The Ravina Project

Solar PV Sustainability

An Examination of Energy Returned on Energy Invested in Monocrystalline PV

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An Introduction to The Ravina Project

The Ravina Project, conceived in late spring 2006 and up and running in November of that year is a household-focused engineering science project. We are collecting high fidelity data and writing formal papers on such topics as: household cooling and heating efficiencies, solar PV efficiencies versus ambient heat and sun angles, solar PV Capacity Factor, the invention and use of a new solar PV efficiency standard, household resiliency, household thermodynamics, and how 'livable' a lower carbon emission lifestyle can be, among other things.

Our high fidelity databases are large and growing, totaling over 100,000 pieces of data. They allow us to validate or falsify various speculative hypotheses. They also allow us to anchor our published papers in data rich analysis. Some papers rely upon the analysis of several thousands of observations.

Our programmable dynamic solar array structure is unique. It is specifically designed to enable the collecting surface to tilt and compensate for the sun's altitude in the sky on an hourly basis. This ability is critical here at 43.7 degrees latitude where for about 90 days a year, the sun does not get above 30 degrees in altitude above the horizon at noon, sun time. As a bonus the dynamic array produces observations which allow us to calculate a solar array's aperture. For those areas outside the Tropics, the calculations we have made help us define the best algorithms for low cost, simple, hand operated 2-axis sun tracking systems which lose little in potential harvested energy due to poor sun angles upon the collecting surface.

In addition to the science and data gathering, The Ravina Project is conceived and built as a prototype upgrade to an existing and very common housing type in the Greater Toronto Area. We are testing the integration of various sub-systems over an extended number of years to determine their compatibility both with each other and with the people, plants and pets making up the household. Our modified 1920s era house allows us to empirically test out our resiliency, especially Grid resiliency, as real world disruptive events occur. We understand that technology is changing and the particular technologies we are using to provide resilience will be obsolete in future years. However, we see the resilience functionality we have created being incorporated into future technologies which will be more powerful, compact and probably cheaper in real dollars to adopt. It is our view that future events will create market demand to the extent that Grid resilience is either designed into new houses or provided as an upgrade package to current householders at much lower cost than a new bathroom. Refurbished and reconfigured used electric automobile batteries may provide a key piece among the technologies included in the future Grid resilience packages available to householders.

We envision a future in which the availability of electrical Grid power and carbon based fuels will be, of necessity, much lower than today. Due to growing climate disruption/global warming, residential Grid power supply may become intermittent on a regular basis as it is today in many parts of the Second and Third Worlds. When resiliency to Grid interruptions are built into housing infrastructure, such interruptions will not be as catastrophic as they would be in present day First World neighbourhoods. On a city wide level household Grid resilience allows utilities to build smaller scaled, lower carbon, centralized power supplies because they have the option of disconnecting whole neighbourhoods during peak power demand.

We understand that reducing a household's carbon footprint is vital to reducing overall atmospheric carbon release. We are looking closely at our attitudes and lifestyle for insights into such areas as: household carbon accounting, using software rather than hardware defined devices, carbon based functional analysis of both the technology we employ and the consumer products we purchase. These changes are our attempt to modify our attitudes and desires so that we may decouple ourselves from the current and prevalent consumption based modernity. However, we also know that high technology, applied correctly, will allow for this decoupling on a massive scale.

As the changed lifestyle part of the experiment unfolds today, it becomes apparent we are living a future lifestyle in an old house modified for tomorrow.

All our data and papers are published on our WEB site at: www.theravinaproject.org

Regards,

Susan and Gordon Fraser
Directors

The Ravina Project

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 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 paper 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**.

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).

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.

