

# Residential 4.8kW Grid-tie Photovoltaic

## Abstract

We present the design, engineering analysis, and economic forecast for a rather large grid-tied residential PV system.

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## Preliminary Financial Analysis

Before undertaking further design, a preliminary financial model was prepared evaluating the payoff period for rooftop PV. Models were constructed for both Net Energy Metering (NEM) and wholesale pricing (Schedule Q), equipment only purchases and fully installed pricing, and with and without federal and State of Hawaii tax credits. The results of this analysis are shown below.

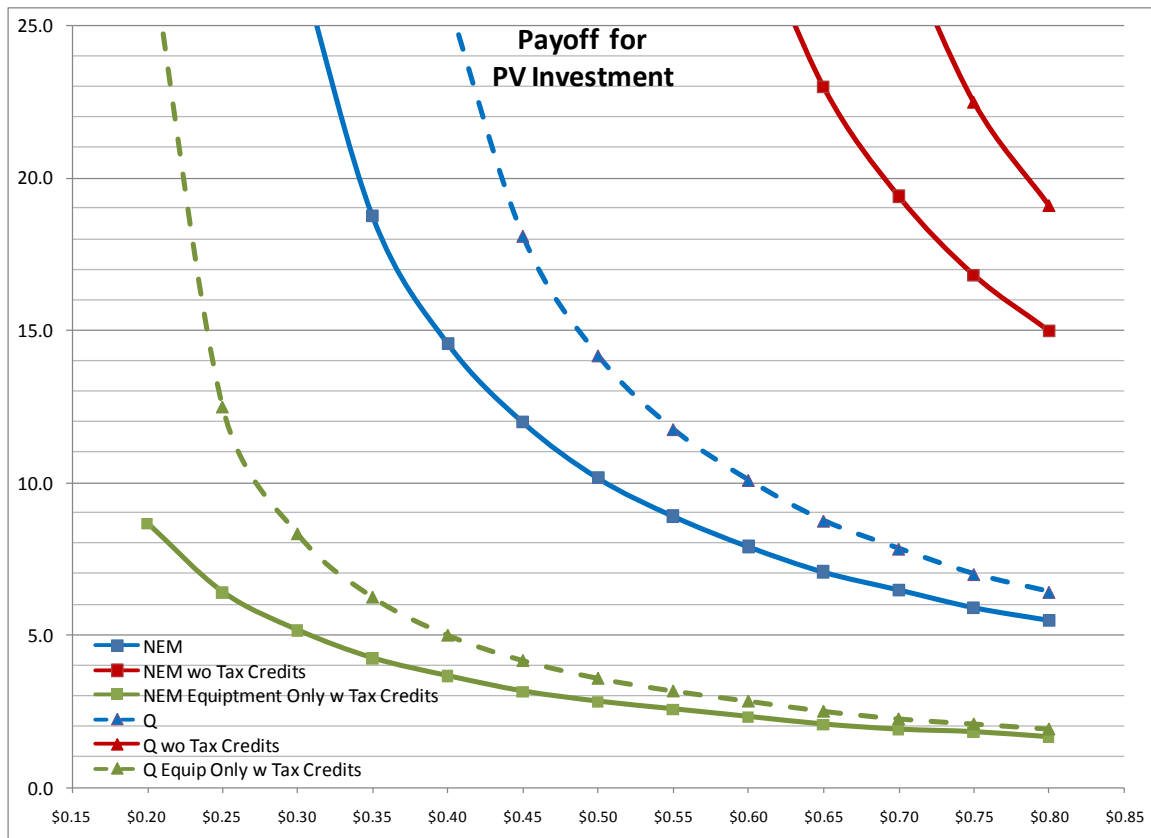


Figure 1. PV Investment Payoff

The payoff for the project under consideration, self-installed PV, tariffed as NEM, and with state and federal tax credits, is highly favorable.

Conclusions beyond the scope of this document are suggested. PV without tax credits is unlikely to ever payoff financially and would require electric rates of \$.75/KWH or greater to be viable. Even with tax credits, paying normal prices for installed PV only become financially viable when electric rates exceed \$.40/KWH.

## Goals, Strategies, & Assumptions

These design alternatives seek an optimum solution for rooftop PV solar for a net-metered grid-tie system.

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We assume self installation for the roof shown here.

