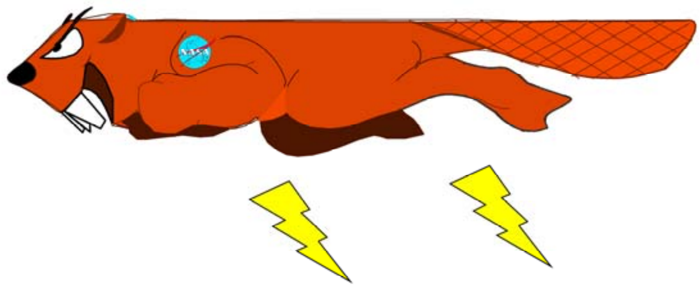
One Engineer's Experience

with a Home Photovoltaic (PV) Array Installation



By Glenn Bever
gbever@roadrunner.com

05-Oct-2010

Outline

- Most common questions
- Definitions
- Why did I build it (requirements)?
- What does it look like?
  - –Pictures
  - –system specs
  - –system construction
- Electric rates
- Performance and Data
- Inverter manufacturers and installers
- Tracking
- Summary

Most Common Questions

- How much did it cost?
- What’s the payback?
- What kind of rebates or tax credits do you get?
- Where can I get some information?
- Is it worth it?
- Would you do it again?

How much did it cost?

System 1 Actual cost (2.7 KW):

```
$20453.79 Initial cost
-$7270.40 State rebate
-$1007.00 tax credit
```

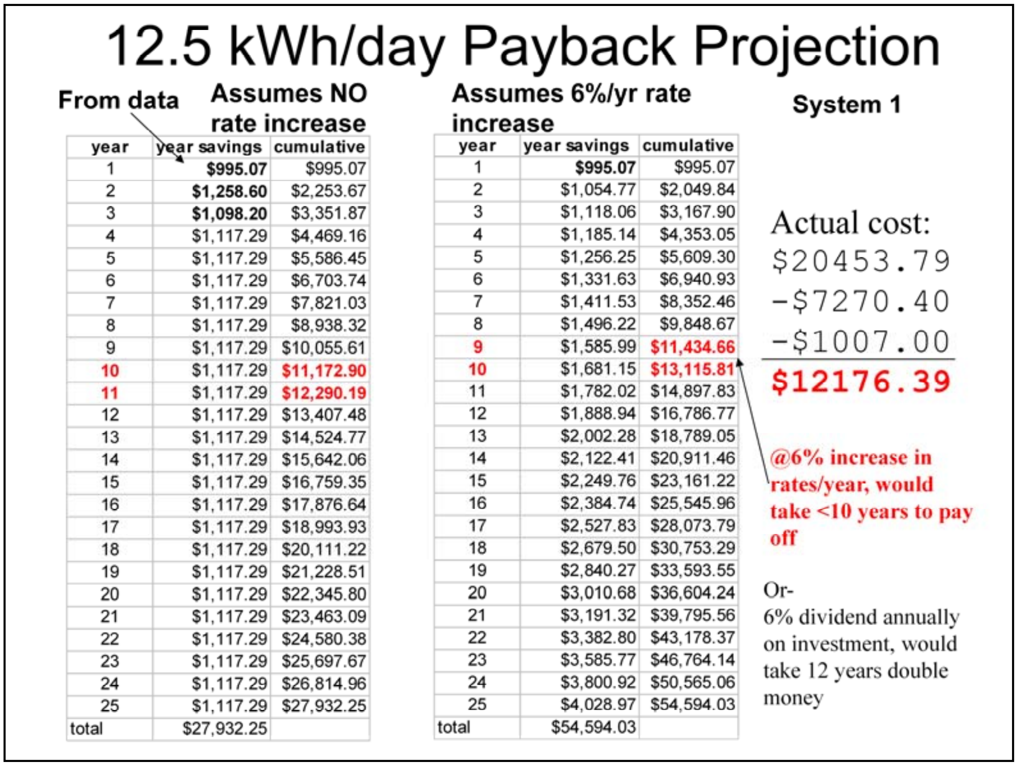
$12176.39 net cost (in 2004)

System 2 Actual cost (3.0 KW):

```
$21637.48 Initial cost
-$3800    State rebate
-$5300    tax credit
```

$12486.24 net cost (in 2010)

Let's hop right to it. How much did it cost? There was the initial outlay, and then later tax credits and possibly rebates enter into it. Installers will typically file for the rebates (with State or power companies). You must file your own energy tax credit.



12.5 kWh/day Payback Projection

year	year savings	cumulative
1	**$995.07**	$995.07
2	**$1,258.60**	$2,253.67
3	**$1,098.20**	$3,351.87
4	$1,117.29	$4,469.16
5	$1,117.29	$5,586.45
6	$1,117.29	$6,703.74
7	$1,117.29	$7,821.03
8	$1,117.29	$8,938.32
9	$1,117.29	$10,055.61
10	$1,117.29	$11,172.90
11	$1,117.29	$12,290.19
12	$1,117.29	$13,407.48
13	$1,117.29	$14,524.77
14	$1,117.29	$15,642.06
15	$1,117.29	$16,759.35
16	$1,117.29	$17,876.64
17	$1,117.29	$18,993.93
18	$1,117.29	$20,111.22
19	$1,117.29	$21,228.51
20	$1,117.29	$22,345.80
21	$1,117.29	$23,463.09
22	$1,117.29	$24,580.38
23	$1,117.29	$25,697.67
24	$1,117.29	$26,814.96
25	$1,117.29	$27,932.25
total	$27,932.25	

year	year savings	cumulative
1	**$995.07**	$995.07
2	$1,054.77	$2,049.84
3	$1,118.06	$3,167.90
4	$1,185.14	$4,353.05
5	$1,256.25	$5,609.30
6	$1,331.63	$6,940.93
7	$1,411.53	$8,352.46
8	$1,496.22	$9,848.67
9	$1,585.99	$11,434.66
10	$1,681.15	$13,115.81
11	$1,782.02	$14,897.83
12	$1,888.94	$16,786.77
13	$2,002.28	$18,789.05
14	$2,122.41	$20,911.46
15	$2,249.76	$23,161.22
16	$2,384.74	$25,545.96
17	$2,527.83	$28,073.79
18	$2,679.50	$30,753.29
19	$2,840.27	$33,593.55
20	$3,010.68	$36,604.24
21	$3,191.32	$39,795.56
22	$3,382.80	$43,178.37
23	$3,585.77	$46,764.14
24	$3,800.92	$50,565.06
25	$4,028.97	$54,594.03
total	$54,594.03	

Using my rate spreadsheet, I went back through every month of three years and calculated exactly how much money I saved by having a PV array power generation system. I did this by adding the energy generated to the energy consumed from SCE and then plugging that number into the spreadsheet as the energy used (this gives me the amount of energy I would have used from SCE had I not had the PV array system). Then taking the difference between those two cost numbers is the savings for that month. Adding that savings up for the first three years yielded the 'year savings' numbers shown in the first three years of the left chart ($995.07, $1258.60, $1098.20). These represent actual savings.

For years 4-25 in the left chart, I averaged these three numbers and replicated it. Given that it cost me $12176.39 for the array installation, it would take between 10 and 11 years to 'pay back.' After 25 years of operation (the warranty period for the PV panels) the amount of energy produced (that I wouldn't be paying SCE for) is about $28000—which is more than twice the system cost.

The right chart, I took the actual data for the first year only, and then assumed a 6%/year increase in energy cost (which is a fairly standard projection). You can see that over the first three years the projection compares favorably with actual data. Continuing this for 25 years, the payback moves up to between 9 and 10 years and the total savings is over $54000—over 4 *times* the original investment. Either way, from a purely money point of view, the money has not been invested foolishly.

Note that if you invested the system cost in something that gave you a 6%/year return, it would take 12 years to double your money.

Payback Criteria

- According to the Appraisal Institute, **the value of the home is increased by $20,000 for every $1000 electricity produced per year**, equating to $15,000 to $23,000 increased home value with my system (remember I paid about $12k after rebates).
- For an 18-panel (150W/panel) system, generating on the average 12.5 kWh/day yielded a savings of about $1117/year [from data—average of 1st three years. This equates to ($1117/yr)/(12.5 kWh/day) / 365 days/yr) = $0.25/kWh]
- Electricity rates have been increasing at 6% per year
- At this rate, during the 25-year power warranty of the solar modules, the array would produce up to $54,000 worth of electricity.
- CA is looking at low interest loans paid via property tax bill
- Another case study of payback:
  - http://www.empire-solar.com/system_case_study.html

There are other ways to figure payback. Just using the Real Estate Appraisal Institute's guidelines, in theory you could sell your house the day after you built the system and still make money on the system—without ever generating any power.

The numbers in the second bullet are derived from the previous chart ($1117) and previous slides (12.5 kWh/day average energy generation).

Some cities in CA are experimenting with allowing a PV system cost to be billed as part of the property tax as a mechanism of granting a low interest loan to fund the construction. When the house is sold, the new owner simply takes over the loan as part of their property tax payment. The state is looking into making this a state-wide option.

The URL points to another way of computing payback.

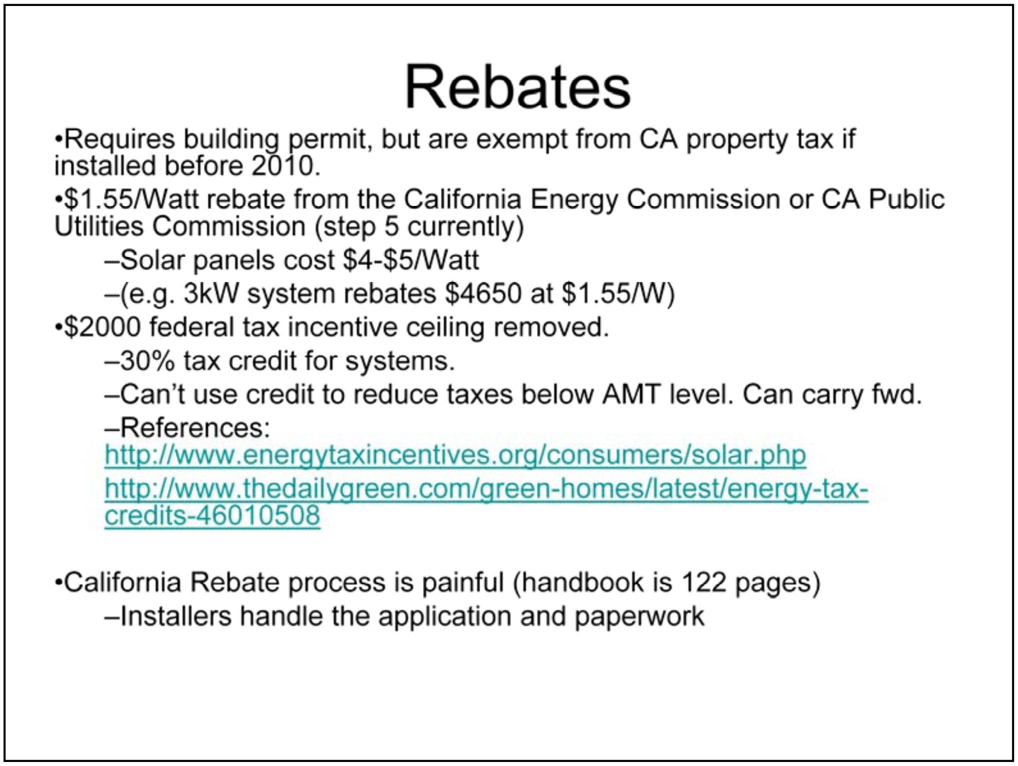
There are any number of ways to calculate payback, but the point is that you are 'buying' energy up front rather than 'renting' it from the power company—at increasingly high rates.

Other Kinds of Payback

- Buying a car is a depreciating experience
- Buying a PV system starts paying you back and appreciates your home value
- It's a hobby that pays back
- It's green
- It helps stimulate the alternative energy market.

Here are some other ways to look at 'justifying' the cost: buying a car—unless you buy a classic—is a pay-for-use fee. The car depreciates. Over the 'payback' period the car loses value. The car wears out—then you buy another car. A PV array actually *increases* value by paying you back for its use.

Not to be lost in all this is that you are generating 'green' power. You are taking steps to decrease pollution and thereby contributing less to global climate change. Further, the more interest there is in purchasing such technology, the more the industry will be stimulated which should improve the technology and options as well as lower the costs of equipment.



Rebates are a continually changing landscape. Most current rebates and tax credits have some kind of sunset clause—either by date or by goal. I don't know what is going to happen next. More incentives could be forthcoming or less—but the trend seems to be less. The rebates available from the State of California are $1/Watt *less* than they were three years ago and will continue to decline (next chart) as solar power generation goals are met.

The federal tax incentive was scheduled to disappear at the end of 2008—but were actually expanded as part of the Patriot Act.

Further, the rebate process is fairly painful. If you don't do this all the time (and we don't) it is a steep learning curve. Installers routinely deal with this and can remove that burden from you.

Is it Worth It?

- Yes, I would do it again—I just did!
- We now generate 2/3 of what we consume
  - –Cost savings disproportionate to amount generated due to tier system (first 1/3 generated saved ½)
- Payback is likely to be 9.5 years
- There are considerations other than payback time—green power, resale value
- I would consider changing a few things
  - –Provision for battery backup
  - –Build in data logging at the beginning

My first system was contracted to an installer. I participated in the design and installation, but they handled the paperwork and construction.

My second system I designed and constructed by myself—and included battery backup capability.

Tracking the Sun

•You get 50% more power out of a 1-Axis tracked system than with a fixed array.

•A 2-axis tracked system has only marginal improvement over a 1-axis tracked system.

•A fixed array costs about the same as a 1-Axis tracked system but without the mechanical complexity.

A single-axis track system tracks the sun from east to west each day (azimuth). It does not track seasonal changes in the sun's track elevation angle.

A 2-axis track system tracks the elevation angle as well as the azimuth.

After assessing the performance of each type of system, there is a very small difference between the 2- and single-axis systems. A fixed array costs about the same as an equivalently performing single-axis system, but without the added complexity of the single-axis system.

Types of PV systems

- **Grid-tie**
  - –Use Electric Company as 'battery.' Spin meter backwards.
  - –Cannot generate electricity when power grid is down
  - –Possible electric power company rebates.
- **Off-grid battery backed up**
  - –No connection to power company—you are on your own
  - –No rebates from electric power company.
- **Hybrid grid-tie with battery back up**
  - –Tied to power company, but can generate power with grid down.
  - –Inputs for generator and/or wind generation
  - –Best of both worlds, but most expensive

The reasons the grid-tie system cannot operate when the grid is down are:

1. Your system would be trying to supply power to the rest of your neighborhood.
2. The inverter must synchronize to an existing 60 Hz power before it can operate.
3. The power company linemen do not want to encounter a live feed where they were expecting a dead system.

There is a cutoff switch that linemen can turn off to deal with #3 (required on your system) and the power company knows that you are a power provider. The hybrid systems generally have dedicated output lines that draw power either from the power company or your battery (like an UPS would do). These are not fed back into the grid and usually you would only put critical systems on those circuits, e.g.: refrigerators, freezers, heart and lung machines…

My Requirements

- Grid-tie (use grid as ‘storage’ when supplying more than using)
- Generate 'green' power.
- Lower monthly electric bills by consuming grid power at closer to baseline rates.
- Track system power generation.

Optionally:

- Produce power when grid is down
- Allow for expansion
- Measure system parameters automatically

These were my requirements for my first system. When I built the second system I did include battery backup.

18-Panel PV Array (System 1)

This is a picture of the panels being installed on the completed frame. I had it constructed concurrently with building the in-ground swimming pool and the structure doubles as a shade by the pool. There are gaps between the panels so that the wind loading is less. I.e., it won't generate lift.

Completed 18-Panel PV Array

DSC08402

Here is a complete array, showing the panels. (Photo facing west). Note the shadow of the array. The picture was taken about mid-day about one month before summer solstice. This configuration operates at peak efficiency in the Spring and Fall due to its orientation, angle, and temperature.

Completed 18-Panel PV Array

DSC09569

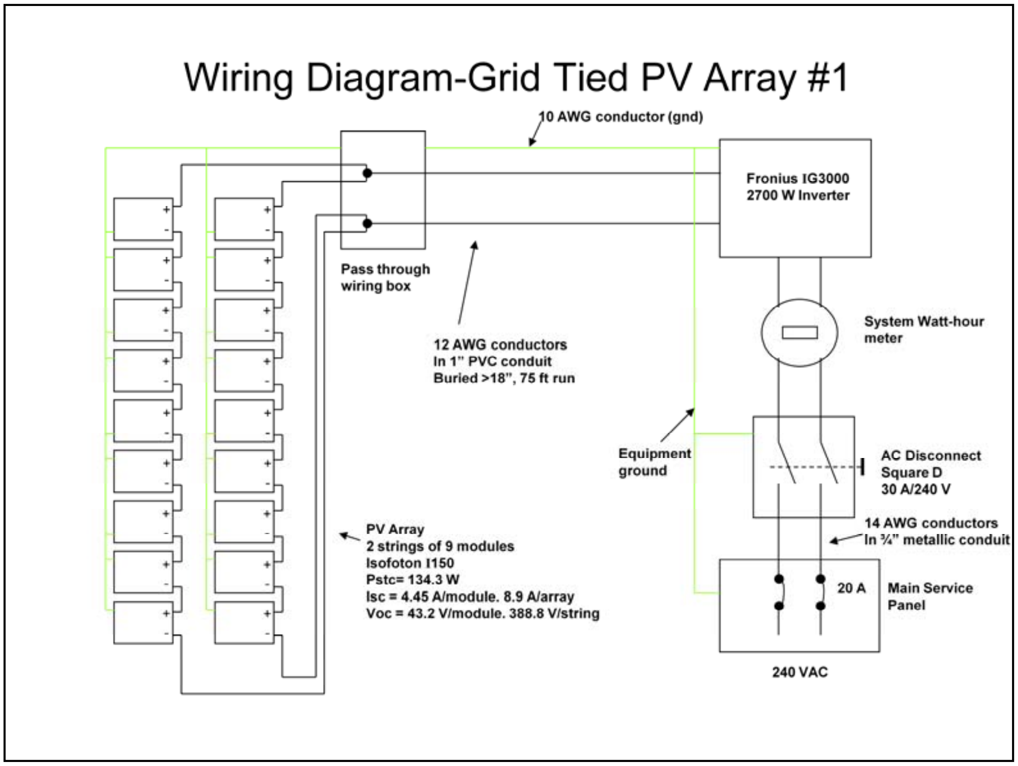
Another picture with a little more context of the surroundings. The array is 5 feet from the wall and 5 feet from the pool per city code.

