to current flow in the hot panels is the problem, actually it's not a problem, it's just physics.

See our paper on solar PV and heat at: www.theravinaproject.org/project_papers.htm titled, "*Ambient Heat and Solar PV Power Output*".

Array Overbuild, Curtailment and ERoEI

So for the micro-FIT contractor with her 10 kW nameplate capacity of solar array installed, the 10 kW limit will be reached with a lower probability each day if it is a hot summertime day rather than a cold late spring day. The heat will take a toll on the power output and that means it will take a toll on her pocketbook. But she has an option to recover her losses. We hear every day that the price per Watt of solar panels is dropping quickly. This trend, praised by many as a great step forward, may have a darker side to it (no pun intended).

Our intrepid solar micro-FIT contractor calculates that additional panels added to her array cost little when compared to the extra revenue generated over 20 years of the micro-FIT contract. She quickly bulks up her 10 kW array to 12 kW … it's sort of a 10 KW array on steroids. So what does this do to her pocketbook? Over the course of a year it means that her 10 kW limit is reached much earlier in the day for each day of good sun. It means that for days of marginal sun she averages much closer or exceeds her 10 kW limit. It means that during the hot summertime days she reaches her 10 kW limit every day on one hand and on the other, she stays there for a long time before the setting sun's azimuth reduces the output.

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All the papers we have read that have attempted to estimate energy returned from solar PV have used averages based upon horizontal irradiance and average panel efficiency. They calculate on a 25 year lifetime while others use a 30 year life span. In all cases they do not account for overbuild as described above or outright panel replacement. And further, parenthetically, few if any of these academic papers rely on years of real generation data. In the papers we have read the energy returned values used seem to us to be unduly inflated.

Let's use our data to demonstrate this overbuild phenomenon. Suppose our micro-FIT is limited to our nameplate capacity of 2,800 Watts. So our cut-off is 2,800 Watts.

Consider the following:

n	736				
Mean	2380.0		Median	2611.5	
95% CI	2315.2	to 2444.9	95.7% CI	2558.0	to 2661.0
SE	33.03				
			Range	3892	
Variance	803187.8		IQR	752.5	
SD	896.2				
95% CI	852.6	to 944.5	Percentile		
			0th	0.0	(minimum)
CV	37.7%		2.5th	220.7	
			25th	2205.5	(1st quartile)
Skewness	-1.15		50th	2611.5	(median)
Kurtosis	0.45		75th	2958.0	(3rd quartile)
			97.5th	3522.0	
Shapiro-Wilk W	0.87		100th	3892.0	(maximum)
p	<0.0001				

This statistical analysis is based upon our database of 736 contiguous days of generation with our 2.8 kW array. The daily datum used is the maximum power recorded by our Outback MX-60 solar charge controller. The daily maximum is one of several daily readings we take. Look at the 50^{th} percentile of 2612 Watts (rounded). Half the time over all these days our 2.8 kilowatt collector never produces our maximum power output. In fact we have to get up to the 75^{th} percentile to get only 158 Watts over our 2,800 Watt micro-FIT cut-off. If we were on the micro-FIT program we'd be losing money … or more correctly we would be leaving money on the table. Solar panels are cheap so let's add another string of two 280 Watt panels to bring our nameplate capacity up to 3,360 Watts. Since we want to make this argument on firm technical ground we must add another whole string of 2 extra panels rather than a partial string because in reality adding a single panel is not technically possible with our existing setup and equipment.

To modify our database we multiply each daily maximum power output by 1.2, that is, we mathematically added another string of panels. We don't see this as a major flaw in statistical analysis because the readings are daily maximum readings. Adding more panels is a linear activity, that is, the extra panels will behave exactly in the same way as the currently installed panels.

Consider the data from our 'modified' database below.

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n	736					
Mean	2856.1		Median	3133.8		
95% CI	2778.2	to 2933.9	95.7% CI	3069.6	to 3193.2	
SE	39.64					
			Range	4670		
Variance	1156590.4		IQR	903.0		
SD	1075.4					
95% CI	1023.2	to 1133.4	Percentile			
			0th	0.0	(minimum)	
CV	37.7%		2.5th	264.9		
			25th	2646.6	(1st quartile)	
Skewness	-1.15		50th	3133.8	(median)	
Kurtosis	0.45		75th	3549.6	(3rd quartile)	
			97.5th	4226.4		
Shapiro-Wilk W	0.87		100th	4670.4	(maximum)	
p	<0.0001					

The 50th percentile is now 3134 Watts and the 25th percentile is essentially the same power as the Median using the original array size. Note the Mean now is over 2,800 Watts.