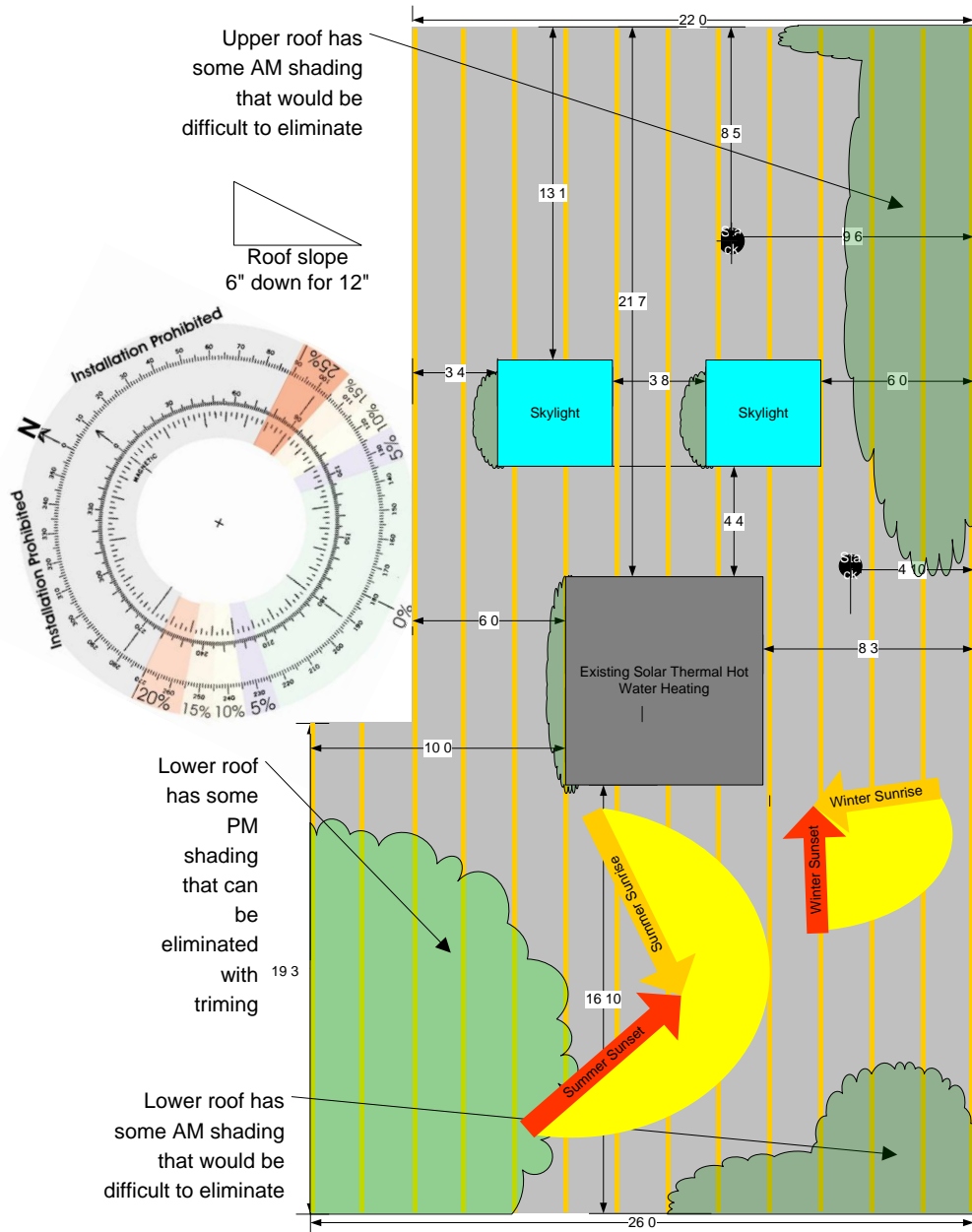


Figure 2. Roof

The residential usage is approximately 25mWh / day and we desire a system with average generation nearing this value to produce a net-metered near zero utility consumption.

Based on location, orientation, and tilt of installation, using the PV Watts calculator at <http://rredc.nrel.gov/solar/calculators/PVWATTS> we generate the following representative performance data and estimate the PV DC Watts needs to supply 25kWh AC / day.

Table 1. Solar Factor for 22°3'N 159°22'W, Facing 245° (true)

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Month	Solar Radiation (kWh/m <sup>2</sup> /day)	PV Watts Needed for 25kWh/day
Jan	4.62	7,676
Feb	5.00	7,877
March	4.79	7,332
Apr	5.16	7,073
May	5.04	7,073
June	5.35	6,963
July	5.16	6,990
Aug	5.50	6,557
Sept	5.69	6,545
Oct	5.20	6,870
Nov	4.30	8,571
Dec	4.30	8,238

On average, to supply 25kWh/day, a 7,314 watt (DC) photovoltaic array is required. It is further desirable, but not required, to support possible expansion to an additional 20kWh / day to power a plug in hybrid for 30 miles/day. Such requirements would represent an increase of almost double the values shown above.

The system will NOT initially incorporate any batteries for grid backup, but it is desirable if the resulting system could be extensible to support this functionality.

## Design Using Typical Single Crystal Si 200W Panels

Packaged systems are available using typical single crystal Si panels.

### *Technology & Limitations*

Typical 200W single crystal Si PV modules are 1m x 1.5m and cost approximately \$800.

### *Cost / Performance*

Packaged systems with 24 200W panels and inverter are available for \$17,405 (including shipping to HI) from dmsolar.com including SB4000US inverter, 24x SF190-27-M modules made by Solar Fun (<http://www.aeesolar.com/PDFs/SF190-27-M.pdf>), and shipping.

Track mounting hardware will cost \$1,256, misc hardware and wiring will cost approximately \$1,197 for a total system cost of \$26,858, reduced by \$2,000 in federal energy tax credit and reduced by \$5,000 for Hawaii tax credit for an all in cost of \$19,858.

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Table 2. Predicted Performance for 4.8kW (DC) Single Crystal PV

Month	kWh/kW Ratio	Daily AC Wh Generated	Monthly Savings @ .35/kWh	Monthly Savings @ (\$110/bbl oil) .50/kWh	Monthly CO2 Reduction in lbs	Monthly Diesel Reduction in gal
Jan	3.3	15,633	\$166	\$238	612	29
Feb	3.2	15,233	\$162	\$232	597	29
March	3.4	16,367	\$174	\$249	641	31
Apr	3.5	16,967	\$181	\$258	665	32
May	3.5	16,967	\$181	\$258	665	32
June	3.6	17,233	\$183	\$262	675	32
July	3.6	17,167	\$183	\$261	673	32
Aug	3.8	18,300	\$195	\$278	717	34
Sept	3.8	18,333	\$195	\$279	718	34
Oct	3.6	17,467	\$186	\$266	684	33
Nov	2.9	14,000	\$149	\$213	548	26
Dec	3.0	14,567	\$155	\$222	571	27
<b>Annual</b>			<b>\$2,110</b>	<b>\$3,015</b>	<b>7,766</b>	<b>371</b>

Notice the actual daily kWh falls short of the 25 required and the annual average generation results in only \$2,563 of the required electricity.

For our simple analysis we will ignore the cost of capital and assume an average savings of \$2,563 / year resulting in a 7.7 year payoff.<sup>1</sup>

## Optimizing Tax Credits

If the system can be installed in two calendar years, additional state and federal tax credits are available. Assuming a two year install with the first year including the 4.8kW inverter and 10 panels (with associated mounting track expenses and misc costs, and a subsequent installation of 14 panels (with associated mounting track expenses and misc costs), the following financials results

Table 3. Financials for Two Year Installation to maximize Tax Credits

Year	PV	Track	Misc	Gross	Credits	Net
1	\$12,080	\$651	\$809	\$13,540	\$6,739	\$6,801
2	\$12,325	\$605	\$388	\$13,318	\$6,661	\$6,657

Notice the total tax credit increases from \$7000 to \$6,739 + \$6,661. The resulting lower net cost means the system financial payoff occurs after only 5.3 years!