Note the patio cover on the left. That is where the second PV array system will be installed (subsequent to this picture being taken).

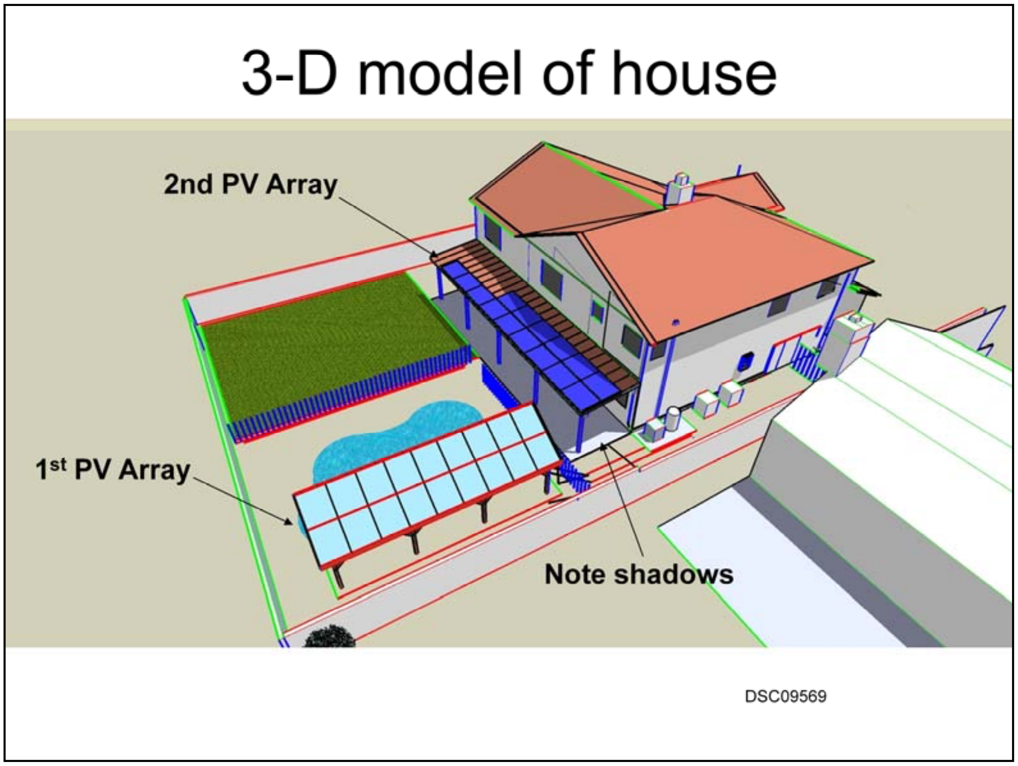
My Specs—System 1

- 18 solar panels, 150W max each
  - (Isofoton I150/24)
- 30 deg angle from horizontal
- Net metering
- Ave 6 'full sun' hours/day
- 150 W panels * 18 = 2700 W max
- Voc=43.2V/module
  43.2Voc/module * 9 modules/string=388.8Voc/string
- 2 strings in parallel
- Isc= 4.45 A/string.   2 strings = 8.9 A/system
- 3000 W inverter (Fronius IG3000)

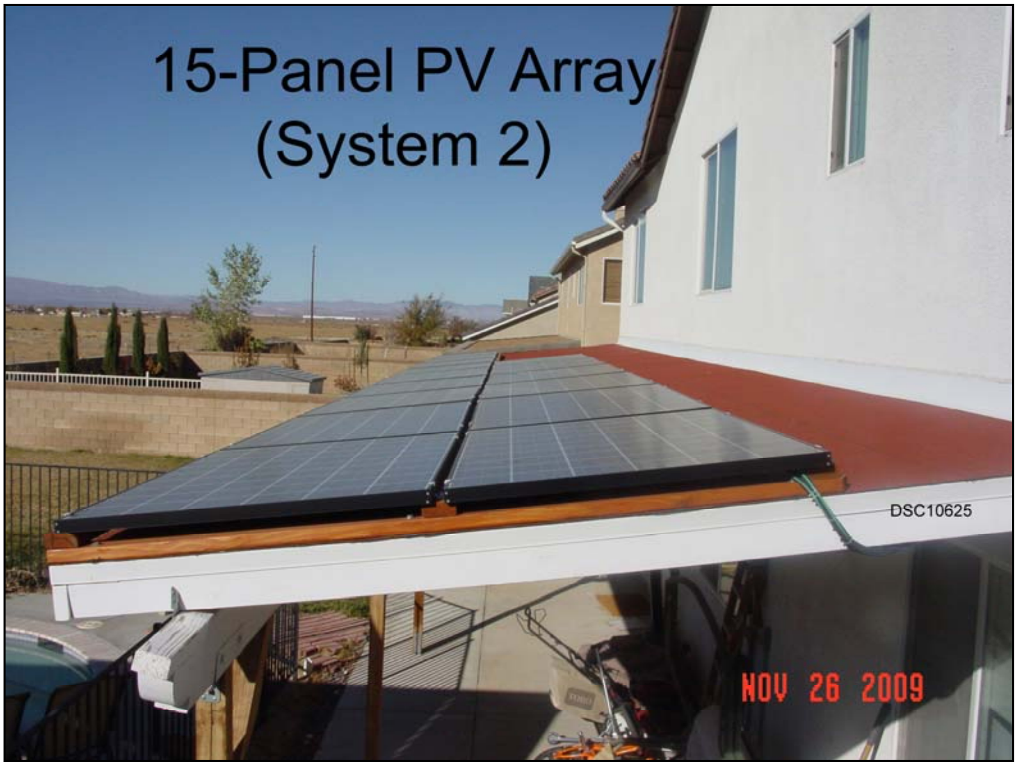
Panels are each 3.5 ft x 4 ft = 14 ft2. So 18 panels is 14 ft2 x 18 = 252 ft2.



This is a schematic diagram of my first system. It is really very simple. Two serial strings of PV panels attached in parallel. The cells all have reverse polarity diode protection, which makes this attachment type possible. Note the disconnect switch, which the power company has access to. The breakers are in the standard breaker panel—it's just that the power flows backwards from the way we are used to thinking.



This is a 3D model that I created of the house and property using Google Sketchup. It shows the relation between the two PV array systems. Note the shade being cast on the 2nd PV array. Sketchup allowed me to model the shadow of the house at any time of day for any day of the year—greatly helping in the planning process.



This is a photo of the second PV array—mounted on the roof of the patio cover—which I built previously. The angle is only about 7 degrees off vertical, facing West. This is not an optimal configuration (due to angle and shading by the house second story)—but was the only place left where I could reasonably install another PV array. Despite it's non-optimal configuration, its performance in the Summer is often better than the first PV array (which faces South at 30 degrees) due to the sun being visible in the western sky longer.

My Requirements--System 2

- Grid-tie (use grid as 'storage' when supplying more than using)
- Generate 'green' power.
- Lower monthly electric bills by consuming grid power at closer to baseline rates.
- Track system power generation.
- Produce power when grid is down
- Measure system parameters automatically

Optionally:

- Provide mechanism for utilizing 1st PV array power when grid is down.

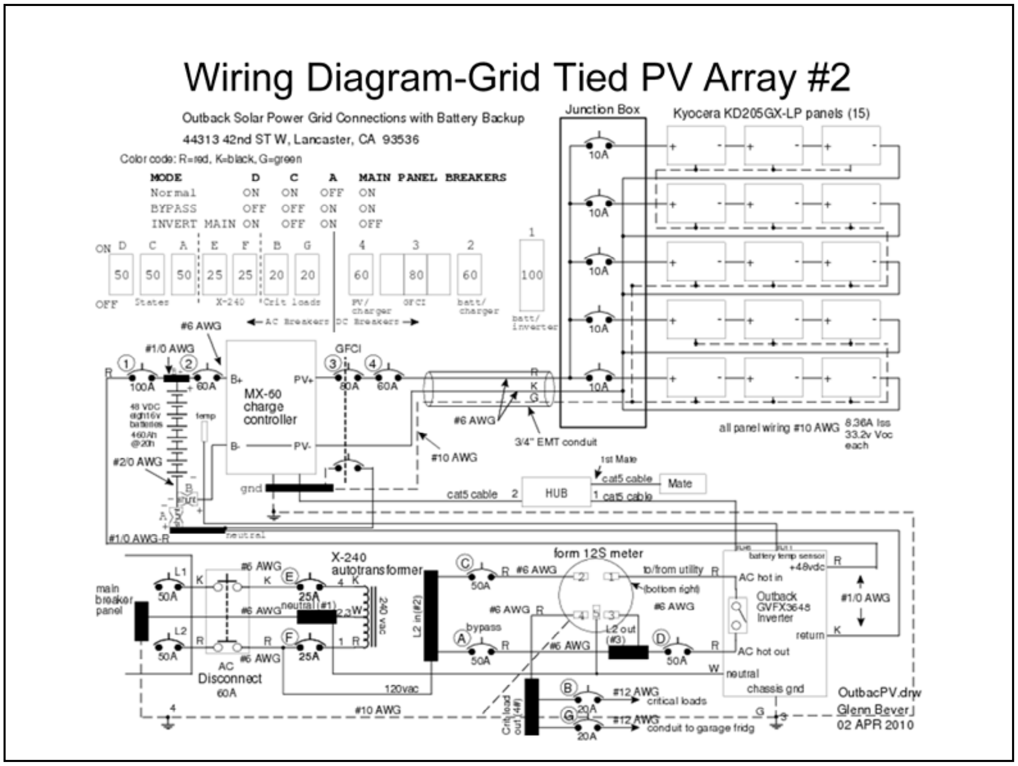
The second system was built primarily to have a system that could operate indefinitely if the grid were down—which required battery storage capability. The system was sized so that even if the grid were down, critical loads could run continuously and automatically off of the batteries or the PV array—and the batteries could be recharged on a daily basis from the PV array. I was not concerned about 'brown outs' or temporary power outages. This is designed so that if we experience a natural disaster that knocks the grid out for days, we still have power to food refrigeration units and access to power for lights.

My Specs—System 2

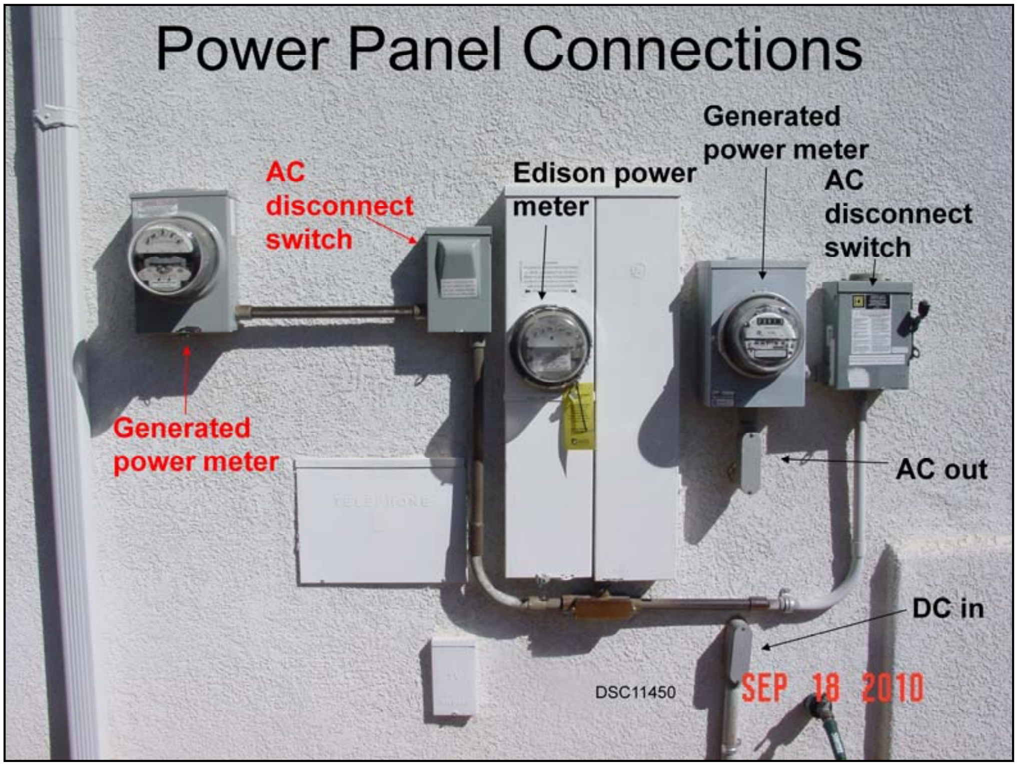
- 15 solar panels, 205W max each
  - (Kyocera KD205GX-LP)
- 7 deg angle from horizontal
- Net metering
- Ave 6 ‘full sun’ hours/day
- 205 W panels * 15= 3075 W max
- Voc=33.2V/module

  33.2Voc/module * 3 modules/string=99.6Voc/string
- 5 strings in parallel
- Isc= 6.82 A/string.   5 strings = 34.1 A/system
- 3600 W inverter (Outback GVFX3648)

Panels are each 3.25 ft x 4.9 ft = 16 ft2. So 15 panels is 16 ft2 x 15 = 240 ft2.

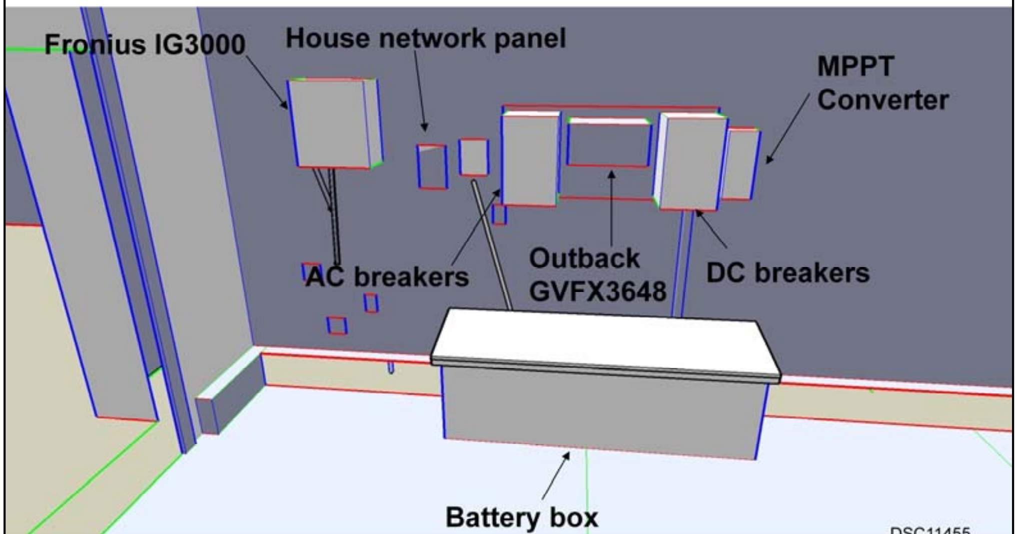


This is a schematic diagram of my second system. You can see that it is much more complex than the first. This is because there are more PV strings and especially because it is a battery backed up system. Power management becomes more critical due to having to manage the case where the grid is off, needing to manage battery charging from both the PV array and the grid, and having to step up the voltage from the 120 VAC inverter system to the 240 VAC power grid.



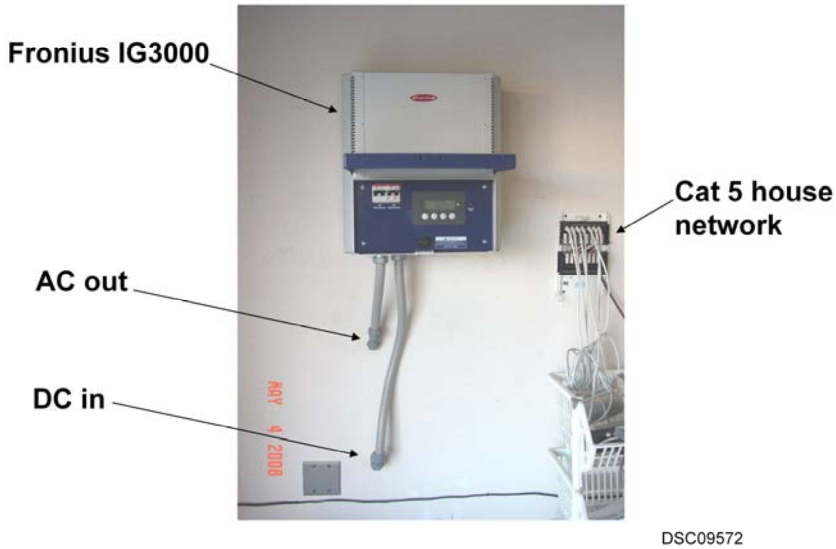
This is a photo of the power meters, main breaker panel, and cutoff switches. The notes in black indicate the first PV array system and the red indicates the second PV array additions. The entire 2nd system installation was designed and built by me.

