Grid Tied Electric Power System for a Home in South Jersey

ECE 7800 Renewable Energy Systems Spring 2019

Matt Ballas

Thursday 24th September, 2020

Contents

1 Introduction

This project aims to create a PV grid-tied system for a home in Millville, NJ. The area of Millville NJ is not known for it's "green" architecture, as most of the homes, including the one being designed on, were built in the 70's. This means that often in the home there are various inefficiencies including drafts, bad insulation, poor use of space, and old utility systems that simply draw too much power in order to properly cool, run, and house an average family. However, these houses are often built with gorgeous large roofs with the potential to house a large array of solar panels, as well as local electric companies offering various incentives and abilities to choose where you get your electric from (in South Jersey, the main provider of electricity is Atlantic Electric, which offers the choice to receive electric from the solar farm in Atlantic City or from some of the various industrial grid-tied systems that are available on some of the farms that are scattered around).

The system chosen to be included on this property is a behind-the-grid grid-tied solar system. The goal of the design will not be to take over the electric bill entirely, but rather to offset some percentage of the cost of electricity, and potentially sell some of that electricity back to the system, earning possible credits. This will, in the end, further develop the property into a more eco-friendly design while also eventually saving money for the residents as well.

2 Methodology

The goal of the design of this system is to work efficiently and well within an area that includes lots of shading and variables in weather. Optimization will be the primary goal with tilt-angle, shading, and other derate factors being taken into careful consideration. When doing derate analysis we will be calculating a temperature related PV derate with data from NREL's Typical Meteorological Year database, as the temperatures in South Jersey can vary from the extremely hot to extremely cold throughout the year, and thus will likely play the largest roll in derate performance. We are also calculating the ground derate factor, and then obtaining other derate factors from a PVWatts calculator.

For the actual solar panels, micro-inverters will be implemented throughout the whole system as an alternative to a PCU. The advantages here lie in the fact that for most parts of the year, some portion of the roof will be shaded, derating the efficiency of the total system. Thus, micro-inverters eliminate the worry of whole lines of the system being taken out should there be some sort of loss of function of one cell, or should some cells be more shaded than others. Given this, the panels will also be wired in parallel to further eliminate the worry for losing any rows of cells. Micro-inverters also have the added benefit of not needing a whole fusible emergency disconnect, as they act as their own individual disconnects should the going get tough.

Thus as the system will be implementing micro-inverters, the only other components that will be required will be a junction array box and a disconnect switch. The system can then be directly wired to the meter, and using net-metering, the homeowner will be able to more efficiently track their use of the panels. There are mobile applications that help with the tracking of energy and net-metering, however today we will just be focusing mainly on the components required for the system.

We note in the above images the area of the front lawn and the available roofing area. Given that the house is situated in the Pinelands area of South Jersey, there are many coniferous trees that do not lose their leaves during the fall months of the year. This ruled out placing the PV system on the front lawn, as it would be blocked too heavily by tree cover at any time of the year, with the added effects of continuously needing to be cleaned, animal interference, and

(a) Showing Lawn

(b) Showing Roof

Figure 1: Front of House

roof	width:	296.4	24.7
	height:	117.6	9.8
	area (unit^2):	34856.64	242.06

Figure 2: Roof Area Sheet

complaints from home-committee's who have nothing better to do than pick at people's yards.

This leaves the roof, which, as it happens, is perfect for placing solar panels, which can be seen in Figure 2. There is a large amount of space for placing panels, leaving a great potential for offsetting a significant amount of electricity per year. The roof also happens to face directly 180 degrees South, and you can't get any better than that. The roof rests at a 40 degree angle, which will play a factor when calculating tilt-angle for optimization.

Taking a look at the energy bill 2018-19 for this household in Figure 3, we note that there is a dramatic increase in kWh usage in the summer months, and directly in January, which is to be expected given that the original design of the house left it poorly insulated. Fortunately, the owners are fairly resilient against most of the colder months, and the total electricity usage for the entire year is around 14000 kWh. To run this, it costs approximately 2500 dollars, which we are looking to take a chunk out of with the system we are building.