## Roof Layout

Finding space for only 24 panels, albeit larger panels, is not difficult. Layout design therefore becomes an exercise to avoid any shaded areas and find compromises between aesthetics and simple mounting and construction. Note that shaded areas of the roof are avoided, and packing density of the panels is high to simplify construction. However, we

<sup>1</sup> A more correct cost / performance / payback calculation would consider the cost of capital, a real estimate of the expected increase in oil prices, and a 1% decrease in module output / year.

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have sacrificed symmetry that might have improved the aesthetics. And we have brought more of the panels down to lower parts of the roof, also sacrificing some aesthetics.

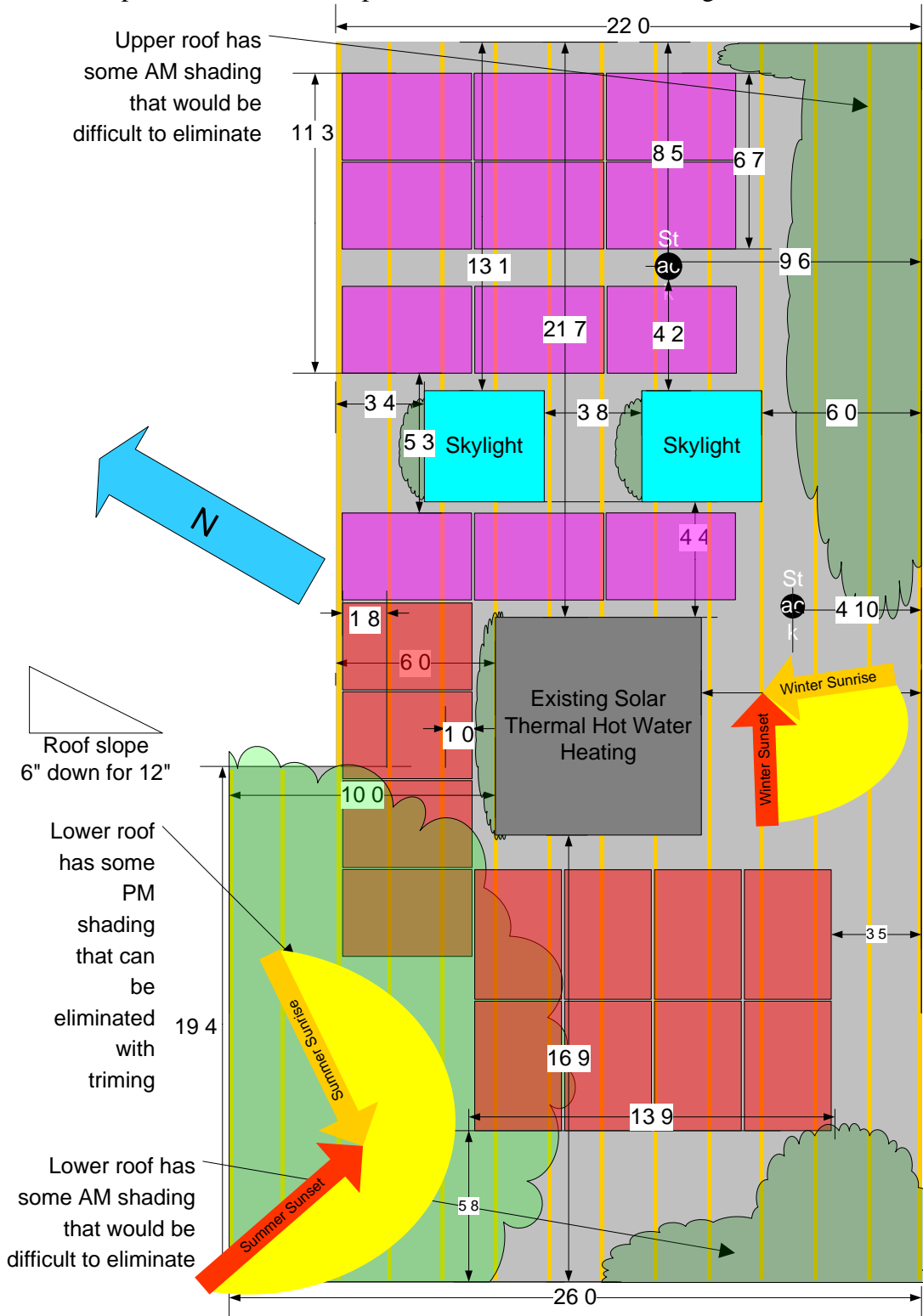


Figure 3. Roof layout for 24x 1m x 1.5m modules

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## Wiring, Invertors, Interconnections

The Sunny Boy 4000US inverter is a perfect fit for 24 panels, 2 strings of 12 panels each, operating near its efficient maximum current and voltage.

**Table 4. PV Array vs. Inverter Specifications**

PV-array of 2x12 SF190-27-M	<b>IDEAL</b>	<i>Sunny Boy 4000US Inverter</i>
Power at STC	4.8kW	< 5.0kW
Min $V_{mpt}$ of at 40°C	320V	> 250V
Max $V_{oc}$ at 10°C	396V	< 480V
DC current of at $V_{mpt}$	14.98A	< 18A
system voltage at STC	396V	< 600V
		Max DC input Power
		Min $V_{mpt}$
		Max $V_{oc}$
		Max DC operating current
		Max voltage

Bringing down DC +/- for each of two strings will connect directly to the SBA DC shut off connected to the inverter. Total DC Wiring loss for 10AWG for both strings (2x 7.5A ), assuming 400ft total will be 23W (0.5%).

The inverter will be collocated by the exterior main AC disconnect panel, making total AC wiring losses for 10AWG (20A) only 2W (0.05%).