3-D Model of Inverters & Battery Box

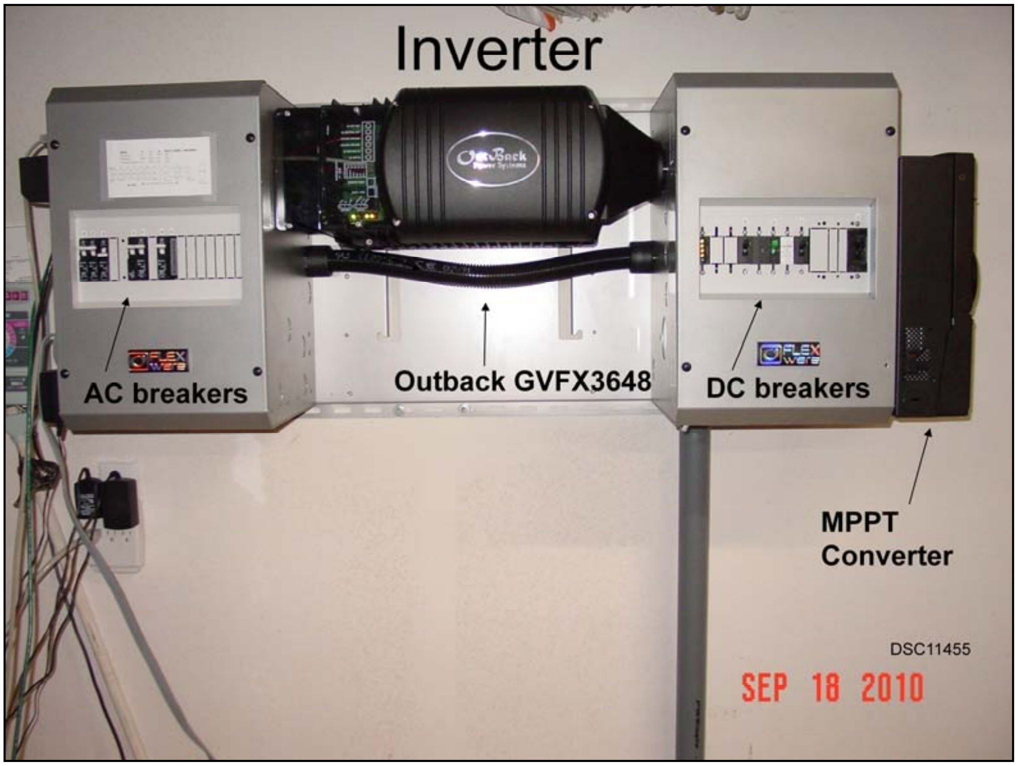


This is a virtual view of my first and second PV array system inverters and battery bank (using Google Sketchup). The Outback GVFX3648 inverts 3600 watts and uses a 48v battery bank. The Maximum power point tracker (MPPT) converter is shown on the right.

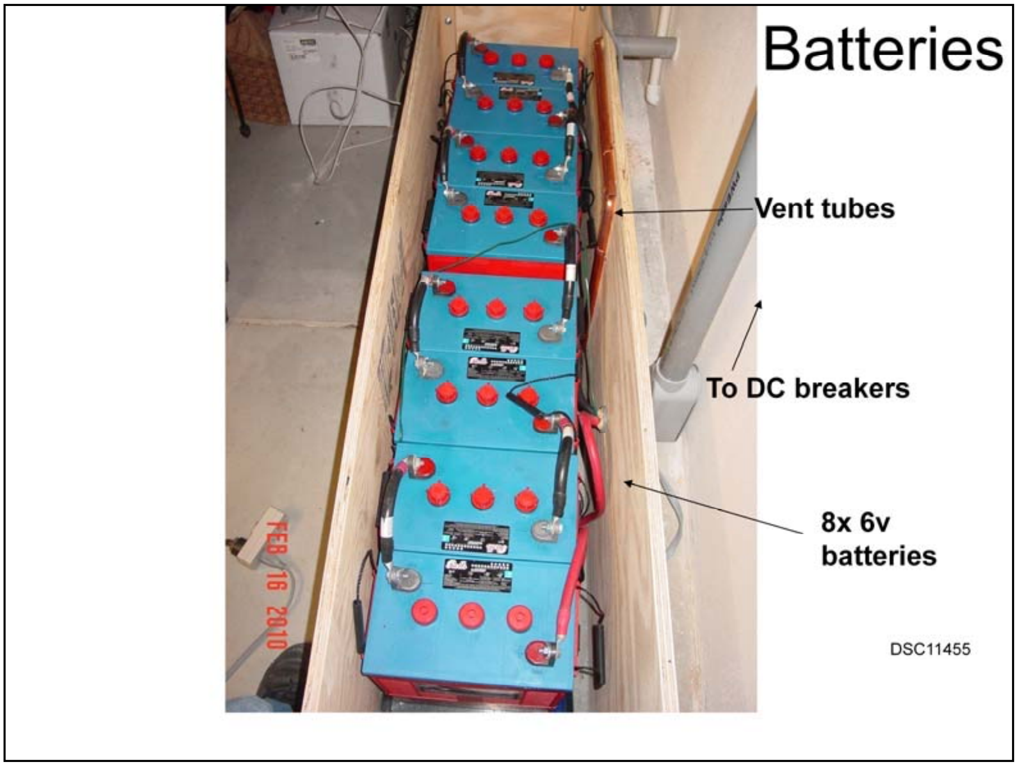
Inverter



Inside the garage, on the wall opposite the equipment shown in the previous picture. This is my first inverter system that is not battery backed-up. However, if the grid goes down, I can physically disconnect the main breaker panel from the power company grid and reroute the breaker connections so that this inverter will think the second inverter is the grid—and synchronize to it so as to produce additional power to the house.

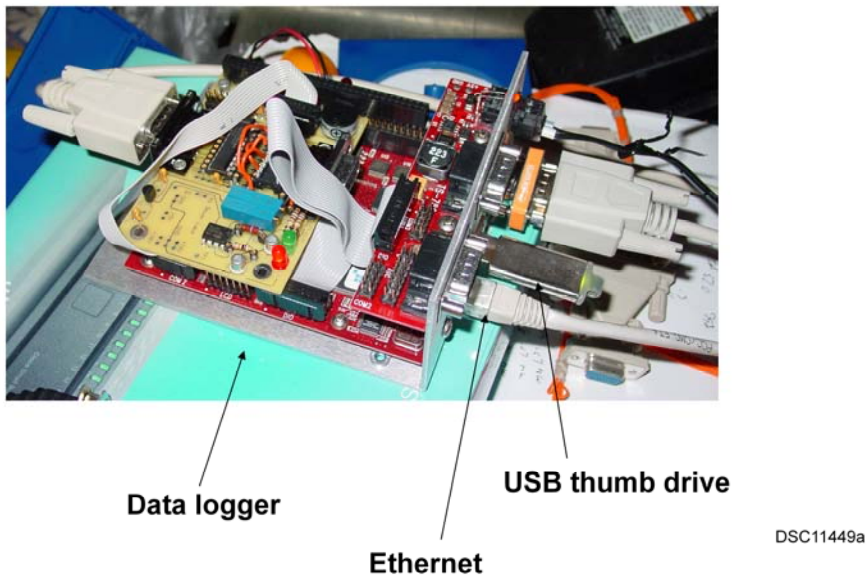


This is a view of my second PV array system inverter—an Outback GVFX3648 which will invert 3500 watts and uses a 48v battery bank. The Maximum power point tracker (MPPT) converter is shown on the right. The Fronius Inverter is mounted to the left of this system off-picture.



This is a view of the eight Rolls-Surrette S-530 6V batteries inside the battery box with the cover removed. Each will provide 20 A for 20 hours (400 AH) or 5.32 A for 100 hours (532 AH). Each weighs about 127 lbs. Note the copper tubing on the right that vents the box—preventing hydrogen buildup from battery outgassing—which is important to prevent potential explosion.

Data logger



The is an inside view of a data logger that is comprised of a commercial single board computer and an interface board that I designed. The software, which was written by me, logs data from the Outback system at set intervals and collects system status information. The files can be offloaded by an ethernet connection or the USB thumb drive. The software also feeds a crude webpage that provides system status to the household computers via the ethernet port.

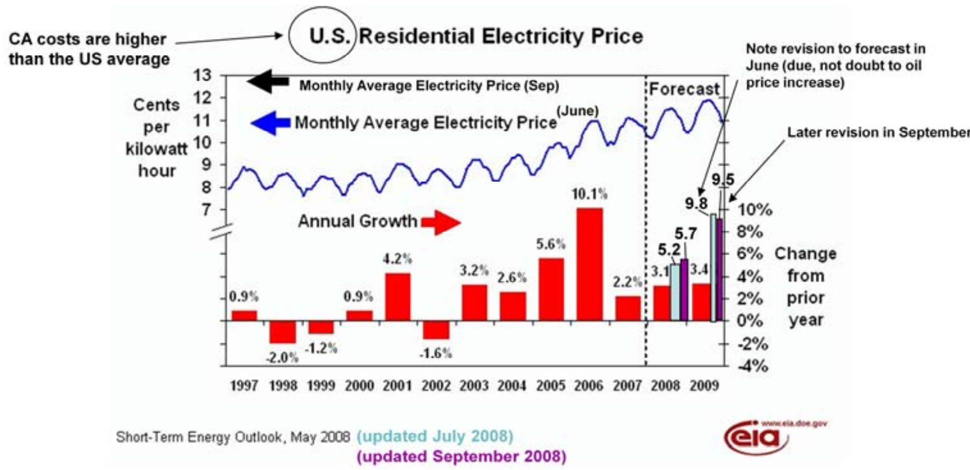
SCE electric charges

- Basic charge
- Tier one-baseline (differs between summer & winter)
- Tier two-101% to 130% of baseline
- Tier three-131% to 200% of baseline
- Tier four-201% to 300% of baseline
- Tier five-more than 300% of baseline
- Rate schedule:
  - Schedule D (standard)
  - NEM (net metering) ref: LauraDiane.Rudison@sce.com
  - TOU-D-1, TOU-D-2 (time of use)
  - TOU-EV-1 (electric vehicle recharge)
  - D-APS, D-APS-E (summer cycling)

I live in an area served by Southern California Edison (SCE) power company. They have a multi-tiered rate structure to encourage people to use less energy. Baseline is not a level that most people are able to achieve—i.e., it is a level that most people exceed. Tier two is up to 30% over baseline. Tier three is 30% to 100% over baseline (up to twice baseline), etc.

Most people use rate schedule D. ‘NEM’ is ‘net metering’ which is the schedule that most solar-power generating homeowners (like me) are one. I show a few other ones here that are of interest. ‘Time of use’ charging charges you more for power used at peak periods of the day. ‘Summer cycling’ is the rate used by people that have a power company radio receiver that remotely cuts off air conditioning during periods of peak demand.

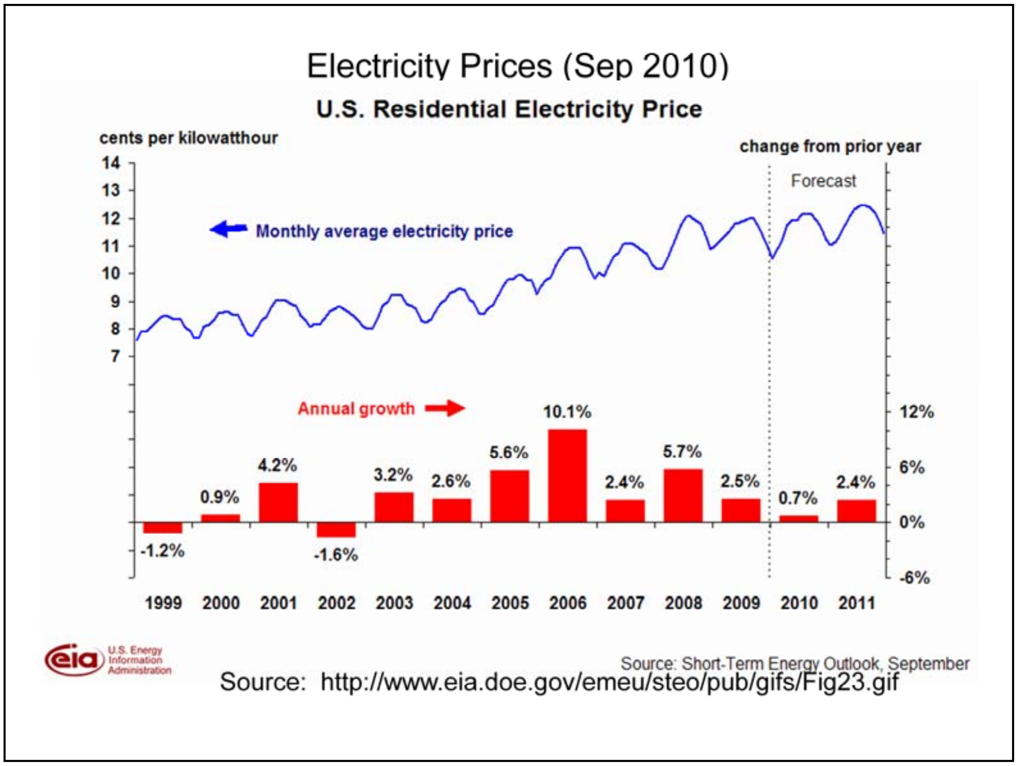
Electricity Prices
(SCE is proposing 30% increase in high tier rates)



Source: http://www.eia.doe.gov/emeu/steo/pub/gifs/Fig21.gif

This chart was pulled from a Department of Energy (DOE) website (URL is shown at the bottom of the slide). It is a composite of three different times (May, June, and September 2008). It shows the US (not California) average electricity prices over an 11-year period and how much it increased or decreased each year. It also show a projection for 2008 and 2009—which changed in June and September from the projection in May.

Some things to pull from the chart: 1) The average electricity price increased from \$0.11/kWh to nearly \$0.13/kWh (California costs are generally higher than this). 2) The projection for 2008 and 2009 have increased dramatically after the cost of oil shot up in early summer 2008, and 3) the average cost of electricity over the last decade or so has continually increased by a greater or lesser amount.



This chart was also pulled from a Department of Energy (DOE) website (URL is shown at the bottom of the slide), but two years later than the last chart. It shows the US (not California) average electricity prices over an 11-year period and how much it increased or decreased each year. It also show a projection for 2010 and 2011. Note that the actual values shown here for 2008 and 2009 are lower than the projections made two years ago (shown on the previous chart).

The recent recession has served to tamp down the costs somewhat more than the projections a few years ago. Even though there is a lot of fluctuation, the forecast is generally in the upward direction.

Rate changes

Comparison of cost per kWh at 'knees' in tier curve
at two points 3 years apart using summer baseline
(rates shown are aggregate, not margin)

	7/21/2005	6/23/2008	delta
tier 1 max	0.124	0.120	-2.93%
tier 2 max	0.127	0.124	-2.09%
tier 3 max	0.142	0.155	9.47%
tier 4 max	0.162	0.186	15.20%
tier 5 pt	0.172	0.211	23.01%

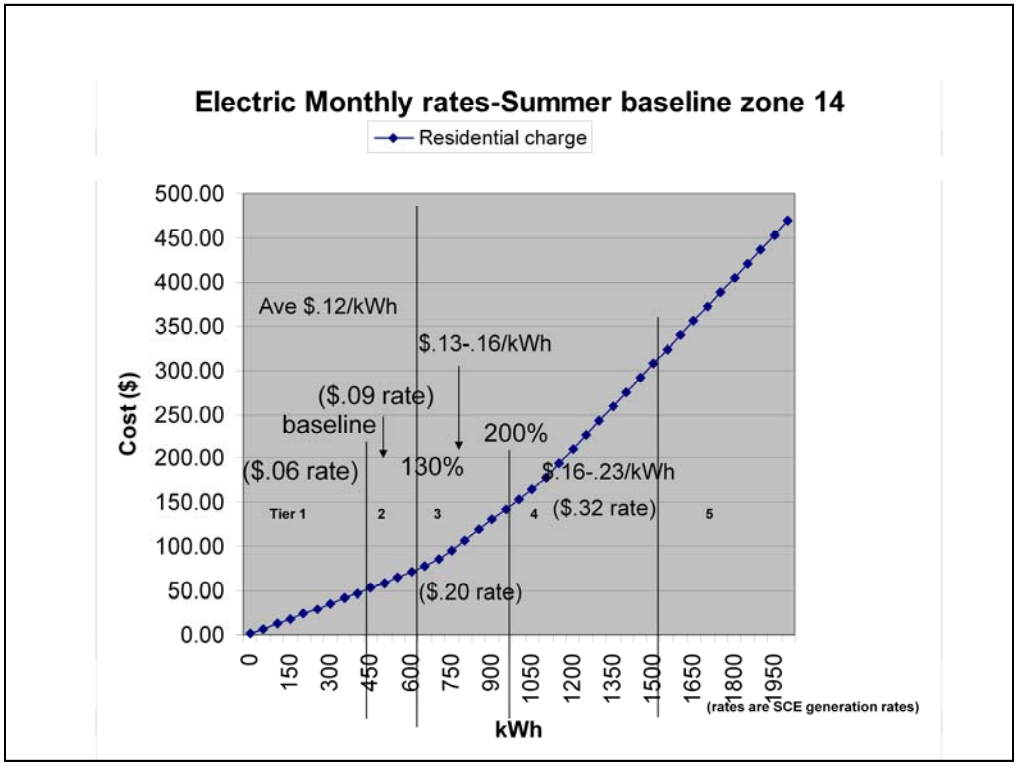
Change in rate over 3 years

Using a spreadsheet that I developed to mimic the eccentricities of the Southern California Edison (SCE) residential rates, I have boiled it down to the chart here. Plugging in kWh usage at the borders between the tier rate changeovers, I derived the total cost per kWh (which includes all the tiers below it). In other words, the electricity costs listed here are the aggregate rates, not the margin, or tier rates. For example, 'tier 4' lists a cost of \$0.186/kWh (for 2008) in the chart. That means that if you used 1530 kWh, you would be using all of tier 1 (tops out at 510 kWh), all of tier 2 (tops out at 633 kWh), all of tier 3 (tops out at 1020 kWh), and all of tier 4 (tops out at 1530 kWh). At 1530 kWh, the cost would be \$284.96, and \$284.96/1530 kWh = \$0.186/kWh. The marginal rate in tier 4 (the cost for just the electricity generated between 1020 kWh and 1530 kWh) is about \$0.20/kWh. (Exactness is difficult due to multiple generation and delivery charges built into the rate structure and SCE changes rates about every 2 months.