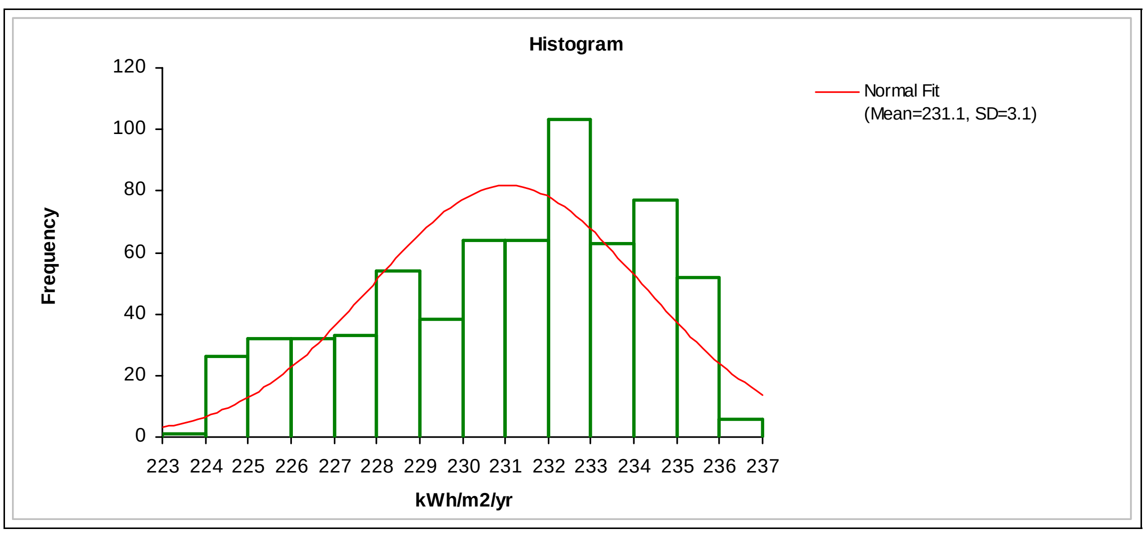
> In order to understand the amount of energy in a kWh the following example will be helpful. A megajoule (MJ) is equal to the approximate kinetic energy of a one megagram (one metric tonne, 2,200 pound) vehicle traveling at 160 km/h (100 mph). A kilowatt-hour (kWh) has 3.6 times more energy in it. Expressed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

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 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%**.

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**.

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.

Using Ferroni & Hopkirk the minimum energy returned to be sustainable will be 5 x 2664 / 25 = **532.8 kWh/m^2/yr** and 8 x 2664 / 25 = **852.5 kWh/m^2/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 1,300 kWh/m^2 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/m^2/yr with an irradiance of 1,300 kWh/m^2/yr which is a ratio of 230/1300= 0.1769. This number is interesting because our panels are 17.1% efficient. The astute 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/m^2/yr and an ERoEI of 5, we need a horizontal irradiance of 345.8/230x1300 = **2,005 kWh/m^2/yr**. For an ERoEI of 8 we need **3,127 kWh/m^2/yr**. Using Ferroni & Hopkirk to get 532.8 kWh/m^2/yr and an ERoEI of 5, we will need an irradiance of **3,011 kWh/m^2/yr** and to get an ERoEI of 8 we will need an irradiance of **4,818 kWh/m^2/yr**.

Except for the horizontal irradiance of about 2000 the other values seem rather high and are most probably extraterrestrial.

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. Even if the two energy invested amounts are way off the mark, that is, have values too large by a huge 25%, we would still be below the sustainability cut off.

When we view our data using our horizontal irradiance of 1,300 and calculate the irradiance required to push us over the 5 or 8 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.

As we have argued in another paper years ago, we see solar PV as a boutique / niche player among the clean energy harvesters. Large industrial sized arrays and large rollouts of rooftop solar may not be ERoEI sustainable.

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 (in R&D at this time of writing) which have approximate ERoEI ratios of 16, 100, 35 and 2000 (estimated).

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.

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 solar PV energy. 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 which is a bane of large rollouts of solar PV on rooftops and in solar PV fields. There are many applications where a small energy harvester that's virtually indestructible is the optimum solution. When getting power into remote areas is either too expensive or just impossible, a battery, solar PV, solar charge controller/inverter combination is the optimal solution in most circumstances. Other viable applications include some we are actively working on here at The Ravina Project which use solar PV as a 'trickle' charge for a small but powerful household backup power supply.

Appendix

For those who would like to crunch our 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 .

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

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Friends of the Ravina Project

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Reader's Notes and Calculations