There is little exceptional about the wiring employing standard exterior wiring techniques from roof to inverter and inverter to main AC disconnect panel. It is worth noting

- Module interconnect wiring is exposed and uses Solarline MC waterproof connectors and USE-2/RHW-2 10AWG cable rated for exterior use in damp conditions and is UV/sunlight resistant.
- Code requires bonding<sup>2</sup> for modules and module track. (Systems relying on the mechanical connection between modules frames and racks for bonding are unreliable.) Most modules have poor or no bonding facilities, therefore tin plated copper lugs with stainless steel screws rated for use with aluminum and for exterior, including direct burial will be used to create a continues bond for all modules brought down to the main panel. The lugs allow a single module to be disconnected and removed without breaking the bond integrity of other modules.<sup>3</sup>
- Track bonding does not require the ability to easily remove one rail, therefore track bonding could be made using two number 10, stainless steel, flat washers on a 10-32



**Figure 4. Solarline connectors**



**Figure 5. IlSCO GBL-4DBT lug**

<sup>2</sup> The term grounding is often used mistakenly when *bonding* is actually intended. Grounding metal parts to the earth in premises wiring is only useful to provide a path for lightning, shunting high-frequency noise, or reducing static discharge; Bonding all metal parts together and then to the system winding (typically to the X0 terminal of a transformer) is done to provide a low-impedance path to the source (system) to facilitate the opening of the circuit-protection device to remove dangerous voltage on metal parts. In addition, bonding the system to metal parts (typically to the X0 terminal of a transformer) stabilizes the system voltage to the metal parts and it provides a zero system reference (to the metal parts).

<sup>3</sup> PV Array Grounding, by John Wiles, Sponsored by the Photovoltaic Systems Assistance Center, Sandia National Laboratories [http://photovoltaics.sandia.gov/docs/PDF/PV\\_grounding\\_CC\\_HP\\_102.pdf](http://photovoltaics.sandia.gov/docs/PDF/PV_grounding_CC_HP_102.pdf)

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screw, and copper wire wrapped around the screw between the two flat washers that isolate the copper bonding conductor from the aluminum track. (The 10-32 screw is required so that at least two threads are cut into the aluminum (a general UL requirement for connections of this kind). The thread-forming screw is required so that an airtight, oxygen-free mating is assured between the screw and the frame to prevent the aluminum from oxidizing.)<sup>4</sup> Of course, it is probably easier just to use the same lugs used for modules.

The following wiring diagram is helpful to understand the interconnections, and is required for the electrical building permit.

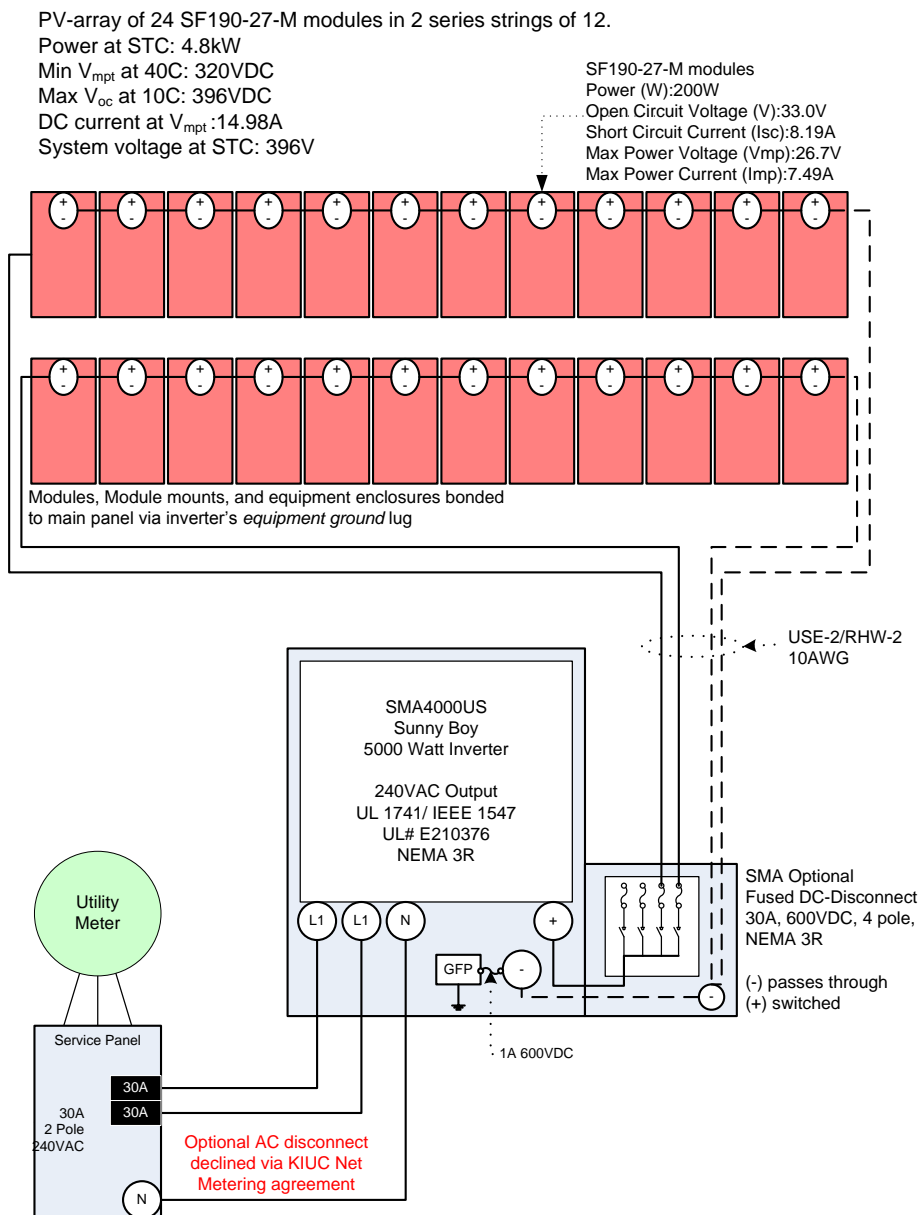


Figure 6. Wiring Diagram

<sup>4</sup> Ibid.

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The following misc items are required and sometimes difficult to obtain locally.

**Table 5. Misc Wiring**

Each	Total	Qty	Part#	
\$35.00	\$105.00	3	51.3414	Bag of 10 lay-in grounding lugs w/ screws
\$21.00	\$21.00	1	52.9107	Solarline 1 6ft m/f extension cable
\$69.00	\$138.00	2	52.9083	10 AWG white negative 100ft Solarline 1 cable
\$68.00	\$136.00	2	52.9082	10 AWG black negative 100ft Solarline 1 cable
\$4.80	\$9.60	2	54.3252	Waterproof strain relief 1/2" w 2 round holes for USE #10
	<b>\$409.60</b>			

## ***PV Track Mounting***

Modules will be mounted on purpose-designed *SolarMount* PV track manufactured by *UniRac*.