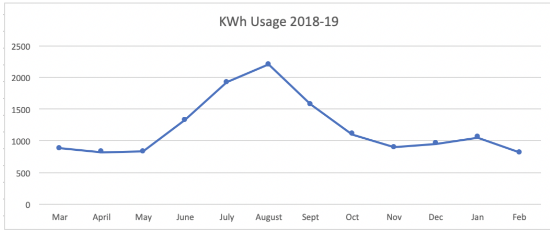
3 Choosing Components

Now that we have an idea of what we can work and what we're looking to optimize, we can pick out a solar panel. Continuing on with the thought process that we will need some sort of micro-inverter, we will be looking for a high-quality model that beats out the competition in terms of lifetime efficiency.

Enter the SunPower-X22-360-D-AC, as seen in Figure 4. The beauty of this panel lies in the

Electric Energy Usage for 2018-2019 *Black Bar*		
Month	**kWh**	**Cost ($)**
Mar	880	158.19
April	820	147.40
May	825	148.30
June	1320	237.28
July	1920	345.14
August	2200	395.47
Sept	1570	282.22
Oct	1100	197.74
Nov	890	159.99
Dec	950	170.77
Jan	1050	180.20
Feb	810	152.20
Total (kWH) :	14335	2574.90776
Daily Use:	39.2739726	7.054541809

(a) Electric Bill 2018-19



(b) Graph of the Electric Usage 2018-19

Figure 3: Bill 2018-19

fact that the micro-inverter is already built into the system, requiring no further installation of another micro-inverter into each panel, making self-installation more of a reality should the owner choose to save some extra money in the end.

The parameters of the panel leave approximately enough room for 13 max, thus to keep our circuits even, we will use a total of 12, leaving them in rows of 6. This configuration which can be seen on the next page fits perfectly across the roof of the house, leaving enough room for adequate spacing for shading optimization later.

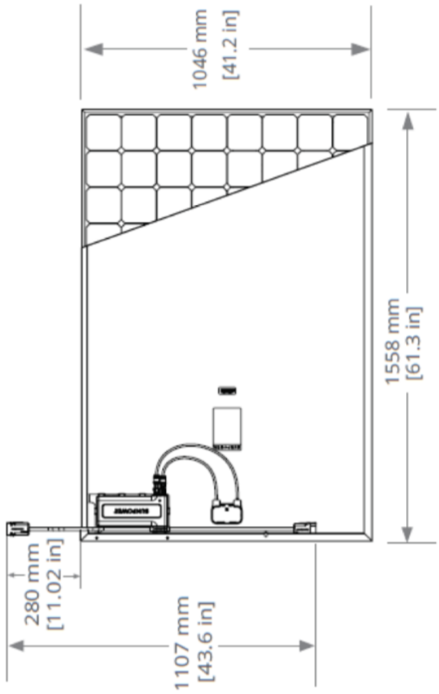
The overall cost of the PV system is approximately 20k; though this is an expensive configuration, it should be noted that the inverters are included in the cost, thus adding to it's price. We argue that it is also worth the price given it's extreme optimization and conversion factors: with a temperature coefficient of -0.29 percent it is one of the lowest on the market, making it perfect for the varied weathers of the North East, and an efficiency factor of 22.10 percent is one of the most competitive out there. SunPower systems also come with a 25-year warranty, and also claims that this specific system will out-perform the competition by approximately 12 percent in 25 years, making it an even better investment in terms of time.

The plan is to arrange the circuit in parallel, thus even further micro-managing the efficiency of the system. Should one circuit be cut out by damage or shading, the other will continue to work. As stated, since micro-inverters act as their own disconnect switches, we only need to consider a few extra parts when analyzing the rest of the system, seen in Figure 5. First we begin with the AC solar array junction box. The purpose here is to combine the two circuits that are in parallel and then feed that to the overall disconnect switch. For the junction box, we went with a Wiley AC Solar Array Junction Box, which is priced at 150 dollars and is rated for outdoor installation per NEC regulation, and meets all local and national codes.