Using my spreadsheet, I was able to do comparisons between 2005 and 2008. Plugging in the rate tables used during each period for the same amounts of energy, I could compare 'apples to apples.' Note that the rates for lower tier usage has actually gone *down* by a little bit, whereas the higher tier rates have gone up *considerably*. So anything you can do to stay out of the high tier charges by conserving or generating power can save you a great deal of money.

The name of the game here is to reduce the amount of energy consumed from the power company to knock you out of the higher tier rates. Sizing a PV array system to do that, versus generating all of your own power, gives you the most 'bang for the buck.'

Further, if you generate more than you consume over the course of a year, you just give it away to the electric company. You don't get paid for it. If you were to pay for it, it would be at wholesale, not retail rates and you become a power generation company—a whole different animal.



This plot attempts to illustrate the cost of energy consumption as usage goes up. You can see that the curve increases at a higher rate for higher usage. The vertical lines correspond to the tier levels. The numbers in parentheses represent the rate of that tier whereas the numbers not in parentheses represent the average cost simply dividing the kWh by the cost (which takes into account all the lower rates of the energy used up to the current usage. The numbers here are not exact—as SCE is constantly tweaking the rate structure.

Power usage measurements

hrs or uses/day		Max Power draw	Power factor	KwH/hr or use	$0.14/kWh (nominal) cost/hr or use	KwH/day	cost/day	cost/month
8	**Desktop Computer**	135	0.75	0.135	$0.02	1.08	$0.15	**$4.54**
1	Desktop monitor off	113		0.113	$0.02	0.11	$0.02	$0.47
15	Desktop standby/off	40	0.75	0.040	$0.01	0.60	$0.08	$2.52
24	**22 w energy bulb**	16	0.62	0.016	$0.00	0.38	$0.05	**$1.61**
6	**air conditioner**	4700			$0.00	28.20	$3.95	**$118.44**
24	garage refrigerator	167	0.95	0.127	$0.02	3.05	$0.43	$12.79
24	garage freezer	106		0.067	$0.01	1.60	$0.22	$6.73
24	**kitchen refrigerator**	175	0.94	0.087	$0.01	2.09	$0.29	**$8.77**
24	2nd desktop computer	63	0.65	0.063	$0.01	1.51	$0.21	$6.35
24	2nd desktop computer			0.055	$0.01	1.32		
1	**washing machine**	60-130		0.100	$0.01	0.10	$0.01	**$0.42**
1	**dryer**	250-750	0.52	0.190	$0.03	0.19	$0.03	**$0.80**
2	**new dishwasher**	246	0.95	0.840	$0.12	1.68	$0.24	**$7.06**
10	kitchen lights	480		0.480	$0.07	4.80	$0.67	$20.16
10	9' xmas tree	800	1	0.800	$0.11	8.00	$1.12	$23.52
1	halogen light	300	1	0.300	$0.04	0.30	$0.04	$1.26
6	**pool pump**	1492		1.492	$0.21	8.95	$1.25	**$37.60**
24	**Dell D630C laptop PC**	28		0.028	$0.00	0.67	$0.09	**$2.82**

This chart shows the energy usage of several appliances and electric equipment my house. The lines in red are items that argueably are of the most interest. Note that the cost/month is based on the number hours or uses per day (1st column) and an assumed energy cost of $0.14 per kWh—which from the previous plot would be tier 3 usage (selected as being fairly representative—and I had to pick *something* to ease comparison). A chart like this is useful to identify the big energy consumers in the house and show you where you would get the most 'bang for the buck' in conserving. The biggest users on this chart are the air conditioner and the pool pump. Cutting down on their usage or replacing them with more efficient devices (e.g. swamp cooler and variable speed pump) could make a large difference in energy consumption.

Note that using a desktop computer for 8 hours per day cost $4.54 whereas using a laptop computer for 24 hours per day cost $2.82. This is because a desktop computer runs at about 5 times the power of a laptop.

Note also the extremely low cost of operating my washing machine. This unit is a front-loader that purports to use 80% less energy than the standard model. The data bears that out.

The data was taken by one of two methods: an inexpensive power meter (Kill-a-Watt) or reading the SCE kW-h meter (see next chart).

Obstruction Conclusions

- An unobstructed array facing east or west loses only about 12-13% over one facing south.
- An obstructed array changes the optimal array elevation and azimuth, but optimizing the angle can give you 2/3 the insolation of an unobstructed array.

- One of my PV arrays is tilted at 30 degrees from the horizontal (normal vector 30 degrees from the vertical)—which is 4 degrees toward the summer sky. from the equinox angle of 34 degrees (latitude-4 deg).

- My other PV array is tilted 7 degrees from the horizontal (facing West) and obstructed in the East. Hardly optimal but performs well in the Summer when my demand is the greatest.

Note that if the array is facing east or west, the optimum angle is no longer the angle of the latitude. It is best if more horizontal—about 15 degrees off of facing straight up.

Performance for System 1

- PV system 1 produces 1/3 of the power that we consume but saves ½ the cost of electricity.
- Average generation is 12.5 kWh/day (from wattmeter)
- Best generated is 15.5 kWh/day
- On a really cloudy day, the output can be reduced by 2/3.
- Average consumed from SCE is 23.8 kWh/day
- Zero maintenance in 3 years of operation
- Only moving part is an inverter ventilation fan.
- Hot temperatures make the cells less efficient. On a hot day I can increase the output (temporarily) by 129 W by hosing the array off.
  - 129W/1945W=6.6% improvement (from previous slide).
  - Cooling by another 15 deg F (down to 25 deg C) would double this
  - so 258W*6.6 equivalent hrs/day=1703 Wh/day less due to heat (1703 Wh/day / 15kWh/day = 11-12% loss)
  - Best nominal performance is about 15% less than rated maximum.

Equivalent hours are the reconstruction of a solar day insolation area under the curve. You take the area and reconstruct it as a rectangle of height equal to the maximum power (at noon) and width equal to the number of hours it takes to equal the energy generated for the day.

In computing the heat loss here, I used 15 kWh/day as the nominal power generated. This is what the inverter reports for a typical summer day.

The statement regarding the best nominal performance comes from a calculation down a couple of slides.

Performance Details
Percent of Power Generated

Year 1 = 30.6%
Year 2 = 34.9%
Year 3 = 39.7%
Years 1-3 = 34.7%

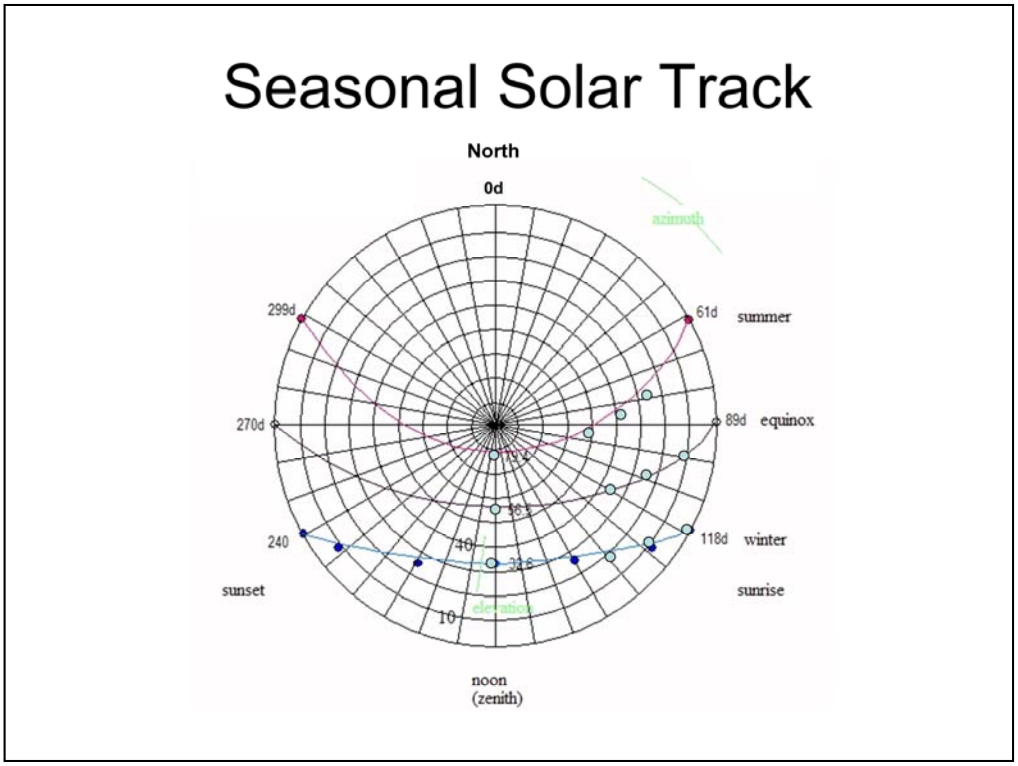
Over 3 years:
13.777 MW-h generated
(15500 MW-h reported by inverter)
26.251 MW-h from SCE

Fall 2005 = 31.7%
Winter 2005-2006 = 33.3%
Spring 2006 = 42.4%
Summer 2006 = 24.9%

Fall 2006 = 31.4%
Winter 2006-2007 = 34%
Spring 2007 = 51.4 %
Summer 2007 = 36.2 %

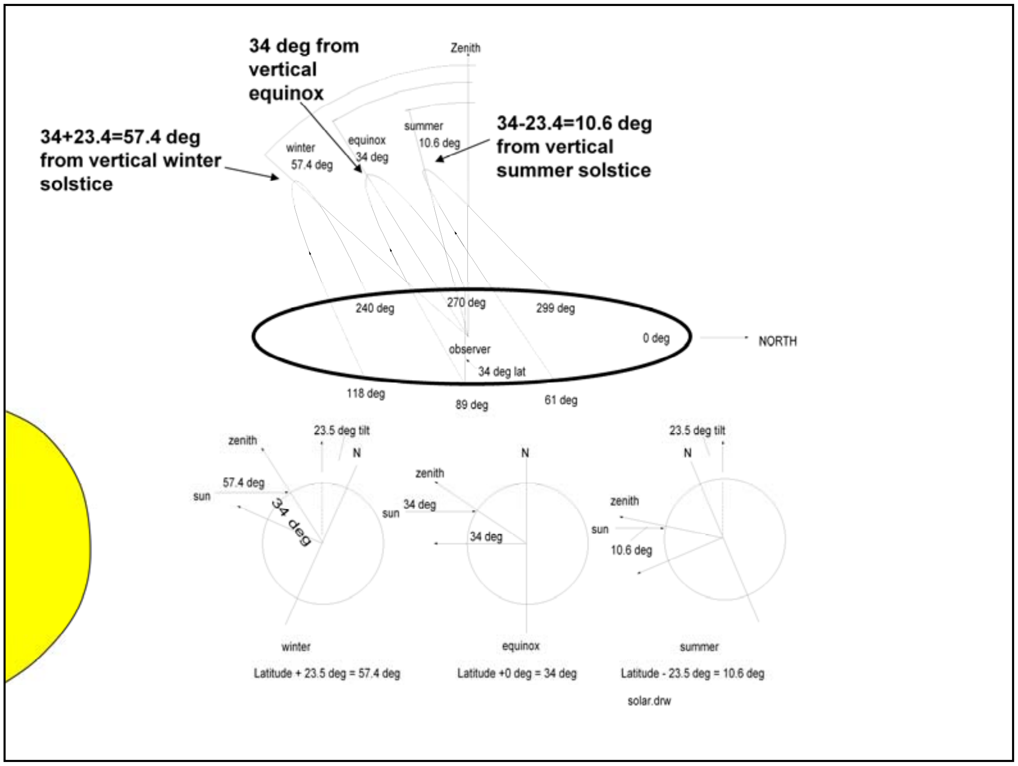
Fall 2007 = 39.1%
Winter 2007-2008 = 38.2%
Spring 2008 = 50.3%
Summer 2008 = 25.5%

From data (1st PV array system only).

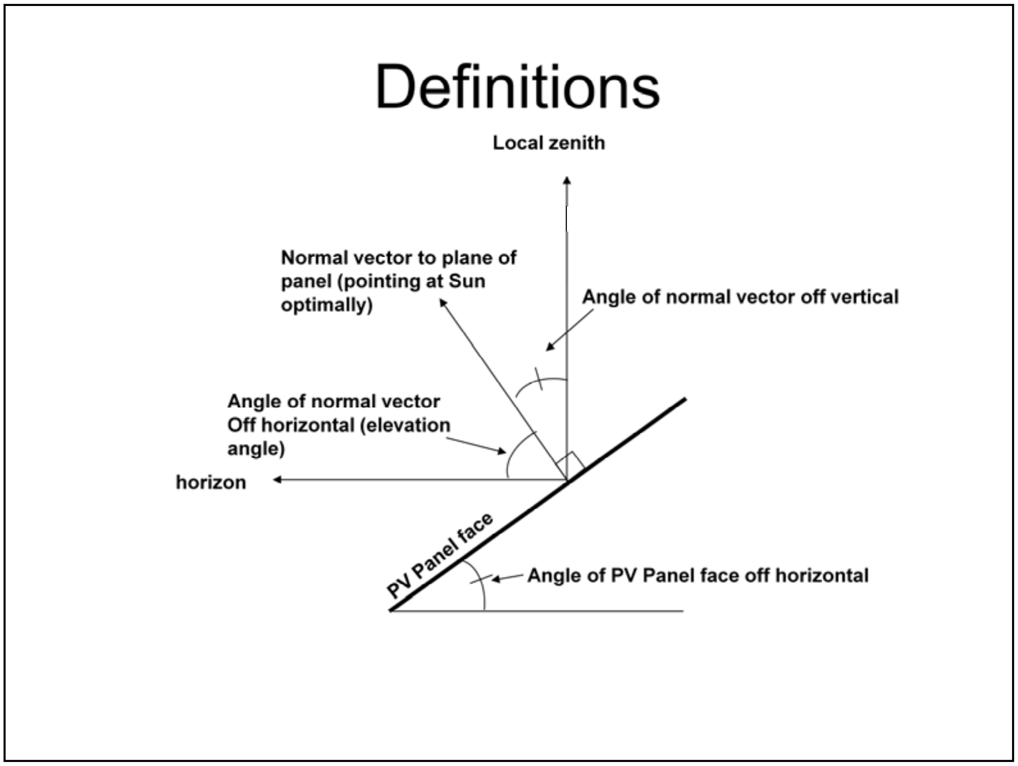


This is a sky chart showing the track of the Sun across the sky at this latitude (34 deg N). Three tracks are show: equinox, summer solstice, and winter solstice. What is illustrated is the significantly different paths the Sun takes across the sky.

In the summer, the Sun rises and sets in the northeast and northwest, passing nearly overhead at its zenith at local noon. In the winter, it rises and sets in the southeast and southwest with its zenith much farther in the southern sky. You can see that if you wanted to point an array at a fixed angle, the optimal angle would be different in the summer than in the winter.



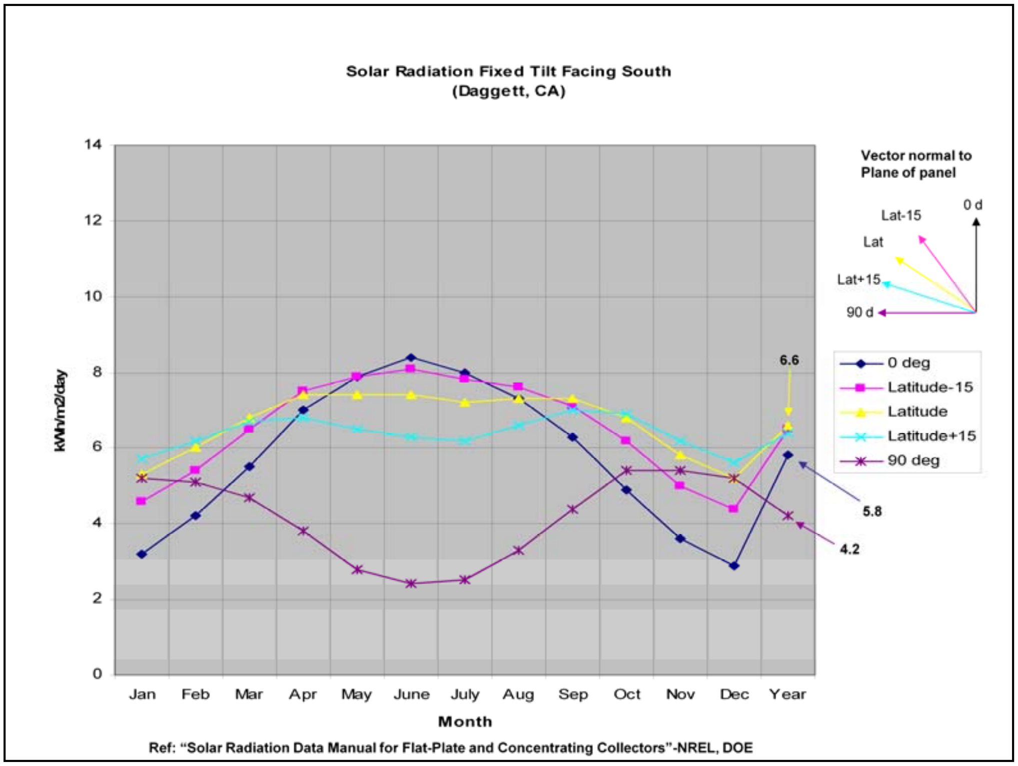
This chart illustrates the same thing from a different angle. The dark elipse represents the local horizon with the observer standing in the middle. The three arcs that intersect the horizon represent Sun's track during (from left to right) the winter, equinox, and summer. The different arcs are a result of the Earth's 23.5 degree tilt with respect to its plane of orbit around the Sun, as the series of diagrams at the bottom of the chart attempt to illustrate. Compare each 'Earth' at the bottom with each of the arcs at the top.