**Table 6. Racking Hardware by UniRac / SolarMount**

Part No	Qty	Each	Total	Desc (UniRac SolarMount)
303114	1	\$485.00	\$485.00	204" Light 2-rail Pro-Pak (10 rails)
303211	1	\$115.43	\$115.43	144" Light 2-rail kits
303211	1	\$130.28	\$130.28	168" Light 2-rail kits
303203	2	\$105.00	\$210.00	72" Light 2-rail kits
310067	2	\$46.58	\$93.16	L-Feet (20) with s/s hardware
320017	2	\$28.19	\$56.38	20x Top Mount End Clamps size F
320021	2	\$28.19	\$56.38	20x Top Mount Mid Clamps size F
			\$300.00	shipping (est)

(Many thanks to Justin at DC Power Systems who looked at my track layout and suggested the 204" Pro-Pak to save me money.)

## ***Incremental Installation***

The system will be installed over two calendar years to maximize federal and state tax credits. In the first year a 2.0kW system will be installed consisting of 10 modules and the inverter. In the second year an additional 14 modules will be installed to bring the total system capacity to 4.8kW.

Note that in year one, we have one string of 10 panels, but after the year 2 expansion we have two strings of 12 panels each.

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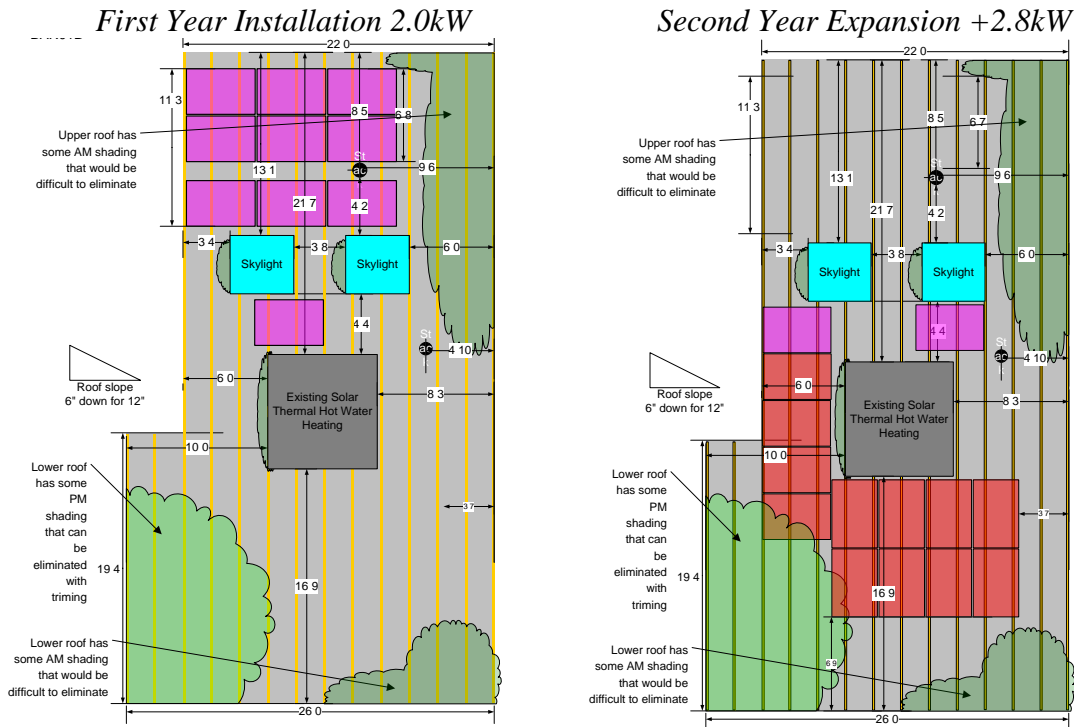


Figure 7. Incremental installation layout

The electrical diagram for the first incremental installation shown below.

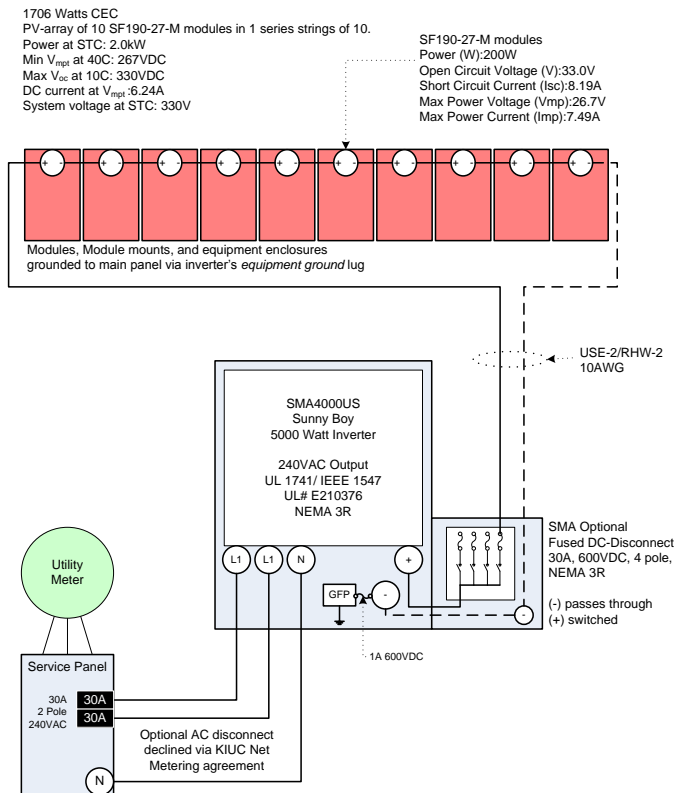


Figure 8. Year One Wiring Diagram

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## Results

The following table presents a comparison of the key differences between the alternatives considered, and some information about having the 4.8kW system professional installed. The table assumes a two year installation to maximize tax credits. (For the professional installed option, presumably the installation could be stretched out over even more years to increase the tax credits and therefore reduce the payoff. However, labor for such a installation would increase nonlinearly and therefore some of the financial advantage of more tax credits would be offset by increased total system cost.)