Local codes for New Jersey stipulate that an overall non-fusible disconnect switch be used when micro-inverters are used in a system, in case of worst-case-scenario. We sized the disconnect switch in accordance with NEC 690.8, meaning that the disconnect switch must account for the array current by 125 percent. Thus we are using a switch rated for 240V and 90A, the Square D DU323RB AC Disconnect ACD, which costs 385. This will follow the Junction box on the circuit and will be the last stop towards the meter. We estimated that approximately 200 ft of wiring will be required, costing an additional 220 dollars.

Thus completes the circuit design. The total cost is approximately 20k before incentives.

(a) SunPower-X22-360-D-AC



(b) Parameters of SPR system

Power Calculations			Cost analysis (from online forum)			
STC:	360W	240V	per watt	4.6	total wattage	4320
Efficency:	22.10%		per panel	1656	total voltage	2880
Temp Coef.	-0.29%		total panel cost	19872		
DC to AC eff	96%					
Rated Voltage (Vmpp)	59.1					
Rated Current (Impp)	6.09					
Voc	69.5					
Isc	6.48					

(c) Analysis of SPR system

Figure 4: SunPower-X22-360-D-AC Diagram

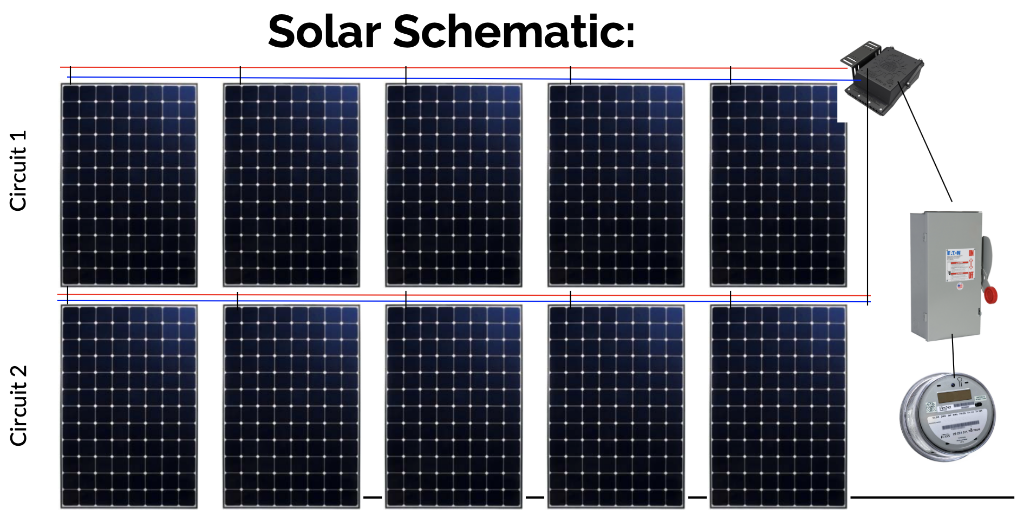
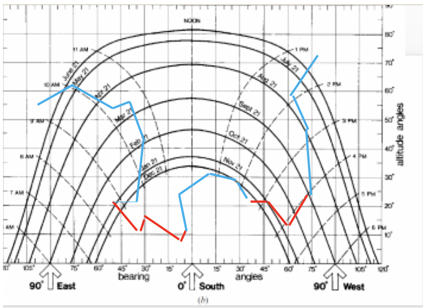


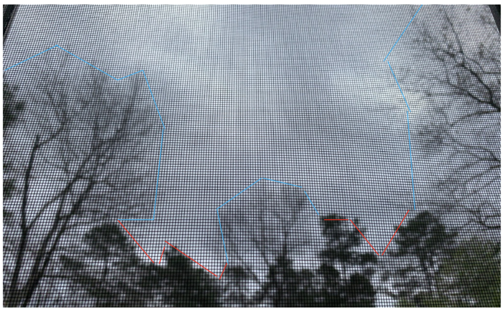
Figure 5: Example Schematic of Total PV System (Real will include 12)