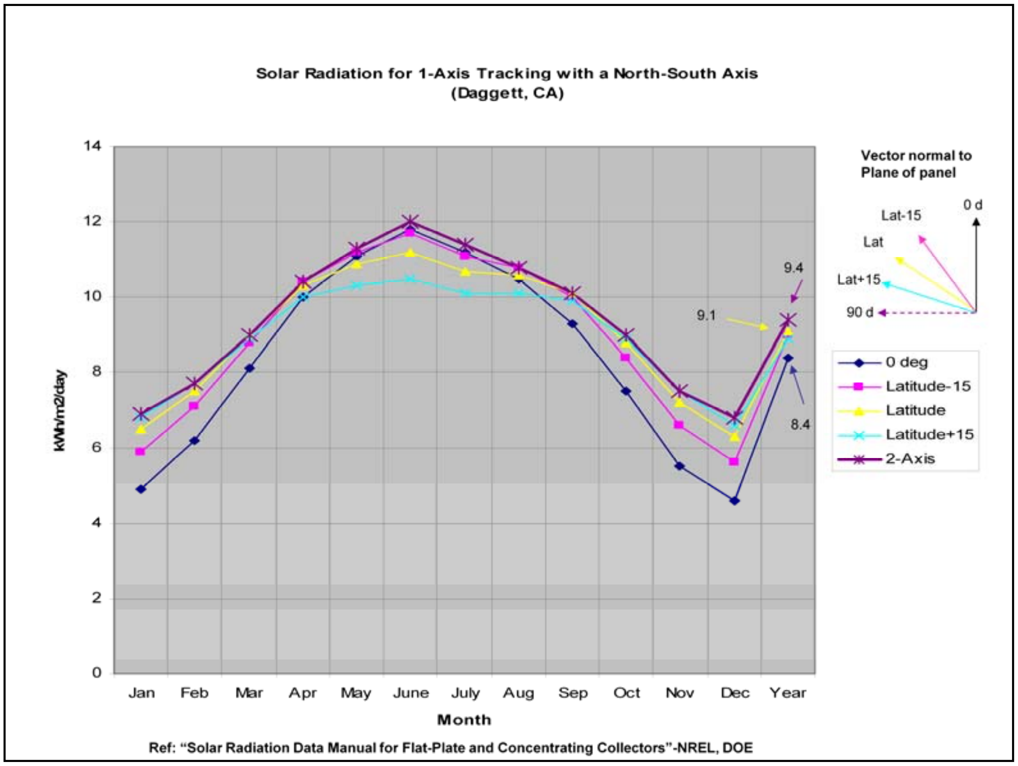
This slide shows some definitions used in the presentation. A confusing point is that both angles off the vertical (or local zenith) and the horizontal (off the horizon) are used. In pointing the array, the azimuth and elevation angles are referred to. The azimuth is the direction, from 0 to 360 degrees, with 0 degrees being north, 90 degrees being east, etc. The elevation is the angle off the horizon, with 0 degrees being pointing at the horizon and 90 degrees pointing straight up (at the local zenith). It is the normal vector to the PV panel that is used to determine these angles.

Note that the angle the PV panel makes with the horizon is the same as the angle of the normal vector off the zenith—but the complement of the elevation angle. For example, an array tilted at 30 degrees has its normal vector pointing at 60 degrees elevation. It is often convenient to use both of these angles, depending on the context.

A few other terms (not shown here, but used a lot later): kWh (or kW-h) is an abbreviation for ‘kiloWatt-hours,’ or a unit of energy that is the product of power (kiloWatts) and time (hours). It is the number displayed on your power company meter. MW-h is ‘megaWatt-hours’ (equal to 1000 kW-h).



This chart, taken from solar radiation data collected at Daggett, CA, shows the effect throughout a year of tilting an array at different (fixed) angles. The last point (labeled 'year' on the x-axis) is the aggregate effect of solar power collected over the year for each pointing angle. It can be seen that the optimal angle is the angle of the latitude, but varying it by +/- 15 degrees makes little difference (about 3%) in terms of the aggregate solar energy received by the array over the course of a year.



Even more interesting is comparing a 1-axis tracking array to a 2-axis tracking array. A 1-axis track tracks east to west (azimuth) and a 2-axis track also tracks north and south (elevation).

As can be seen from the 'year' point on the right side, there is very little difference between the 2-axis track and the 1-axis track set at the latitude elevation angle. In fact, the numbers are 9.4 vs. 9.1 kWh/m2/day– only about a 3% difference. This is consistent with the previous graph showing that varying the elevation by +/-15 degrees varies the aggregate output by only about 3%. In practice, a 2-axis track would be +/-23.5 degrees off of the nominal latitude.

Tracking Conclusions

•Using a 1-Axis tracker instead of a fixed array allows the use of 2/3 as many solar panels for the equivalent power output

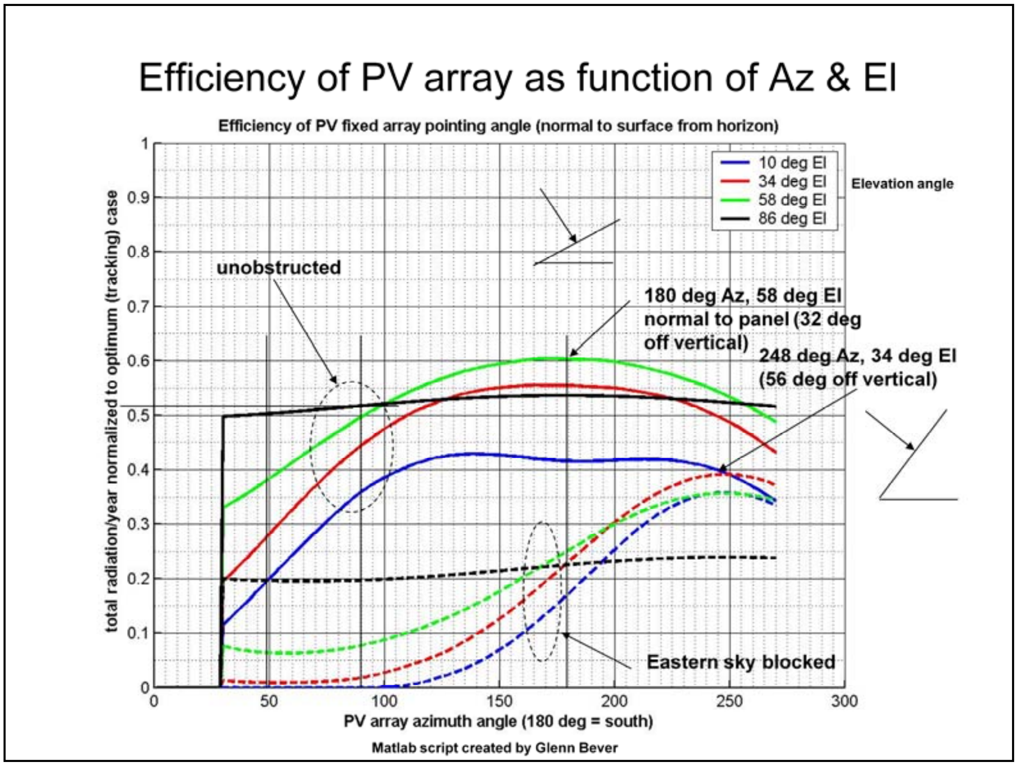
–Put another way, you get 50% more power out of a 1-Axis tracked system than with a fixed array.

•A 2-axis tracked system has only marginal improvement over a 1-axis tracked system.

– tilting the elevation to account for seasonal sun variation yields only very minor improvement in power generated.

•Tilting a fixed array to equal the latitude is the optimal angle. If you expect more cloudy days in the winter than the summer (or get a better rebate optimizing for max power demand in the summer), angling it higher optimizes summer month power generation. However, elevation variations of +/- 15 degrees yields insignificant differences aggregate over the course of a year.

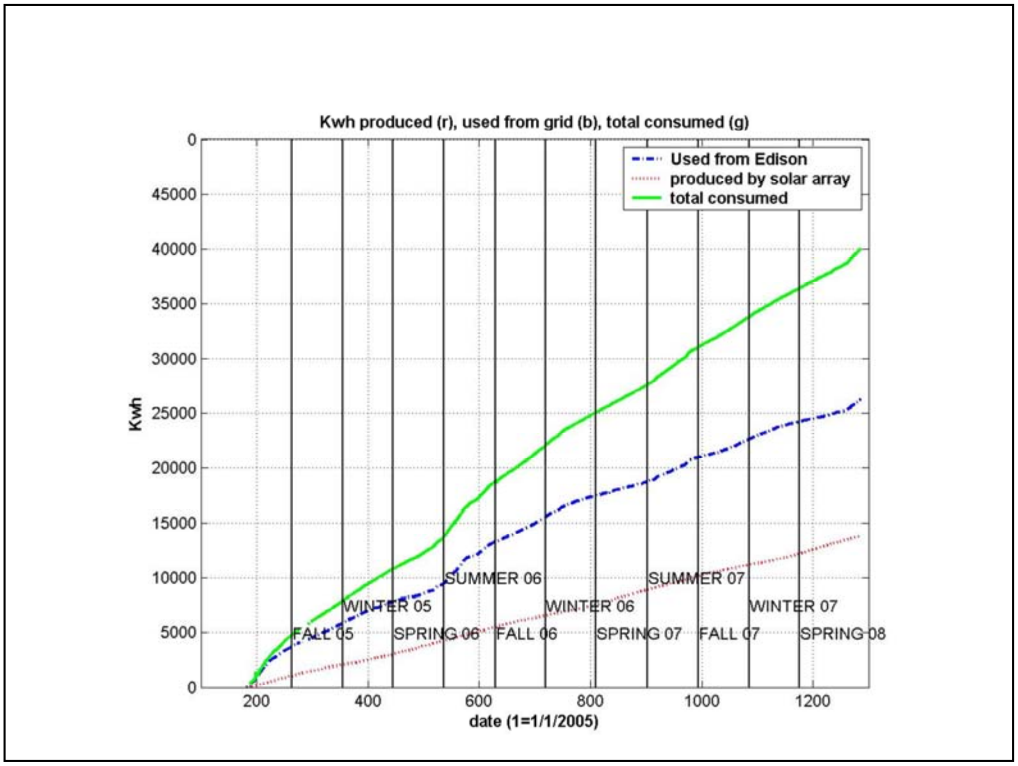
This is largely a repeat of what I said earlier in the presentation, but now you can see the data (plots) upon which the statements were made.



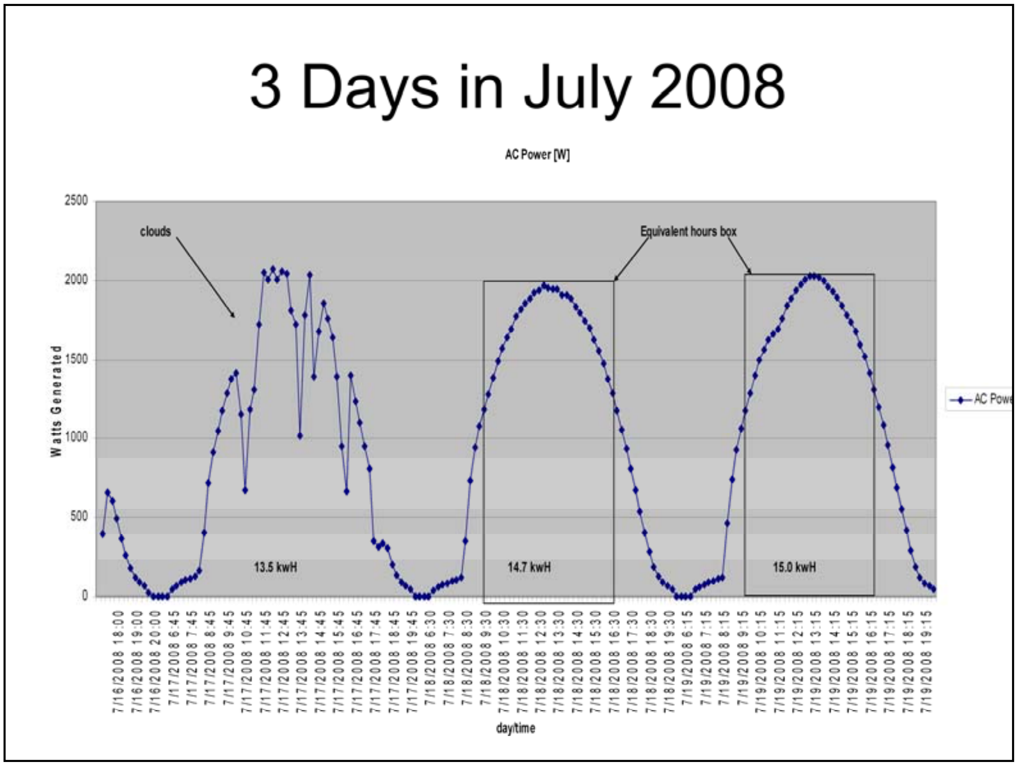
This is a composite plot that displays the relative solar radiation values seen by arrays at four different elevation angles (10 deg, 34 deg, 58 deg, and 85 deg) and every possible azimuth. In other words, it illustrates the relative effects of pointing the array at different fixed parts of the sky over a year. There are two families of curves: ‘unobstructed’ (solid) and ‘obstructed eastern sky’ (dashed). The chart allows you to get a pretty good idea of the relative effect of pointing the array at different azimuths and elevations. For example you can see that if the array is pointed east (90 degrees azimuth) at 85 degrees elevation (surface of array nearly horizontal) you only lose about 12-13% in efficiency over an array pointed south (180 degrees azimuth) at 58 degrees elevation.

The optimal angle for this latitude is seen to be 180 deg Az (facing South) and 58 deg Elevation (array face normal vector is 58 deg off of horizontal or 32 deg off of vertical). This shows an annual insolation, or solar radiation received by the array, of 60% of an array that tracked the Sun in both azimuth and elevation—pointing at the Sun at all times when Sun is up. The insolation of a tracking array is represented on this graph as the normalized value of 1 on the y-axis. So ‘1’ is the best possible case.

If the Eastern sky is obstructed (say, with a wall), the Sun will not be directly on the array until local noon—this is illustrated by the lower set of dashed curves. This shows that the optimal angle over the course of a year is 248 deg Az (southwest) and 34 deg Elevation (array face normal vector is 34 deg off of horizontal or 56 deg off of vertical)—nearly the complement of the unobstructed angle. Further, it can be seen that at best, you will collect only 2/3 of the energy possible were the obstruction not there.



This plot shows three curves. The bottom curve shows the total amount of energy produced by my 1st PV array during its first three years of operation. The middle curve is what energy I used from the electric company. The top curve is the total energy that my house consumed (which is the sum of the other two curves).



This plot illustrates the same thing as the previous plot, except the data was taken with automatic data acquisition equipment over a 3-day period. The first day curve also illustrates what happens to the power generation when clouds cover the Sun from time to time.

Inverter Manufacturers

- Manufacturers
  - Fronius
  - Xantrax
  - Outback
  - Sunnyboy
- Buy vs. lease

There are a handful of manufacturers that are big in the inverter manufacturing arena. Outback and Xantrax are the only two that really are geared toward battery-backed up systems. Sunnyboy is a popular brand. Fronius (from my own personal experience) is very reliable and the lightest of all the inverters.

Many installers will offer lease deals or finance arrangements. The tradeoffs between those and buying a system are similar to the tradeoffs in different car financing options. The claim in leasing or time-pay is that your payments will be less than buying that produced energy from the power company. While I have my doubts about that, I did not look seriously into it as I just bought my systems outright.

Questions to Ask Installers

- What roofing guarantees do you give?
- What inverter manufacturer(s) do you install and why?
- What solar panels do you use and why?
- What are the warranties on the equipment and installation?
- Do you file rebate paperwork?
- Do you do battery backed-up systems or grid tie only?
- What expansion possibilities are there?
- What is the expected KWH output FOR THIS LOCATION?
- How is the KWH output spread throughout the year?
  - Most generation in what months?
- What percentage of my power usage will be generated by your system?

California Solar Initiative Resources

- The statewide consumer website
  www.GoSolarCalifornia.ca.gov
- The CSI Program Handbook includes eligibility information and application information:
  www.GoSolarCalifornia.ca.gov/documents/index.html
- The CSI Program Administrators developed a tool to calculate the up-front EPBB incentive, known as the EPBB Calculator:
  www.csi-epbb.com
- The CSI Program Administrators launched an online application tool and reporting database, known as Powerclerk:
  csi.powerclerk.com
- Up-to-date information about the program's current incentive level, or "step" can be found on the online CSI Trigger Tracker:
  www.csi-trigger.com
- Information about the CPUC regulatory proceeding that deals with the CSI program can be found online at:
  www.cpuc.ca.gov/static/energy/solar/_index.htm

California Solar Initiative: Resources

Here are some websites that delve into some of the rebate issues (California only).