This exercise demonstrates two pocketbook advantages of overbuild as mentioned above. Firstly, we see that the 25th percentile is very close to the cut-off Wattage. It is very probable that for 70% of the 736 days in the sample, we will reach our micro-FIT cut-off. Each day as the sun rises in the best 6 months of generation the power limit will be reached earlier and remain at the maximum until later in the day. Secondly, considering this sample data is recorded across all sky/generation conditions, even days which have marginal opportunities for generation at the original array size will get close to or achieve the cut off Wattage.

The pocket book is maximized but how about the ERoEI calculation for these panels? Clearly there will be substantial curtailment with almost 75% of the days at or above the cut-off limit. In fact the Mean's 95% CI tells us that it is highly likely that the average day will provoke curtailment. The energy returned for this array drops even lower than our calculations above.

Commercial PV Power Plants, Curtailment and ERoEI

Let's examine the case of outright panel replacement when the generator is a large scale solar PV power plant with a formal Power Purchase Agreement (PPA) with the local utility. Overbuild will be maxed out again because the extra panels are cheap given the cash flow and length of contract. However, there is another factor that comes into play that does not affect the micro-FIT generator … panel upgrades. The micro-FIT contractor can't increase her panel efficiency by 30-50% like we did going from 12.5% panels to 17.1%, an increase of 38%. It's not worth while because she still has the 10 kW limit. However, large generators can change their PPA with the utility all else being equal or alternatively, use panel upgrades as a form of overbuild. So for them, like us, being able to increase generation after 10 years by gradually replacing panels with ones able to generate about 40% more is a no-brainer. The old panels are not stored like ours but are sent to waste/re-cycling. They will not be sold. There is no second hand market for panels from what we can tell. Why? It's because buyers want panels that are much more efficient, that have no 'mileage' on them and that are about the same price as used ones.

So the bottom line for this discussion of curtailment, there is an important difference between the academic treatment of Energy Returned and the real world return. In the real world the dropping

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price per Watt of solar PV and dramatic increase in solar PV efficiency per square meter of surface area means that few panels currently part of large commercial solar PV power plants may not survive even half their 'useful' lifetimes without being replaced. These two forces cripple the ERoEI of the original solar panels … and in our case since we replaced after 7 years panels that have a projected lifetime of 25 years, our pitiful ERoEI ratios are dropped by a factor of 3.6. That is, our initial panels have a negative ERoEI which means we, as a society would be better off, have had more energy available, if those panels did not exist.

On a grander scale this idea of negative ERoEI creeping into our solar PV generation infrastructure is astounding and concerning. We do not want to drown in hyperbole here but the current industrial use solar PV may be a huge mistake for everyone and especially for world decarbonization.

Off-Grid Curtailment and ERoEI

We are not off-grid. But we have all the off-grid components required to be off-grid. And we could be off-grid for most of this last summer with the help of our tri-fuel 2.8 kW Yamaha generator.

So what's our setup? We have 2.8 kW of 17.1% efficient mono solar PV in five strings of two 280 Watt panels mounted on a 'home brew' one-axis, programmable, sun tracking support structure pointed at 150 degrees azimuth. See it in operation with our initial set of 12.5% (1,500 W) panels at: www.theravinaproject.org/movies.htm . The power is delivered to an Outback MX-60 (60 amp) solar charge controller which charges 8 series-connected Trojan L16E-AC 6 Volt flooded deep cycle lead acid batteries each with a 20-hour rate of 370 Amp-Hours for a combined total of about 17 kWh of storage. We can use about 14 kWh of this total. Using more would damage the battery. The inverter is a Xantrex 4048 drawing on the 48 Volt DC bus at all times to provide uninterruptible power to a secondary distribution panel which services all household circuits we never want to fail because of Grid outages. This technology overlaps with the 'household resilience' part of The Ravina Project. The Xantrex floats the battery at a temperature compensated voltage according to Trojan specifications when Grid connected and further, it is programmed to send back to the Grid any excess power that becomes available. Typically the house uses between 10 and 15 kWh per day and during the non-winter daytime may average a pull of 500 Watts at most from the battery. The array, with any kind of diffuse sun available generates at least 1,500 W. As you can see the power difference is substantial and must be dealt with. The Xantrex activates its bi-directional circuit to the Grid and sends the excess to the grid through our bi-directional, utility owned and read, meter. The meter has two running totals we read every day, one for energy used from the Grid and the other for energy exported.

From our Utility statement from July 31 to August 31, 2016 the following totals were included:

kWh used: 267.7
kWh generated: 222.0 (pushed back to the Grid)
Net kWh: 36

So there you have it … all the technical details. Anyone familiar with off-Grid living knows the functions of all the equipment mentioned and may even own and use the very devices we have here. Xantrex and Outback are well known, established brands.

Now for an off-grid curtailment discussion.