Solar Declination Angle:		n = 1	n = 227	calculations inside of sin for SDA	
$\delta = 23.45^* \sin((360/365)^* (n - 81))$		8.35	-11.51	-78.90	144
Altitude Angle:					
$\beta_N = 90 - L + \delta$		58.95	39.08		
TILT ANGLE:		31.05	50.92		
Tilt angle of roof already:		45.00	45.00		
FINAL TILT		-13.95	5.92		

Figure 6: Tilt Angle Calculations



(a) Shade Chart



(b) Approximate view from roof

Figure 7: Shading Analysis

4 Optimization/Derate Factors

As with any good engineering project, there will always be factors that need to be accounted for that will outwardly act on your system in ways that you did not intend. As such, we are looking to optimize our PV system the best we can.

We are beginning with tilt angle. Above the calculations can be seen for how final numbers were gotten to. We figured that since we are going to be implementing a fixed tilt system it would be best to calculate a tilt angle for both extreme times of year to begin with (summer and winter). We note that for winter we will need a negative angle to compensate for the steep angle of the roof as it sits currently, meaning that we will simply raise the front of the solar panel approximately 14 degrees in order to compensate.

Next we will focus on shading. In Figure 7 we conducted a simple analysis of shading using a standard shading graph. Note that the lines in blue are around trees that are not coniferous, meaning that they will allow more light through in the winter months than the ones in red.

In order to get a more accurate number on the derate factor for shading, we used excel and NREL TMY data in order to calculate solar radiation so that we could use a ground cover ratio (collector area/ground area) graph in order to get an accurate number of what to expect for our derate factor. TMY data exists for Millville NJ, meaning that we were able to find accurate

Millville, NJ Data from SUNY, looking at 2008 full year insolation data W/m^2			
	Ibc	Idc	Ib
TOTAL FOR 2008:	41.75	568608.85	568650.59
Total insolation:	568650.59		
Avg Insolation per day:	1557.95		

Figure 8: Final Insolation data for 2008 Millville NJ

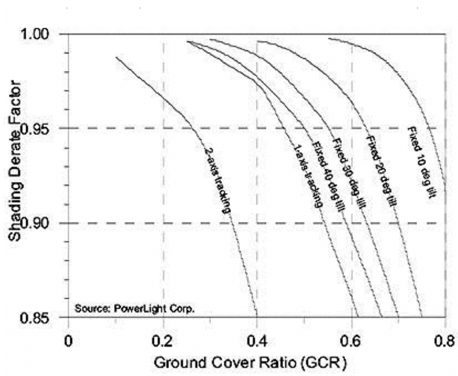


Figure 9: Ground Cover Ratio

Derate Calculations:	
Tcell = Tamb + ((NOCT -20C)/0.8kW/m^2) * S(kW/m^2)	
Daily NOCT derate factor:	1.03
PV module DC rating	0.96
Inverter and Transformer	0.92
Mismatch	0.98
Diodes and Connections	1.00
DC wiring	0.98
AC wiring	0.99
Soiling	0.95
GCR Derate	0.90
TOTAL	0.73641142

Figure 10: Total Derate Factors

data in order to most accurately calculate a total insolation for the year in 2008. A full example of the excel calculation can be seen in the appendix. From this we were able to use the graph in Figure 8 to calculate a GCR of approximately 0.9.

The last derate factor we were able to calculate on our own from available TMY data was the Normal Operating Conditions Temperature derate. This required a couple of excel functions in order to sort through all of the available data available for the year, which, again, an example of will be provided in the appendix of the paper. The following equations were necessary:

$$T_{cell} = T_{amb} + ((NOCT - 20C)/0.8kW/m^2) * S(kW/m^2) \quad (1)$$

$$P_{max} = 0.29 * (T_{cell} - STC) \quad (2)$$

$$NOCTDerate = 1 - P_{max}decrease \quad (3)$$

Above are the total derate calculations necessary. The ones in bold were the ones using TMY data for the full year of 2008, that we did on our own. The others were taken from a PVWatts calculator using inputted data to assume the above.