Websites

Southern California Edison bill information:

•http://www.sce.com/newbill/pageone.htm

Sample installer website:

•http://www.rainorshinepower.com/lancaster.htm

Sun ‘wobble’:

•http://www.analemma.com/Pages/framesPage.html

Solar position calculator:

•http://www.srrb.noaa.gov/highlights/sunrise/azel.html

Comparative prices on solar panels:

•http://www.ecobusinesslinks.com/solar_panels.htm

DOE tutorial on solar energy:

•http://www.eere.energy.gov/consumer/renewable_energy/solar/index.cfm/mytopic=50012

Photovoltaic systems research and development:

•http://photovoltaics.sandia.gov/docs/PVRMChapter_3.htm

Here are some websites that I have found useful.

Conclusions

•Resale value of home increases to match system cost

•Energy produced over the life of the system more than pays for itself

•It’s fun to watch the kWh meter turn backwards

•It’s a hedge against energy inflation--an up front cost vs. a pay-as-you go plan (buy as opposed to ‘renting’ energy)

•Offsets higher cost tiered rates

•It’s green power

•The desert is ideal for this kind of system

•The system installation is not subject to property tax under CA state law

•Rebate and tax incentives from both state and federal governments
(getting less with time)

BUT

•It represents a capital investment up front

•It is infrastructure subject to maintenance and possible damage

•Sizing the system is important when judging payback time

End of Presentation
Backup Slides follow

Utility meter power calculations

kH = 7.2 (7.2 watt-hours per revolution of disk)
(7.2 W-h/1 rev) * (3600 secs/hr) / x = watts used
(where ‘x’ = # seconds per revolution of disk)

•So

$$\frac{(7.2 * 3600)}{\text{secs/rev}} = W$$

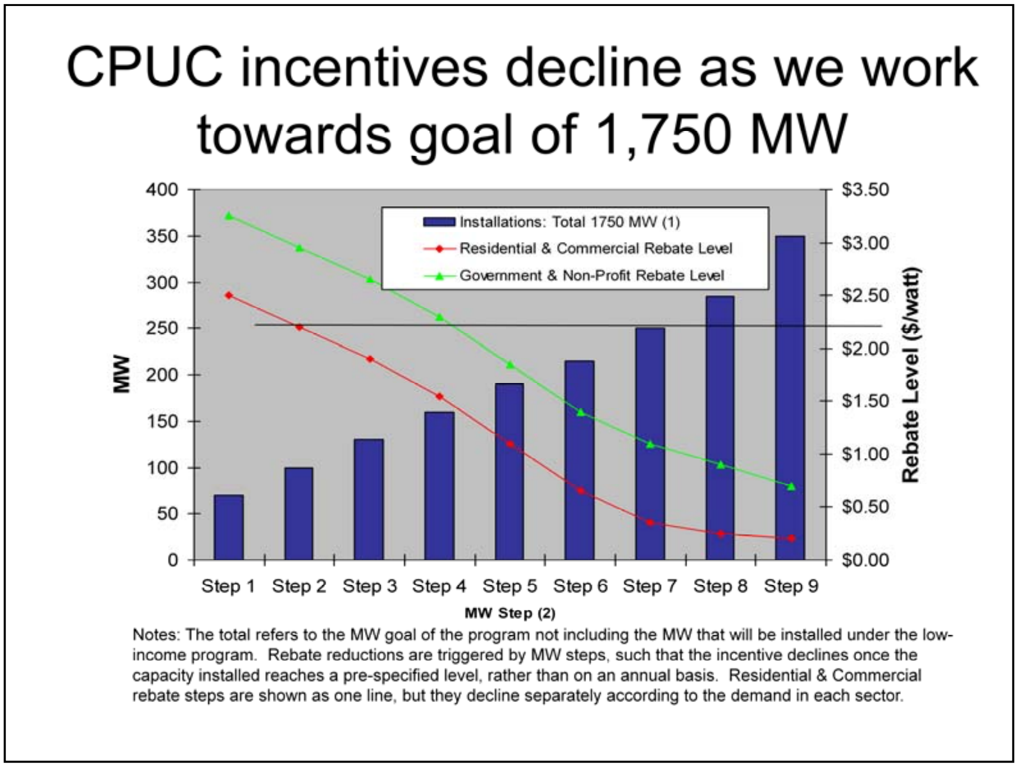
Making two measurements (one with device on and one with device off) and subtracting them yields the power consumption of the device.

This illustrates a simple method of determining the power usage of appliances in your house that can’t be directly measured. For example, an air conditioner is typically a 220V device that you can’t unplug and put a power meter in line with. You could clamp a hall-effect ammeter around the line, but you don’t need to go to that expense.

Every kW-h meter has a number on it labelled with a ‘kH.’ That number is typically 7.2. Plugging that number into the formula as a constant and then counting the number of seconds it takes for the rotating disk to rotate once (the number in red) yields the power being consumed in the house at that time. If you can be reasonably assured that no other big appliances are cutting on and off over the few minutes it takes to take this measurement, comparing the secs/revolution between turning the appliance on and off tells you the power consumption of that device.

If the disk is rotating rapidly, it might be useful to count the time for several revolutions and then divide by that number. E.g., if it takes 5 seconds for 10 revolutions, 5 secs/10 revolutions = 0.5 secs/rev, which would be the number plugged into the formula on the slide.

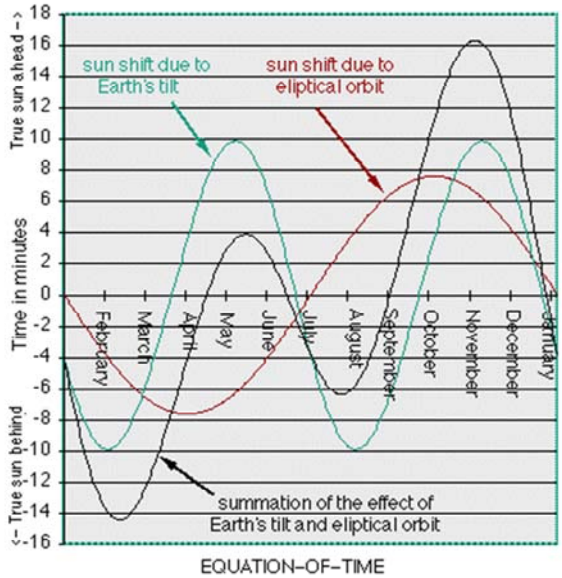
Electricity Costs



This chart shows the plan for decreasing rebates as milestones are met (California Public Utilities Commission). The more people apply for rebates for installing solar power generation systems, the faster each milestone will be met and the faster the rebates will disappear. Note that government and non-profit organization rebate incentives are greater than those for commercial and residential. The black horizontal line shows where the rebate level is as of August 2008 (step two, $2.20/watt generated).

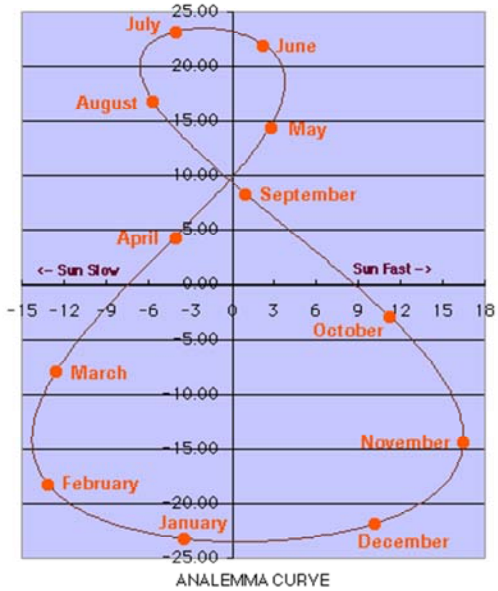
Note also that the rebate is for watts *generated*, not rated. As part of the rebate calculation you are required to assess blockages, etc. that lessen the amount of energy you can generate from what your system is rated. Further, there is a minimum sized array under which you are not eligible for rebates (I believe 1000 watts). If you bought five 200-watt panels (1000 watts) it is unlikely that you would meet the minimum. 1000 watts here would be the *rating*, not what it actually would generate.

Analemma



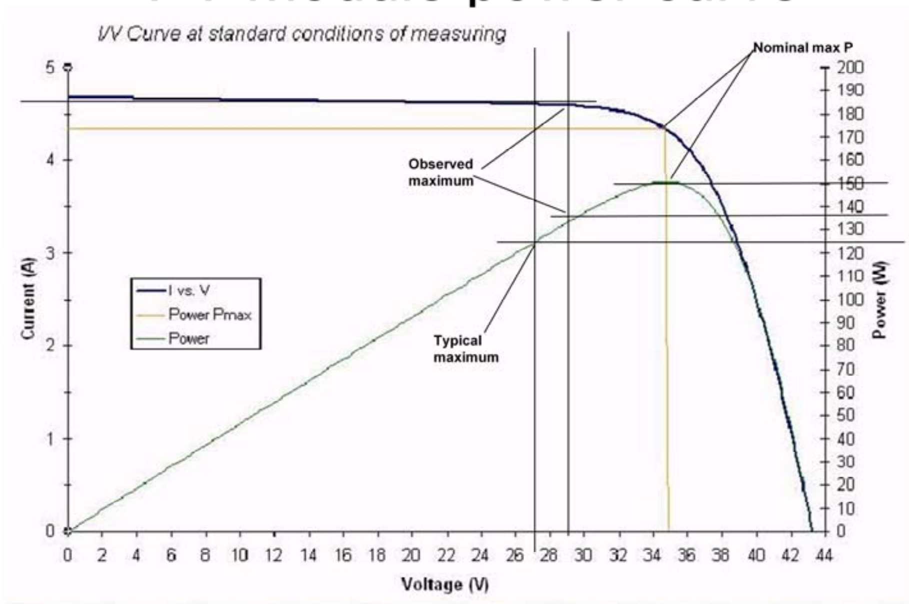
One aberration of note is the effect of the Earth's tilt and elliptical orbit on the actual time of local noon. There is a 'wobble' to it. This chart shows the variation due to each component and their composite. The time of local noon actually varies by about +/-15 minutes throughout the course of the year.

Analemma Track



This is a different representation of the same thing, showing the lissajous figure that you often see somewhere on a globe.

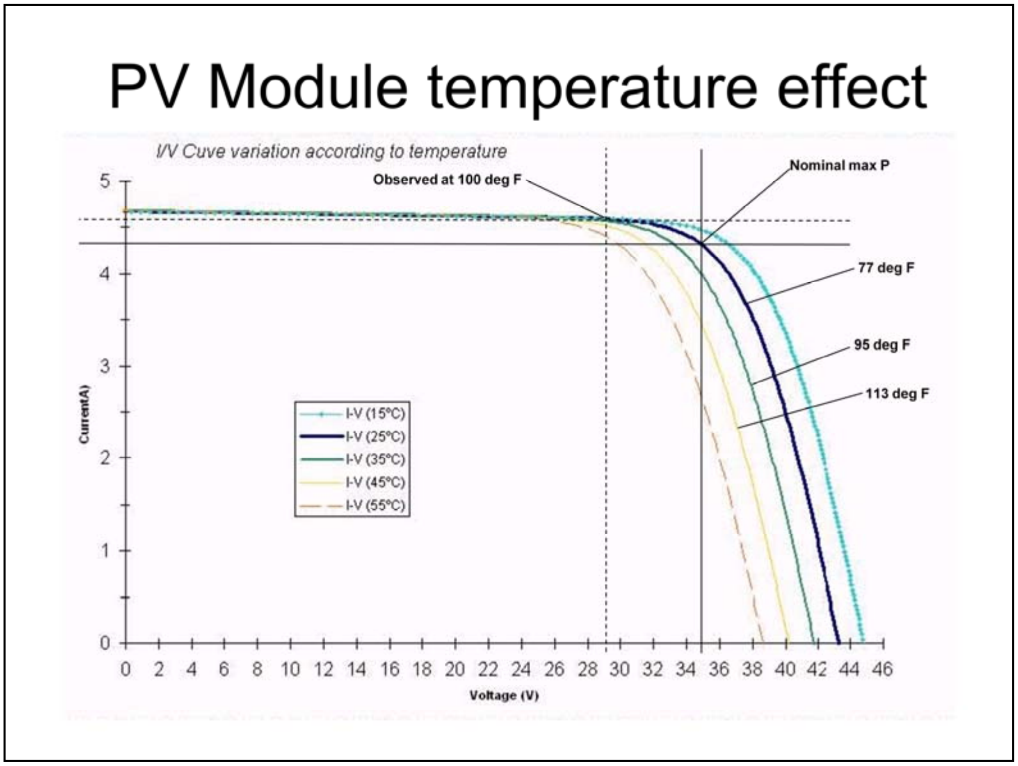
PV module power curve



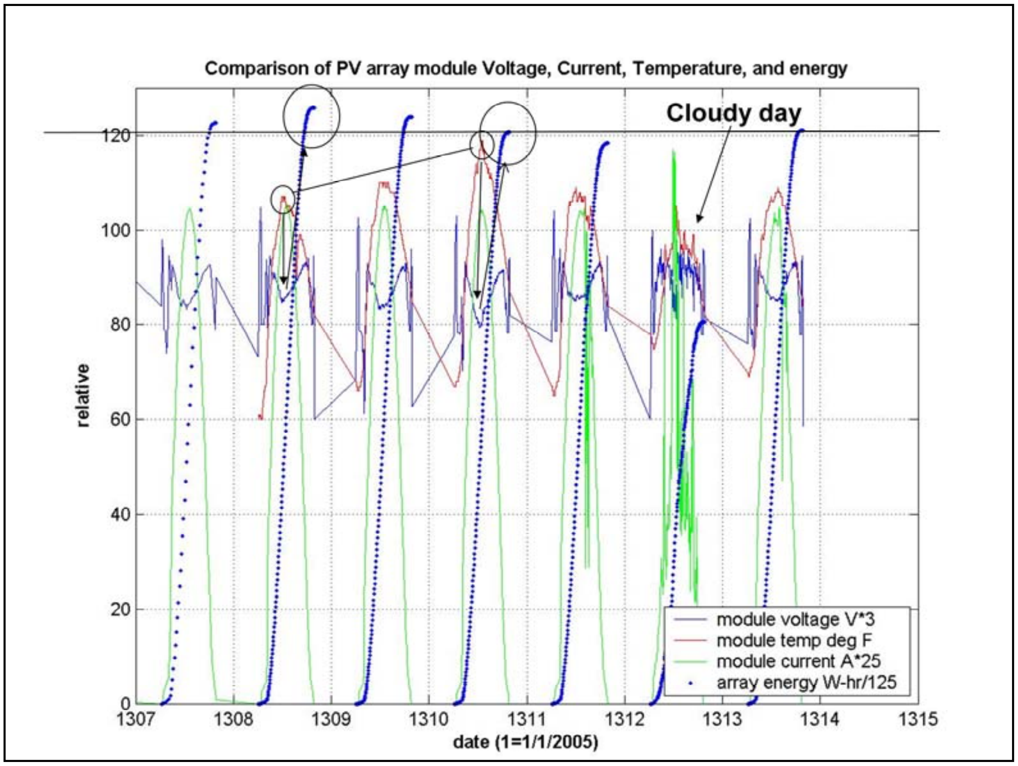
This graph is a plot of a PV panel current generated as a function of voltage. If you multiply the voltage by the current along the curve you get the power curve shown 'inside' the VI curve. Its Y-axis is on the right.

The 'maximum power point' of the panel is when operation is at the peak of the power curve—which is where the most power is generated. When the cell has no load (open circuit), the voltage is on the right side of the curve (43V) and no current is flowing. It doesn't take much light to bring the voltage up to Voc. When a load is applied, the voltage comes down along the curve as the current increases. A little past the maximum power point, the current flattens out but the voltage continues to drop—hence the reduction in power generated. The greater the load (lower resistance), the more to the left of the power curve you go.

The 'observed maximum' points shown are the highest nominal power that I usually observe in the summer. The 'typical maximum' is more commonly seen.

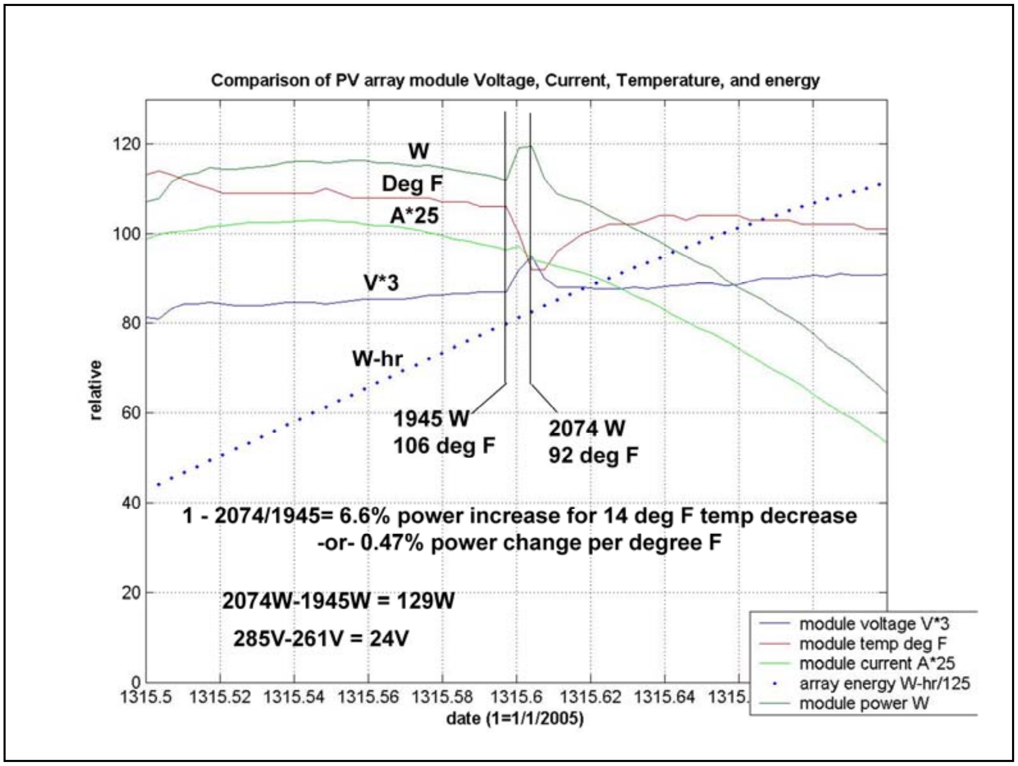


This plot shows a family of VI curves that illustrate the effect of temperature on the power generation. The higher the temperature, the more to the left the curve shifts. This has the effect of shifting the maximum power point to the left and down—as the voltage for a given current is less. In other words, the PV panel is less efficient at higher temperatures. There are some calculations that illustrate this later.