Our bi-directional meter provides us, at sun down, with a convenient measure of the total amount of energy we have sent back to the Grid … energy we cannot use because our house is drawing little energy from the battery and the amount of generated energy covers off floating the battery. The Grid is, in technical terms, our load of last resort. What's pertinent to our discussion is that IF we were off-Grid the energy we currently send back to the Grid would be lost. That energy is our curtailed energy.

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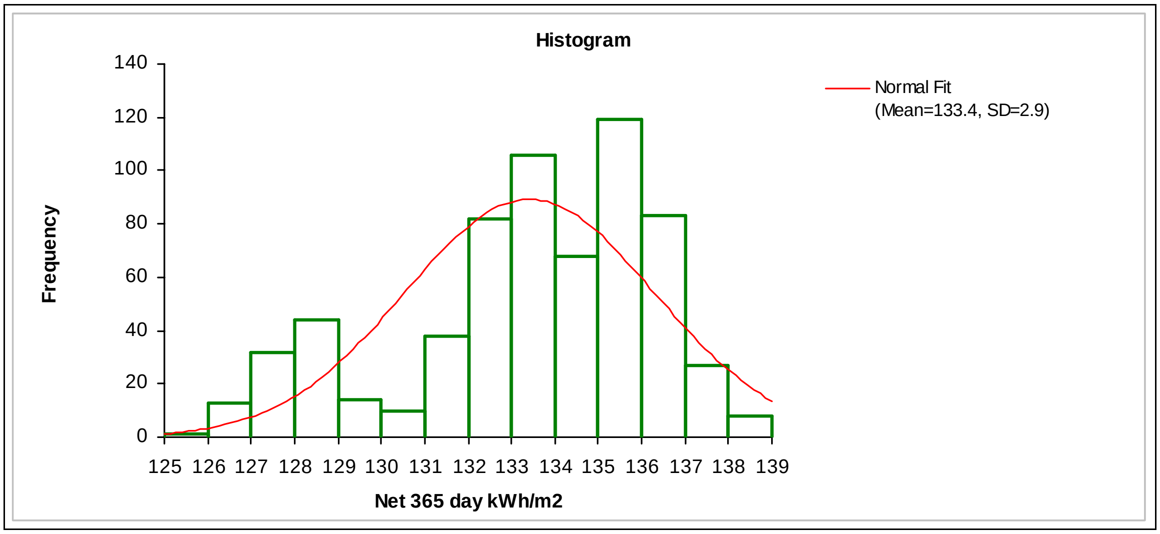
What would be our off-Grid 365 day kWh/m^2 generation amount? It is the daily generation minus the amount sent to the grid totaled over the last 365 days and divided by our array area in square meters (16).

If we were off-Grid the following would be our daily generation statistics. Note we are using the same data we used above to calculate our Energy Returned number.



Like the charts above, these data are closely grouped around the Mean.

n	645				
Mean	133.41		Median	133.70	
95% CI	133.19	to 133.64	95.1% CI	133.51	to 134.11
SE	0.113				
			Range	12.6	
Variance	8.31		IQR	3.50	
SD	2.88				
95% CI	2.73	to 3.05	Percentile		
			0th	125.93	(minimum)
CV	2.2%		2.5th	127.17	
			25th	132.19	(1st quartile)
Skewness	-0.74		50th	133.70	(median)
Kurtosis	-0.25		75th	135.69	(3rd quartile)
			97.5th	137.72	
Shapiro-Wilk W	0.93		100th	138.58	(maximum)
p	<0.0001				

The reader will observe that we are exporting energy as 120V AC but generating, storing and accessing it as DC energy. Our Xantrex converts DC energy to AC energy at about a 96% efficiency. To put it another way, the energy reported as curtailed is metered AC energy and represents a slightly larger DC energy total. The slight difference is conversion loss. For this argument we will ignore it.

As above we will use the stats package to discover our Mean daily net generation over the same period of 645 contiguous daily calculations. We will take the crunched 365 day value of 133.4 kWh/m^2 as our generation if we were off-Grid.

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Over 25 years of life our panels will return 25 x 133.4 = 3,335.0 kWh/m^2 and not the 5,776.5 as we calculated initially. Below we will re-do our calculations using **3,335.0 kWh/m^2/yr**.

Off-Grid ERoEI Calculation

Let's execute the same calculations as above.

Bhandari et al

Using the Mean value for energy invested from the Bhandari et al paper of 1,729 kWh/m^2 our off-Grid ERoEI becomes 3,335.0/1,729 = **1.93**.

Ferroni & Hopkirk

Using the energy invested number from Ferroni & Hopkirk of 2,664 kWh/m^2 we calculate our off-Grid ERoEI as: 3,335.0/2664 = **1.25**.

These are brutal numbers.