5 Economic Analysis

Now that we've calculated our total derate factor, we can calculate the total savings that our Solar system will provide. Multiplying together the area of the system, the efficiency percent, avg solar radiation, and our new derate factor, we see that our system takes off approximately 19 percent of the kWh and cost of the standalone system. This is a fantastic start with only a

Total Solar Panel Output a year			
E = Area * Efficiency % * Avg Solar radiation * Derate			Savings ($)
Total	2716.85	kWh	488.38
Per Day (avg)	7.44		1.34
Offset Cost %	18.95		

Figure 11: Total Solar Savings

Comparison of Maximum HERS Scores and Entry Level Incentives by Program Tier and Year						
Program Year	2015			2016		
Tiers 1 and 2						
Unit Type	Single family	Multi-Single	Multifamily	Single family	Multi-Single	Multifamily
Maximum Qualifying HERS Index (Before Renewable)	75	75	75	65	70	75
Entry Level Incentive (Tier1/Tier 2)	$1250/$2250	$938/$1688	$625/$1125	$750/$1750	$375/$1125	$125/$625
Tier 3						
Unit Type	Single family	Multi-Single	Multifamily	Single family	Multi-Single	Multifamily
Maximum Qualifying HERS Index (before Renewable)	50	50	50	50	50	50
Entry Level Incentive (Tier1/Tier 2)	$10,000	$7,000	$4,000	$6,500	$4,875	$3,250

Figure 12: Caption

small percentage of panels actually being used, and meaning that over the course of 5 years 1 year of energy will have come entirely from renewable PV energy, doing it's job for the planet.

However, the system on it's own is still pretty expensive for any family, especially when looking to just pay for it out of pocket and not using any loan programs (for this analysis, anyway). Thus we must look at incentives that are available in the New Jersey area.

First there's net-metering, which "allows consumers who generate some or all of their own electricity to use that electricity anytime, instead of when it is generated". This is a standard incentive anywhere, and obviously won't see immediate cash results. However, it does provide some savings on an electric bill.

Next we can look at SRECs, which are Solar Renewable Energy Certificates. For every 1000kW generated, the certificates can be sold for the current market price, which was 232 dollars the last time it was updated in New Jersey. This would save this particular household approximately 630 dollars a year at their current usage rates.

The New Jersey Residential Construction Program is one of the more lucrative incentives available, with it varying across several factors. "The program provides a range of financial incentives depending on the energy efficiency of the homes. Both single family and multifamily buildings are eligible for the program."

Finally the last true incentive to be found was the Residential Renewable Tax Credit. "A taxpayer may claim a credit of 30 percent of qualified expenditures for a system that serves a dwelling unit located in the United States that is owned and used as a residence by the taxpayer." Thus this will save the household approximately 5329 dollars with a system that costs 20k in total.

Overall this is a nice 7500 dollars in savings for the homeowner, which can be factored into the cost analysis for the system.

Doing a basic cost analysis, we see that the actual net present value on the system is 18494.14 dollars, which is a good margin different than what was paid for. This indicates the value of

NPV		IRR (with incentives)	
ΔA	2091.27	simple payback	26.89
PVF(d,n) where d is 0.1 and n is 25	9.08	IRRe % (e=0.03)	6.09
PV	18982.52		
NPV (PV-cost)	18494.14		

Figure 13: Cost Analysis

the system increasing as time moves on in 25 years. A simple payback plan of approximately 27 years is a bit of a stretch however the system will be insured for 25 of those years and with the guarantee to continue working 12 percent better than the competition the system still holds it's value.

6 Conclusion

The system ended up being a grid-tied system using high caliber components while also being economically feasible out of pocket. The derate analysis used TMY data that was conveniently located in Millville NJ (likely due to our airport that, though small, is a crucial one for locals in the area). We have optimized by using the maximum amount of solar panels while having two tilt angles, and placing the whole system towards the equator with microinverters and a parallel tied system.