This plot is a bit complicated, but it illustrates the effect of temperature on the array and the effect of clouds. This is all data captured by dataloggers. The two larger circles show that the power generated is greater on the left, where the temperature is lower. Correspondingly, the voltage is lower when the power is lower due to temperature. The temperature has no noticeable effect on the current. This corresponds the the shifting left of the VI curve on the last slide.

The cloudy day shows considerably less power generated and much more effect on the current.



I hosed off the array to lower the temperature temporarily. This is illustrated by the 'bump' in the temperature in the plot. Correspondingly, the voltage increased and therefore the power.

The specifications for my photovoltaic arrays call out a 2.22 mV/deg C degradation.

Comparing this with my experimental evidence shown on the plot:

Spec sheet:

9 panels * 72 cells/panel *2.22 mV/deg C/cell * (14 deg F/1.8 deg F/deg C) = 9 *72 * 0.017 V = 11.2 V drop across 9 panels.

Data:

(285v – 261v) 24 V drop across 9 panels.

Factor of 2 difference. Possible error source: temperature measurement not measuring the true surface temperature of the panels. Sensor was on the back side of the panel not the front side.

The point is, the cooler the panels, the more efficient they are.

Calculations

Conversions:

•1 in/2.54 cm/in = .3937 in/cm -> 39.37 in/m

•39.37 in/m * 39.37 in/m = 1550 in2/m2

My array is:

•(3.5 ft x 4 ft)/panel = 14 ft2/panel

•14 ft2/panel * 144 in2/ft2 = 2016 in2/panel

•18 panels/array * 2016 in2/panel = 36288 in2/array

•36288 in2/array / 1550 in2/m2 = 23.4 m2/array

•2700 W/array (max) / 23.4 m2/array = 115.38 W/m2

•Max solar power/m2 = 1000 W 'insolation' average

•115.38/1000 W = 11.5 % efficiency

•My generation is 33% of my consumption. If the cell efficiency tripled, or about 35% efficient, then I could generate all that I used in a year. This efficiency has been demonstrated in the lab—but is expensive

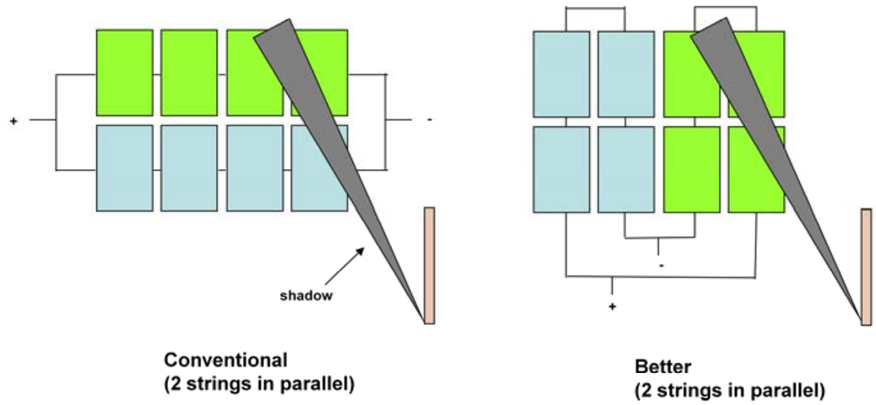
Note that kW is not to be confused with kW-h. kW is the unit of power at a given instant whereas kW-h or kWh is the measure of energy produced over a period of time. For example, one kW-h is 1 kW of power generated or consumed for 1 hour.

If you produced 1 kW of power for 6.6 hours, you would have generated 6.6 kW-h of energy—which is what we saw on slide 8 and how we derived the 'equivalent hour' number of 6.6.

6.6 kW-h/m2/day * 23.4 m2/array * 11.5% efficiency = 17.76 kW-h/day rated max.

Best seen is about 15 kW-h/day, so 15/17.76 = 84.4%, or about 15% less than rated maximum.

shading

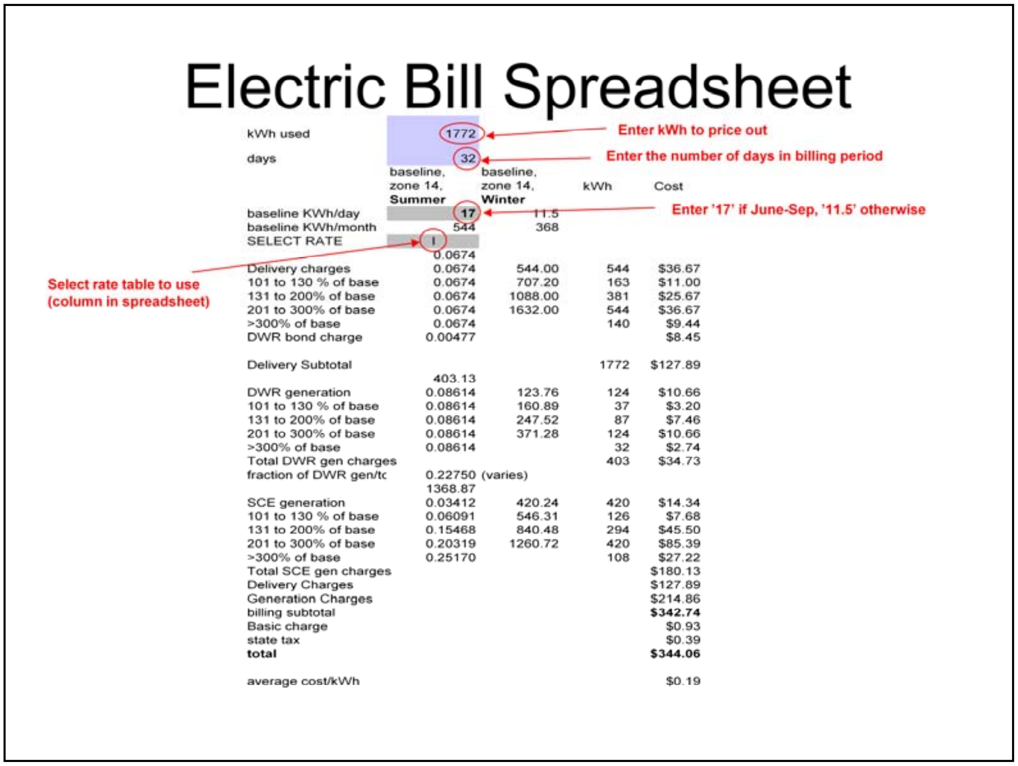


The left diagram shows a conventional arrangement of panels as two serial strings in parallel. An obstruction casting a shadow over both parallel strings has a greater effect on the power generation than shadowing only one of the two strings. So if you can characterize obstructions you might be able to alter the geometry of how the panels are strung together to minimize loss.

Misc. facts/data

- If you have obstructions, it is best to arrange the PV connections so that they concentrate on as few strings as possible.
- Maximum Power Point Tracking (MPPT) works best on single strings of modules.
  - However, it's OK to have parallel strings pointing at different angles on one MPPT controller. The difference in efficiency is about 1%.

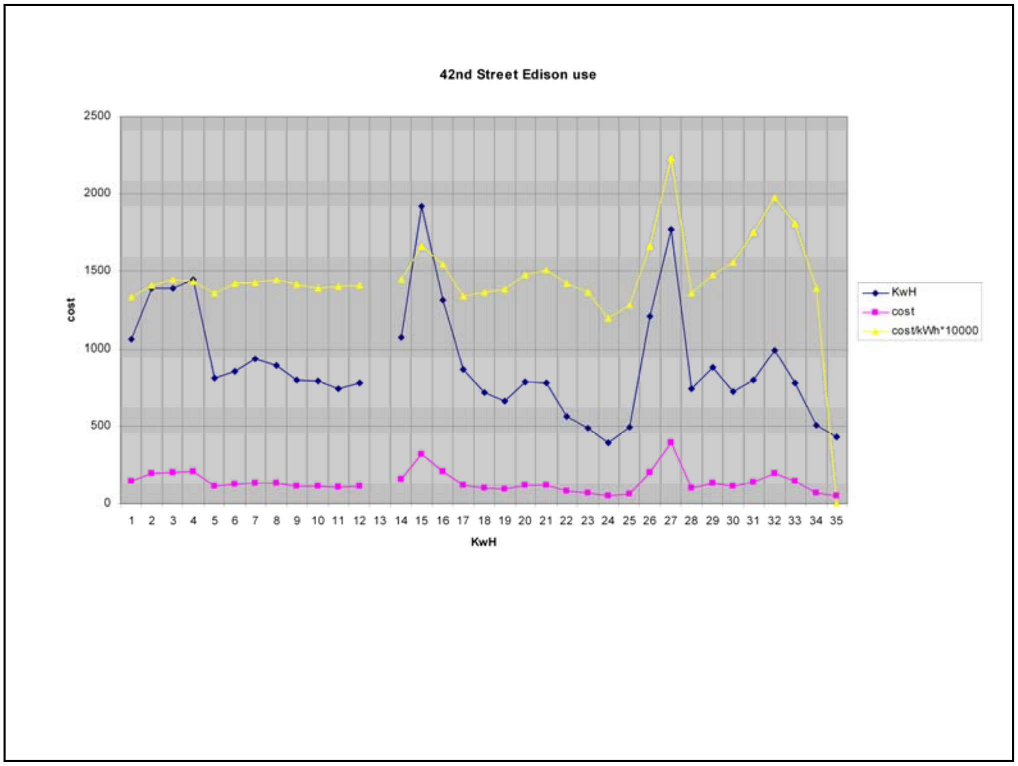
Ideally, you would have one MPPT controller for every panel, but that is cost prohibitive and impractical. It is more common to have one MPPT controller for each serial string, but it is perfectly acceptable to have only one MPPT controller for two or more serial strings paralleled. Experimental evidence shows a difference in efficiency of only about 1%.

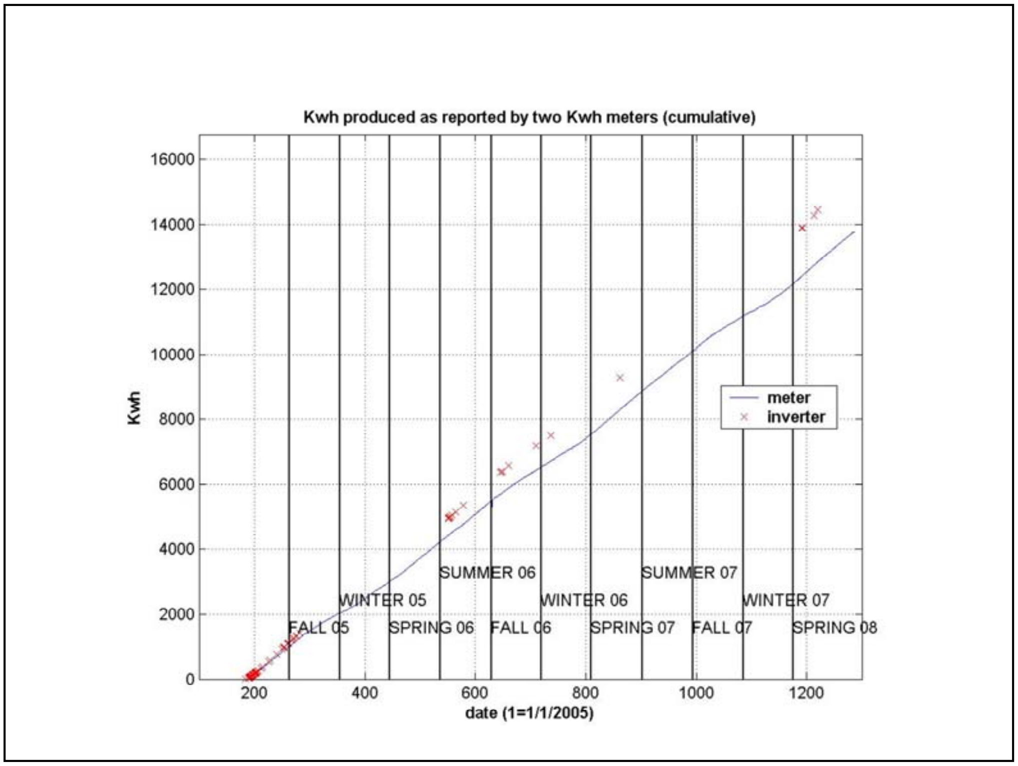


Electric Bill Spreadsheet

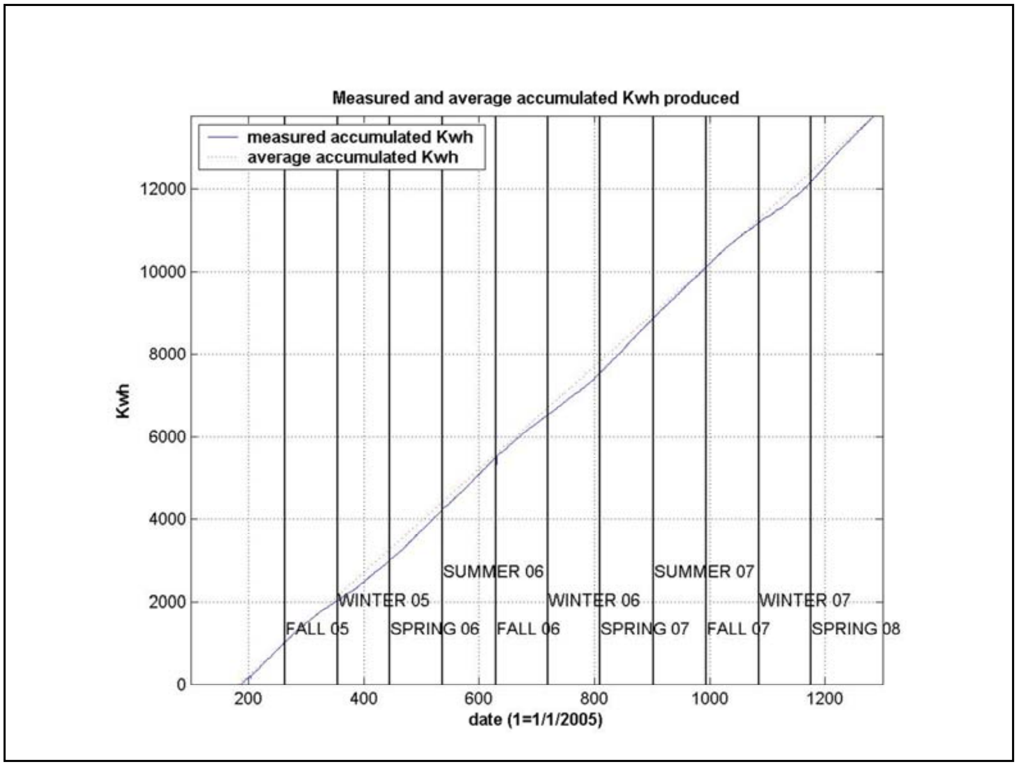
kWh used	1772			
days	32			
	baseline, zone 14, **Summer**	baseline, zone 14, **Winter**	kWh	Cost
baseline KWh/day	17	11.5		
baseline KWh/month	544	368		
SELECT RATE	I			
	0.0674			
Delivery charges	0.0674	544.00	544	$36.67
101 to 130 % of base	0.0674	707.20	163	$11.00
131 to 200% of base	0.0674	1088.00	381	$25.67
201 to 300% of base	0.0674	1632.00	544	$36.67
>300% of base	0.0674		140	$9.44
DWR bond charge	0.00477			$8.45
Delivery Subtotal			1772	$127.89
	403.13			
DWR generation	0.08614	123.76	124	$10.66
101 to 130 % of base	0.08614	160.89	37	$3.20
131 to 200% of base	0.08614	247.52	87	$7.46
201 to 300% of base	0.08614	371.28	124	$10.66
>300% of base	0.08614		32	$2.74
Total DWR gen charges			403	$34.73
fraction of DWR gen/tc	0.22750	(varies)		
	1368.87			
SCE generation	0.03412	420.24	420	$14.34
101 to 130 % of base	0.06091	546.31	126	$7.68
131 to 200% of base	0.15468	840.48	294	$45.50
201 to 300% of base	0.20319	1260.72	420	$85.39
>300% of base	0.25170		108	$27.22
Total SCE gen charges				$180.13
Delivery Charges				$127.89
Generation Charges				$214.86
billing subtotal				**$342.74**
Basic charge				$0.93
state tax				$0.39
total				**$344.06**
average cost/kWh				$0.19

I created a spreadsheet that mimics in some detail the machinations of the SCE electric bill. It was a bit like code-breaking. SCE breaks the bill into generation and delivery charges. The generation charge is further divided between DWR generation and SCE generation. Further, there is a different baseline rate in the summer than the winter. The number of billing days vary, and they change the rates on the average about every two months. This latter item is captured in a series of columns in the spreadsheet (out of view in this slide). I have captured rate changes from April 2005 to July 2008. By entering the column number here you can select what rate structure you want to use. Great for what-if comparisons. Changing the number of kWh used can be a good way of comparing costs with different usages.