**Table 7. Comparison of a-Si, Single Crystal Si, and Professionally Installed Solutions**

	<i>3,780W (90x a-Si thin-film Modules) Equipment Only</i>	<i>4,800W (24x Single crystal Si Modules) Equipment Only</i>	<i>4,800W Professional Installed</i>
<i>Panel cost/watt</i>	\$3.00/w	\$4.00/w	
<i>Panel watts/m<sup>2</sup></i>	53 W/m <sup>2</sup>	133 W/m <sup>2</sup>	
<i>Net cost after Fed &amp; HI tax credits</i>	\$10,396	\$13,458	\$34,000
<i>Payoff</i>	5.4 years	5.3 years	13.3 years
<i>kWh Contribution</i>	50%	66%	
<i>CO2 Savings</i>	278 lbs CO <sup>2</sup> / year	7,766 lbs CO <sup>2</sup> / year	
<i>Diesel Savings</i>	gallons / year	gallons / year	
<i>Effort (deltas only)</i>	Mounting 90 panels / wiring 15 strings	Mounting 24 panels / wiring 2 strings	Easy – just watch!
<i>Aesthetics</i>	cool looking 100% coverage		
<i>Performance</i>	some panels forced into partial shade; A-Si panels better in low light	Superior concentration of panels on the never shaded highest roof	
<i>Expansion</i>	None available	1kW – 2kW possible increase	

## Conclusions

- The planned sizing for a 4.8kW DC system is appropriate. It approaches 73% of the required capacity in summer months and supplies an average of 66% of our required capacity. Expecting further conservation and slightly lower usage, a much larger system might exceed needs and become un-economic because net-metering limits the payback to net zero.
- The low w/cm<sup>2</sup> for thin-film a-Si is impractical for our needs because of the roof coverage required for the large number of panels and the complexity of installation. (This technology seems more appropriate for large projects where space is not at a premium and where uniform mounting structures are fabricated, e.g. for ground utility-scale installation or large commercial building installations.
- Professional installation is not completely contraindicated by this analysis, especially when non-financial criteria are considered, e.g. carbon footprint. However before that option should be pursued, more sophisticated financial analysis should consider the cost of capital, realistic estimates of future oil prices, and declining module effectiveness.

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- Although we did not subject the financial results to a formal sensitivity analysis around the tax credits, it seems clear the \$5,000 State of Hawaii tax credit and to a lesser degree the \$2,000 federal tax credit are essential to providing a reasonably favorable financial payback. (Thus the financial payback gets progressively poorer as the total *annual* system cost exceeds \$15,000 where the Hawaii tax credit tops out, necessitating a multi-year installation.)

The remaining conclusions focus on the self-installed 4.8kW results presented above.

- There is a reasonable pay off time, e.g. around 5.3 years when installed over 2 years to maximize tax credits,
- It has other substantial advantages, e.g. reducing our CO<sup>2</sup> footprint by 7,766 lbs annually.
- There might be a better payback by waiting for additional or larger tax credits, but that unknown seems too risky to wait for.
- It's a fun project, I'll enjoy doing it.

All of these conclusions make the self-installed option a choice worth proceeding with, contingent on personal equity. If equity supports the \$26,858 investment, dropping to \$13,458 after tax credits, then this project is worth doing.

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## Appendix 1 Design Using Lowest Cost / Watt a-Si Panels

Currently, the lowest cost/watt PV panels generally available are EPV SOLAR, Inc's amorphous silicon (a-Si) thin-film modules. Their 42W 25 in. x 49 in. modules are available for \$120/panel in quantities appropriate for this application.

### Technology & Limitations

The striking benefit of this technology is its low price per watt. The serious limitation is the inefficiency manifesting itself as low watt/cm<sup>2</sup> performance.

In practice, this limits the total capacity available for our project to the maximum number of panels we can install. The roof layout for these panels shown below covers the entire roof with 90 panels but leaves absolutely no room for expansion.

### Cost / Performance

Dominating the cost of the system, 96 panels are \$12,096.<sup>5</sup> Mounting hardware and wiring will cost approximately \$2000. And a KACO Blue Planet 2901xi grid-tied inverter will cost approximately \$1800 for a total system cost of \$17,396, reduced by \$2,000 in federal energy tax credit and reduced by \$5,000 for Hawaii tax credit for an all in cost of \$10,396.

The following table shows the expected generation performance and monthly savings for such a system.

**Table 8. Predicted Performance for 3.8kW (DC) a-Si PV**

Month	kWh/kW Ratio	Daily AC Wh Generated	Monthly Savings @ .35/kWh	Monthly Savings @ .50/kWh (\$110/bbl oil)	Monthly CO2 Reduction in lbs	Monthly Diesel Reduction in gal
Jan	3.3	11,725	\$125	\$178	459	22
Feb	3.2	11,425	\$122	\$174	448	21
March	3.4	12,275	\$131	\$187	481	23
Apr	3.5	12,725	\$135	\$194	499	24
May	3.5	12,725	\$135	\$194	499	24
June	3.6	12,925	\$138	\$197	506	24
July	3.6	12,875	\$137	\$196	504	24
Aug	3.8	13,725	\$146	\$209	538	26
Sept	3.8	13,750	\$146	\$209	539	26
Oct	3.6	13,100	\$139	\$199	513	25
Nov	2.9	10,500	\$112	\$160	411	20
Dec	3.0	10,925	\$116	\$166	428	20
<b>Annual</b>			<b>\$1,583</b>	<b>\$2,261</b>	<b>5,825</b>	<b>278</b>

Notice the actual daily kWh falls significantly short of the 25 required and the annual average generation results in only \$1,922 of the required electricity.

<sup>5</sup> Although we only need 85 modules, they are only sold in quantities of 16 or 32.

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For our simple analysis we will ignore the cost of capital and assume an average savings of \$8,896 / year resulting in a year payoff.