In the end, this system is a good step forward towards making this house a more eco-friendly and worthwhile buy, even in it's older age. This will increase the value on the home, and will save the family money every year, with a standard payback plan of 27 years, the system will pay itself off. To further offset the price, the design is simple and could be reasonably installed with guided supervision by the homeowners and some friends if they so chose. This is a valuable system and another step closer to reducing the home's carbon footprint, while also saving valuable cash.

Personally, I learned a great deal about the design and focus of building a renewable energy system through this project. If I had to go back and do it differently, or if I had more time, I would compare and contrast several different solar panels and solar panel sizes. I think though the design is well executed and there is a good plan in place for pay-back (especially with incentives) the cost of the solar panels is ultimately what keeps the system back. I imagine as time goes on and solar is more accessible the initial hurdle of the price will become less of an obstacle and the bar of entry will be lowered so that more can participate in removing themselves from the grid. The economic analysis of the system is probably the most crucial step in the process of the design. You can have the most award winning components, however if the system doesn't pay itself off in a reasonable amount of time what really is the point?

I would also like to experiment with a battery backup system. My father, who lives in the house with my mom currently, used to drive an all electric car and had a system that was hooked up in the garage to charge the car at night. I imagine with the implementation of a solar roof the ability to charge the car from completely renewable energy would be more enticing.

References

[1] Gilbert M. Masters [*Renewable and Efficent Electric Power Systems*]. John Wiley Sons, Hoboken, New Jersey, 2013.

- http://programs.dsireusa.org/system/program/detail/219
- http://programs.dsireusa.org/system/program/detail/38
- http://programs.dsireusa.org/system/program/detail/5687
- http://programs.dsireusa.org/system/program/detail/5811
- http://programs.dsireusa.org/system/program/detail/1235
- http://www.njcleanenergy.com/files/file/6-17-15-8F.pdf
- https://us.sunpower.com/solar-resources/sunpower-x-series-residential-ac-x22-370-d-ac-x22-360-d-ac
- https://us.sunpower.com/sites/default/files/media-library/data-sheets/sunpower-x-series-residential-solar-panels-x22-360-datasheet-514618-revc.pdf
- https://www.solarpanelstore.com/collections/solar-pv-cable/products/pv-wire-10-awg-wire-500-ft-spool-black
- https://earthenergy.us.com/index.php/apsystems-ac-junction-box.html
- https://www.wholesalesolar.com/8937359/square-d/disconnects/square-d-du323rb-ac-disconnect-acd
- https://www.atlanticcityelectric.com/SiteCollectionDocuments/ACE1MWorLess10709.pdf
- https://photovoltaic-software.com/principle-ressources/how-calculate-solar-energy-power-pv-systems
- https://en.wikipedia.org/wiki/Solarirradiance
- https://us.sunpower.com/blog/2017/11/16/how-much-do-solar-panels-cost
- https://www.atlanticcityelectric.com/SiteCollectionDocuments/ACE1MWorLess10709.pdf
- https://atlanticcity.wattplan.com/pv/