And it's worse than these numbers. This energy never gets back to the Grid, no Energy Returned to society … the ERoEI ratio becomes zero which means society provides the energy to: mine, refine, manufacture, assemble, transport, install, maintain and ultimately re-cycle the panels plus the energy used to create the racking, wiring, and electronics, but gets zero energy back from the panels.

Off-Grid Comments

We understand both the romance and necessity of living off-Grid. It is perceived as an exceedingly low carbon lifestyle but so is an all-electric household fed by a carbon free Grid. From a total energy investment in solar PV by a society, off-Grid living using solar has a very high probability of being a total waste of time, energy and resources. Actually we can say this for any generator that has consumed Grid energy resources and is used for its generation lifetime in an off-Grid application.

A micro-Grid if it is perpetually off-Grid is of the same ilk. We do not have a lot of data about the thermodynamics of isolated micro-Grids but really we don't need to analyze their data. Why? Because they have the same energy use paradigm as an off-grid generator even though a micro-Grid is more complex and uses much more non-energy producing equipment. All the components of a micro-Grid are manufactured by society at large using energy generated by society. But as with any other isolated generator, none of the energy produced by the micro-Grid returns to society to provide a value for the Energy Returned part of the ERoEI ratio. Self contained micro-Grids are energy throwaways. However, that's not to say that society as a whole can't tolerate micro-Grids because that would lead to other problems. There may be no other way for communities to power themselves without micro-Grids, allowing these communities to participate in modernity with all its associated advantages.

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Conclusions

Needless to say we were shocked by the above calculations. It's not that we are bit below sustainability so that with more efficient panels we can make the ERoEI cut off, we are very much below ERoEI sustainability.

When we view our data using our horizontal irradiance of 1,300 kWh/m^2/yr and calculate the irradiance required to push us over the 5:1 or 8:1 ratio we see that only one value is realistic, that is, a value that is compatible with only a minority of places on the earth's surface.

This paper highlights the absolute necessity of understanding the energy accounting of solar PV. It is our view that we are drowning in energy returned data. Hence then, it is vital that we understand exactly what constitutes items that contribute to energy investment and for each the value they bring to the total. Our energy investments in solar PV may be negative such that the total energy available increases if they are never made in the first place. Such a situation in this time of AGW crisis would be, in our view, highly counterproductive and may even contribute to a tipping point against humanity in the worst case.

This paper if it does nothing else should give those, who fully support a wind, water and solar solution to our greenhouse gas emissions, a pause for thought or at least a forced examination of their assumptions about the value of solar PV from an energy returned on energy invested perspective. Their assumptions could be wrong in a dramatic way. That means of course that there are real doubts any huge energy investment into solar PV will ever return a useful amount of clean energy to drive our civilizations. This is a critical idea because that same energy can be invested in other forms of clean energy return like: wind, hydro, geothermal and the latest nuclear power technology (Molten Salt Reactors and Small Modular Reactors are in R&D at this time of writing) which have approximate ERoEI ratios of 16, 100, 35 and 1000 (estimated for Gen IV nuclear power plants).

Renewable energy policy makers must now accept that there is at least a probability that energy invested into solar PV in the majority of locations is a waste of time and energy because the solar PV is stationary, that is, their mounts are not dynamic, they can't move in any way in relation to sun ray angles. This paper through calculations meant to illustrate other points made in the paper, has made the huge unintentional point that sun tracking racking of some sort allows for large and significant gains in solar PV effective efficiency. It could be that the only way to produce very positively sustainable solar PV ERoEI, the highest efficiency panels should be used in the best locations in the world mounted on 2 axis trackers.

One may argue that to fabricate solar PV in a clean and green way, one should construct a manufacturing facility that is energized totally from a solar PV powered micro-Grid. However, to truly use the potential of solar PV it must be mated with new battery technologies that will allow for 24 hour use of solar PV energy either directly from the sun or indirectly from battery storage. The awful fact is that batteries are not an energy source, that is, they do not add to the energy returned part of the ERoEI ratio. They add to the energy invested part of the ratio thereby decreasing the magnitude of the ERoEI. And the depressing part of this analysis is that any type of battery no matter how efficiently it stores energy and no matter how cheaply it can be manufactured, any battery added to solar PV drives down an already pitifully poor ERoEI.

And finally, there are applications that use the strengths of solar PV and that are not sensitive to small ERoEI, for instance, applications where a small energy harvester that's virtually indestructible is the optimum solution. And further, when getting power into remote areas is either too expensive or just impossible, a properly scaled battery, wind turbine, solar PV, charge controller and inverter powering a micro-Grid driving high efficiency loads may be the optimal power plant solution.

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Appendix

For those who would like to crunch our generation and curtailment data, please follow this link to our WEB site and download our .CSV file into your Excel spreadsheet and have fun!

The data is located at: www.theravinaproject.org/raw_data.htm .

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

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