42nd Street Edison use
2500
2000
1500
1000
500
0
cost
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32 33 34 35
KwH
KwH
cost
cost/kWh*10000



This plot shows the difference between two kW-h meters. One is part of the inverter that converts the solar-generated DC to AC and ties to the grid (red). The other is the kW-h meter with the spinning wheel. There is a consistent drift apart at a rate of about 12-14%.


Measured and average accumulated Kwh produced
measured accumulated Kwh
average accumulated Kwh
Kwh
0
2000
4000
6000
8000
10000
12000
200
400
600
800
1000
1200
date (1=1/1/2005)
FALL 05
WINTER 05
SPRING 06
SUMMER 06
FALL 06
WINTER 06
SPRING 07
SUMMER 07
FALL 07
WINTER 07
SPRING 08

A Tracking System Quote

not the system I ended up with

SYSTEM DESCRIPTION				
Solar Modules:	12	Isofoton	150 Watt	$ 6,948
Inverter:	1	R-Powr/ SMA	1.8 kW	$ 2,595
Module Mounting Hardware	2	Zomeworks Trackers		$ 2,986
Balance of System				$ 660
Equipment Subtotal				**$ 13,189**

COST AND SAVINGS	
Equipment Subtotal	$ 13,189
Tax	$ 956
Shipping (est)	$ 300
Installation	$ 2,240
Permit (est - payable to building department)	$ 501
TOU meter (est - payable to utility)	n/a
TOTAL SYSTEM VALUE	**$ 17,186**
Rebate ($3 per AC Watt)	$ 4,496
Tax Credit (7.5%)	$ 952
TOTAL COST TO YOU	**$ 11,738**
Example Savings per month	**$ 54**
Example Savings per Year	**$ 652**

Another Quote--Not the system I ended up with

SYSTEM DESCRIPTION			
Solar Modules:	16 Isofoton	150 Watt	$ 9,265
Inverter:	1 R-Powr/ SMA	2.5 kW	$ 3,066
Module Mounting Hardware	5 Unirac Flush Mount		$ 1,022
Balance of System			$ 480
Equipment Subtotal			**$ 13,833**

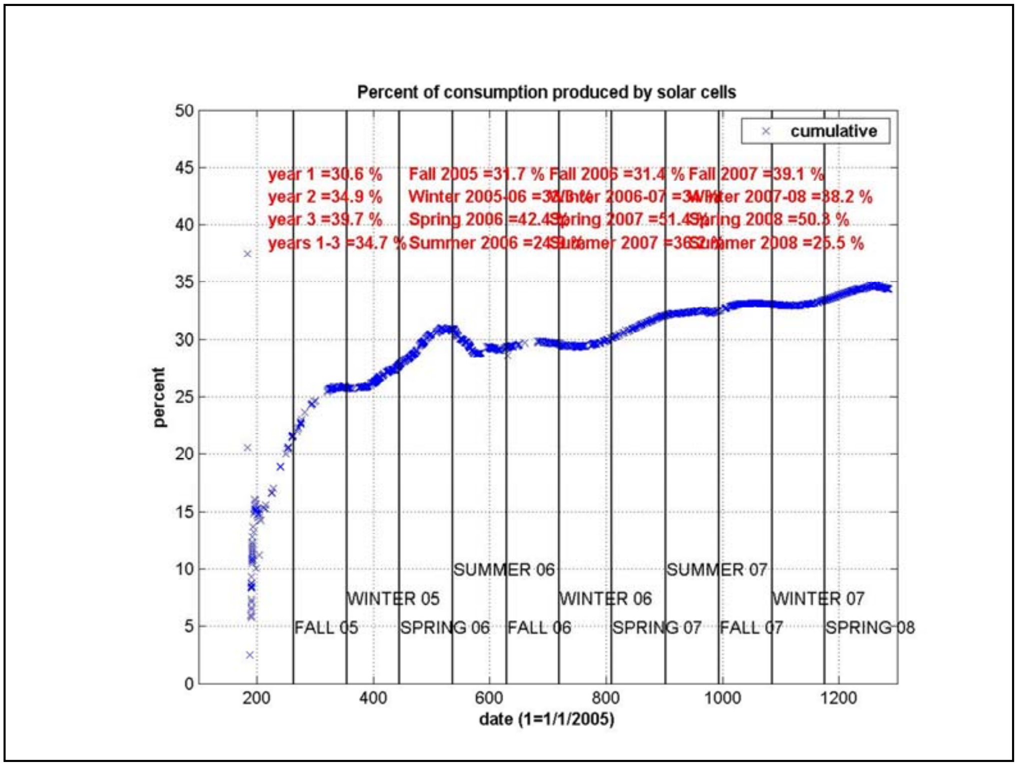
COST AND SAVINGS	
Equipment Subtotal	$ 13,833
Tax	$ 1,003
Shipping (est)	$ 300
Installation	$ 3,840
Permit (est - payable to building department)	$ 569
TOU meter (est - payable to utility)	n/a
TOTAL SYSTEM VALUE	**$ 19,545**
Rebate ($3 per AC Watt)	$ 6,060
Tax Credit (7.5%)	$ 1,011
TOTAL COST TO YOU	**$ 12,474**
Example Savings per month	**$ 56**
Example Savings per Year	**$ 670**

Quote for my system (2004)

SYSTEM DESCRIPTION			
Solar Modules:	18 Isofoton I-150S/24	150 Watt	$ 10,423
Inverter:	1 Fronius IG 3000	2700 Watt	$ 3,066
System Meter:	1 GE Cyclometer I70S		incl.
Module Mounting:	1 Custom Wood Shade Structure		$ 1,200
Balance of System			$ 1,080
Equipment Subtotal			**$ 15,769**

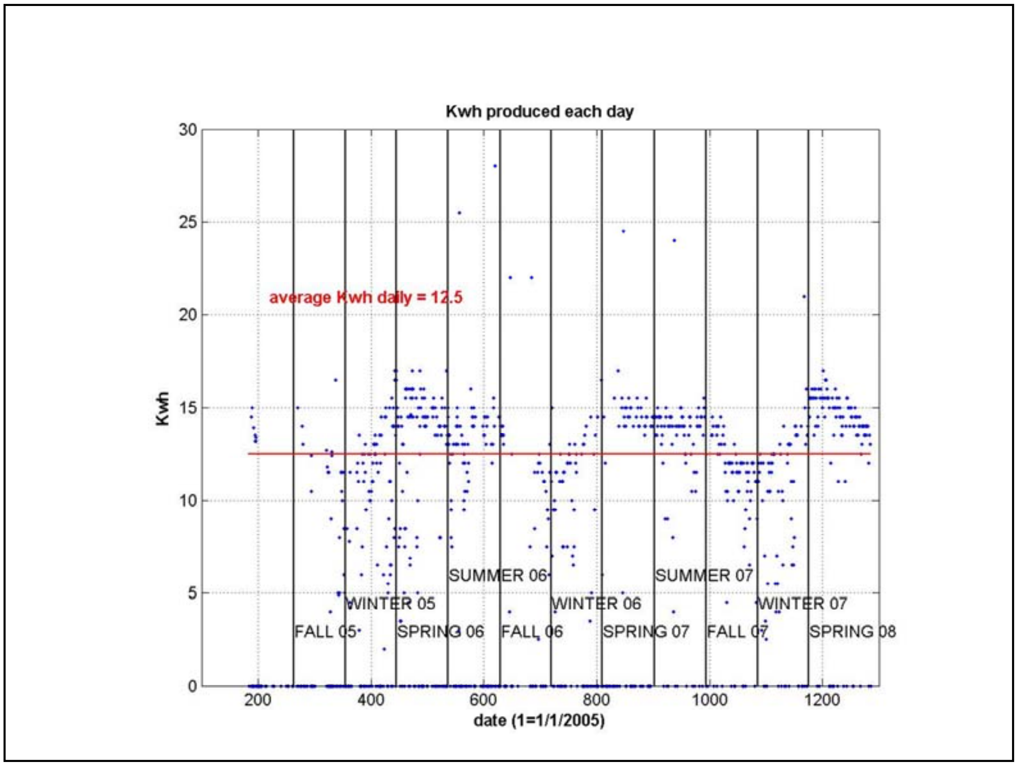
COST AND SAVINGS	
Equipment Subtotal	$ 15,769
Tax	$ 1,143
Shipping (est)	$ 300
Installation	$ 2,880
Permit	$ 603
TOU meter (est - payable to utility)	n/a
TOTAL SYSTEM VALUE	**$ 20,695**
Rebate ($3.20 per AC Watt)	$ 7,270.40
State Tax Credit (7.5%)	$ 1,007
TOTAL COST TO YOU	**$ 12,418**
Example Savings per month	**$ 61**
Example Savings per Year	**$ 734**

This is an exact copy of the system purchase and installation quote I got in July 2004. I had the system installed one year later and the actual cost was actually \$12418-\$12176.39= \$241.61 *less* than the estimate.

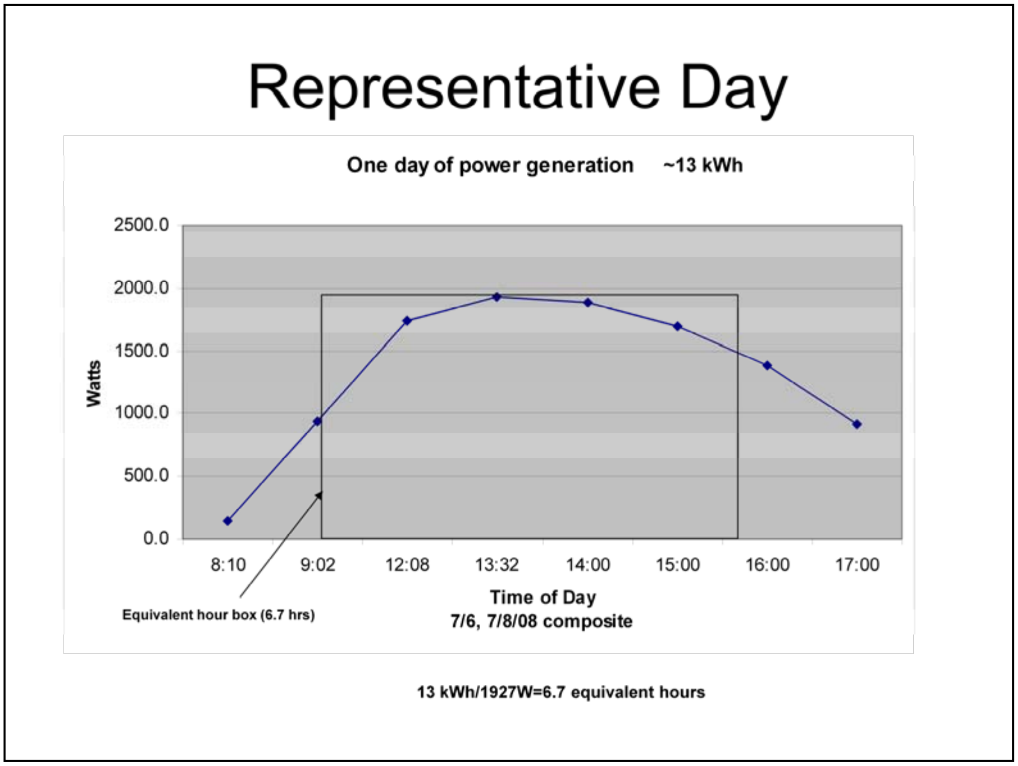


This plot shows the percent of energy consumption generated by my 1st PV array during its first three years of operation. It is an aggregate plot, a sort of ‘infinite response.’ It shows that as time goes on, I am increasing the percentage generated. The array is not getting more efficient, but I am conserving more—less air conditioning, CF bulbs, more energy efficient appliances, turning off electronics that aren’t being used, etc.

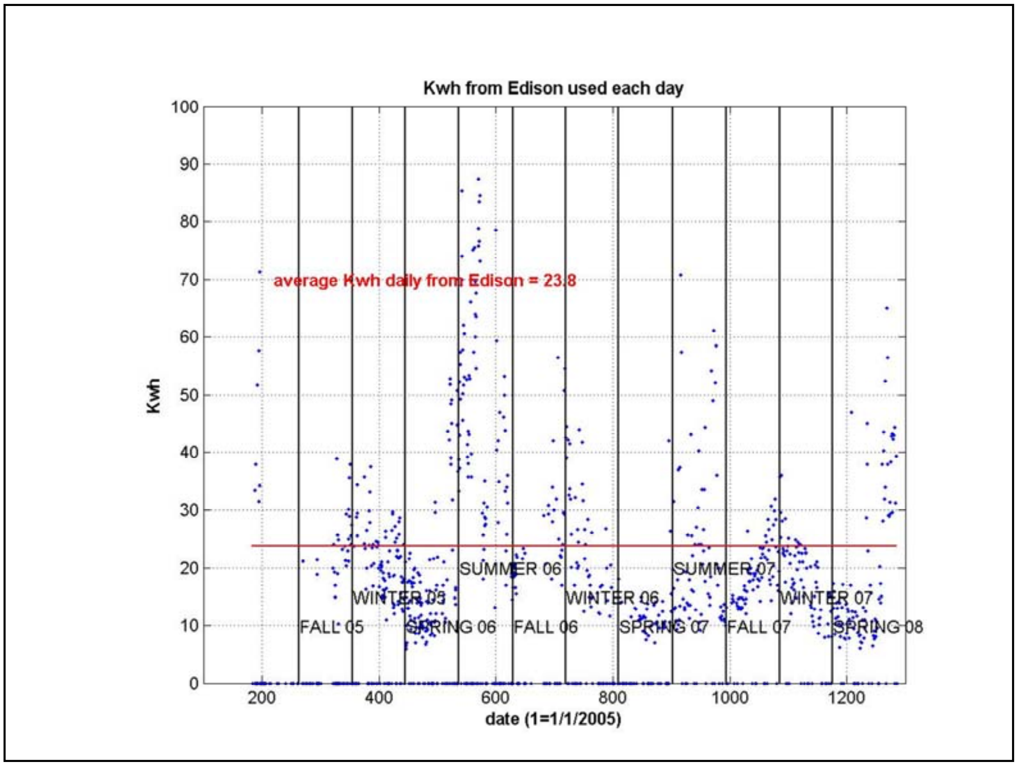
The extremely low percentages to the left are an artifact of a different way I was taking the data. I was taking the data several times a day instead of once a day as I did later.



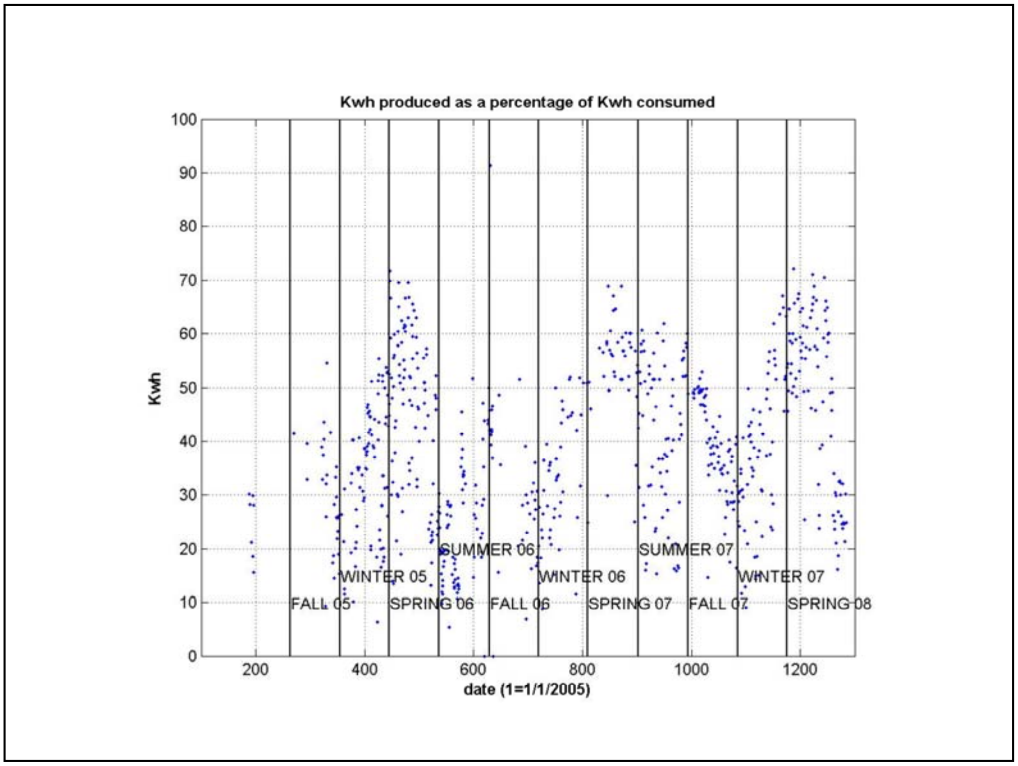
This plot shows the number of kWh (energy) used each day over three years. You can see that more energy is used in the summer than in the winter. The red line is the average daily energy usage over the three year period (12.5 kWh).



This plot illustrates a typical power generation curve over the course of a day. As the data was hand-collected, it is actually a composite over a couple of days. It shows a maximum power of about 2000 watts around noon solar time (13:00 daylight time) and illustrates the concept of 'equivalent hours,' which is a way of conveying the area under the curve for a day. As shown here, equivalent hours (6.7) times the maximum power (2000 watts) yields the total watt-hours of energy generated for the day (13400 W-h or 13.4 kW-h).



This plot shows the energy that I used from the power company each day over three years. Much more energy was consumed in the summer due to the use of a whole house air conditioner. The red line is the average daily energy consumption from the power company over three years (23.8 kWh).



This plot illustrates the energy produced by the 1st PV array as a percentage of energy consumed during its first three years of operation. You can see that in the spring the percentage goes up (geometry of the array is such that it produces the most energy at the same time that the least energy is consumed—less air conditioning, heating).