## Roof Layout

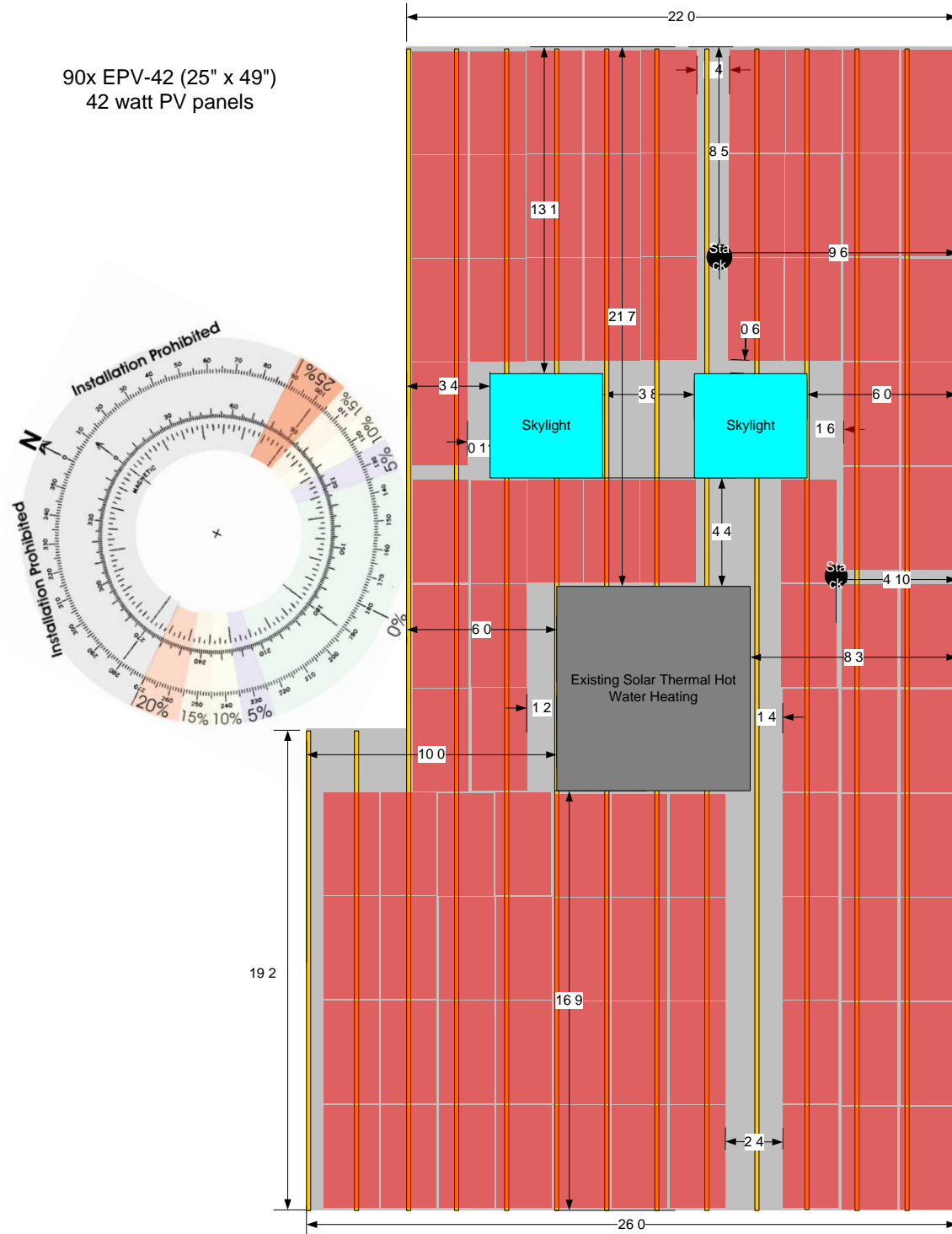


Figure 9. Roof layout for 25" x 49" EPV modules

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Notice panels must be added modulo the string size, but the string size can be changed in the design phase.

## ***Wiring, Invertors, Interconnections***

Increasing string size simplifies wiring, but results in higher voltages between the panels and combiner / inverter. Assuming the typical 600V limit of USA UL wiring, maximum string size is limited to 6 panels, resulting in a design for 90 panels of 15 strings of 6 panels.

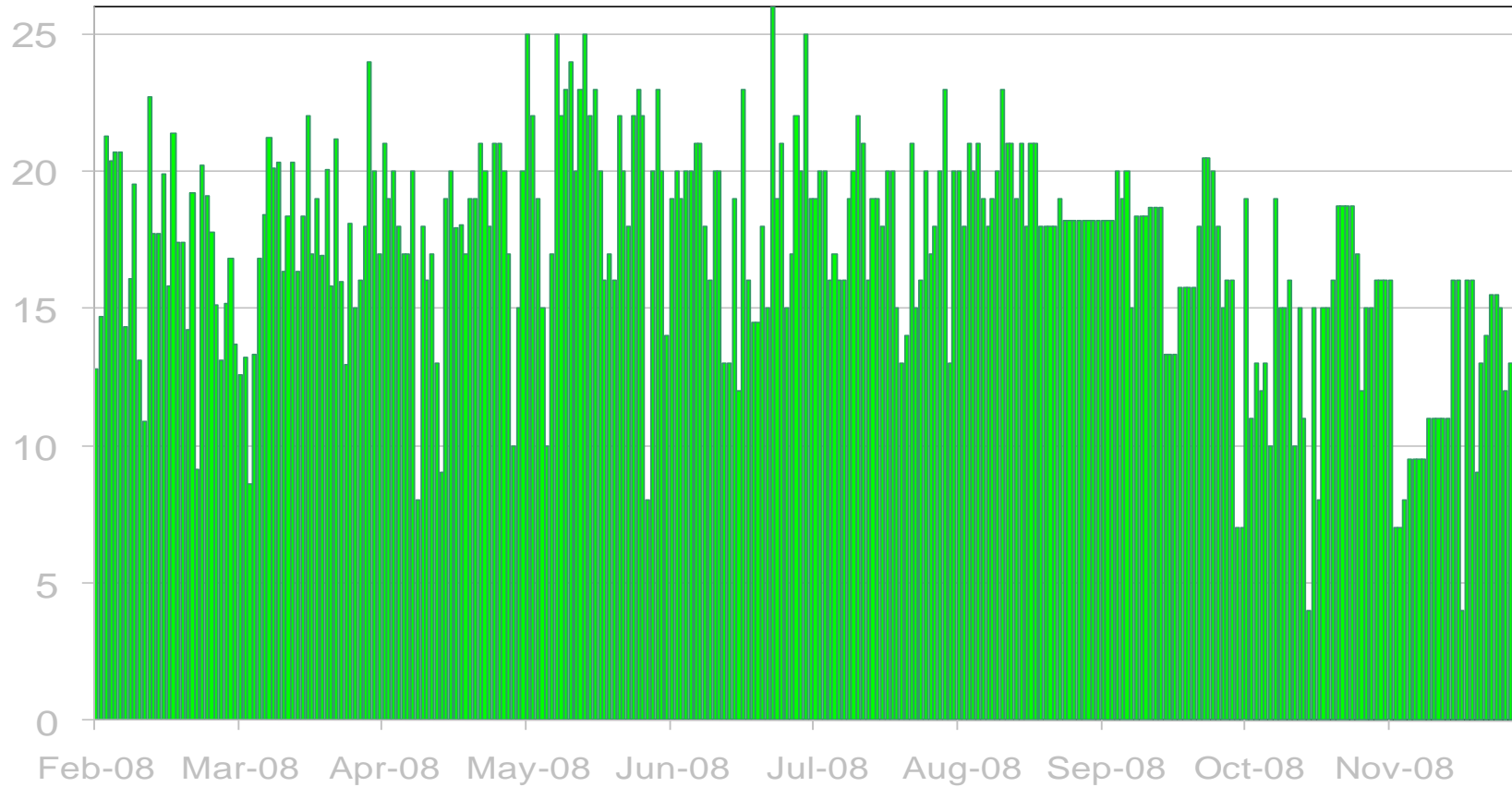
## ***Conclusions***

This design is impractical for our requirements: the lower  $W/cm^2$  performance limits the total system output below the desired level even when roof packing density exceeds a practical level.

# Residential 4.8kW Grid-tie Photovoltaic

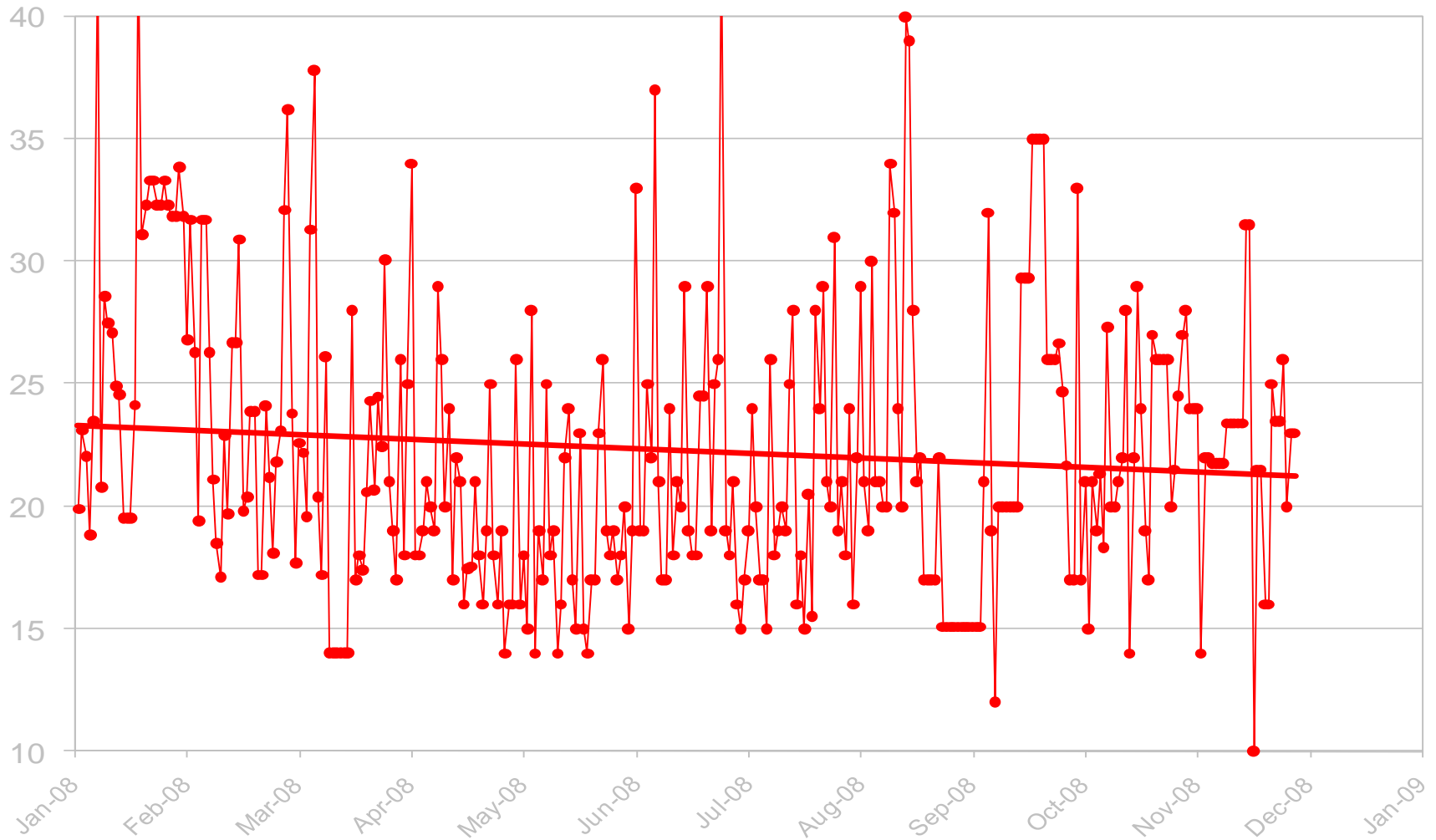
## Appendix 2 Results

### *Photovoltaic Generation*



# Residential 4.8kW Grid-tie Photovoltaic

## Demand Reduction



# Residential 4.8kW Grid-tie Photovoltaic

Net Daily PV Production, kWh Purchased / Sold