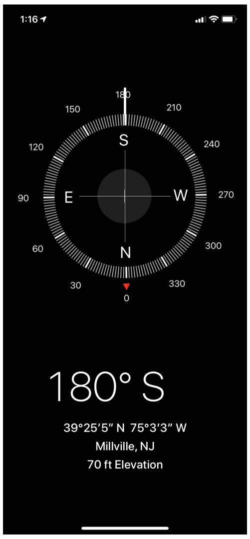


Figure 14: Compass Showing South House

Date	Time (6am-8pm)	Zenith (deg)	Azimuth (deg)	SUNY Dir (Wh/m^2)	SUNY Dif (Wh/m^2)	altitude angle (beta)	cos(angle of incide cos(theta)	Ibc	Idc	Ib	Ic
1/1/08	1:00	99	-99	0	0	-9	-0.020520	0.000000	0.000000	0.000000	0.000000
1/1/08	2:00	99	-99	0	0	-9	-0.020520	0.000000	0.000000	0.000000	0.000000
1/1/08	3:00	99	-99	0	0	-9	-0.020520	0.000000	0.000000	0.000000	0.000000
1/1/08	4:00	99	-99	0	0	-9	-0.020520	0.000000	0.000000	0.000000	0.000000
1/1/08	5:00	99	-99	0	0	-9	-0.020520	0.000000	0.000000	0.000000	0.000000
1/1/08	6:00	99	-99	0	0	-9	-0.020520	0.000000	0.000000	0.000000	0.000000
1/1/08	7:00	99	-99	0	0	2.8	0.137855	0.137855	4.415680	4.553535	4.553535
1/1/08	8:00	87.2	122.9	1	5	10.2	0.479283	0.000000	47.689341	47.689341	47.689341
1/1/08	9:00	79.8	131.4	0	54	18	0.640999	0.000000	116.573945	116.573945	116.573945
1/1/08	10:00	72	143.1	0	132	23.8	0.779448	0.000000	72.417148	72.417148	72.417148
1/1/08	11:00	66.2	156.5	0	82	27	0.873003	0.000000	69.767740	69.767740	69.767740
1/1/08	12:00	63	171.3	0	79	27.2	0.915285	0.000000	69.767740	69.767740	69.767740
1/1/08	13:00	62.8	186.8	0	79	24.4	0.897715	0.000000	160.730742	160.730742	160.730742
1/1/08	14:00	65.6	201.7	0	182	18.9	0.813170	0.000000	96.261818	96.261818	96.261818
1/1/08	15:00	71.1	215.3	0	109	11.2	0.663404	0.000000	64.468924	64.468924	64.468924
1/1/08	16:00	78.8	227.2	0	73	3.4	0.481399	0.000000	5.298816	5.298816	5.298816
1/1/08	17:00	86.6	236.5	0	6	-9	0.230575	0.000000	0.000000	0.000000	0.000000
1/1/08	18:00	99	-99	0	0	-9	-0.020520	0.000000	0.000000	0.000000	0.000000
1/1/08	19:00	99	-99	0	0	-9	-0.020520	0.000000	0.000000	0.000000	0.000000
1/1/08	20:00	99	-99	0	0	-9	-0.020520	0.000000	0.000000	0.000000	0.000000
1/1/08	21:00	99	-99	0	0	-9	-0.020520	0.000000	0.000000	0.000000	0.000000

(a) TMY data 1

AMB Temperature C	Tcell (assuming NOCT of 45)	Pmax decrease (=0.29%/C *(tcell-STC))	NOCT Derate (=1-Pmax decrease)
	Tcell = Tamb + ((NOCT -20C)/0.8kW/m^2) * S(kW/m^2)		
0	0	-7.25	1.0725
1	1	-6.96	1.0696
2	2	-6.67	1.0667
3	3	-6.38	1.0638
3	3	-6.38	1.0638
3	3	-6.38	1.0638
4	4.142297966	-6.04873359	1.060487336
6	7.490291909	-5.077815346	1.050778153
8	11.64293578	-3.873548624	1.038735486
9	11.26303586	-3.9837196	1.039837196
8	10.18024187	-4.297729858	1.042977299
8	10.18024187	-4.297729858	1.042977299
9	14.02283569	-3.183377649	1.031833776
8	11.00818182	-4.057627273	1.040576273
7	9.014653877	-4.635750376	1.046357504
6	6.16558799	-5.461979483	1.054619795
4	4	-6.09	1.0609
3	3	-6.38	1.0638
2	2	-6.67	1.0667
1	1	-6.96	1.0696
1	1	-6.96	1.0696
0	0	-7.25	1.0725
0	0	-7.25	1.0725
0	0	-7.25	1.0725
0	0	-7.25	1.0725
0	0	-7.25	1.0725
0	0	-7.25	1.0725

(b) TMY data 2

Manufacturer Name	Model Number[1]	UL 1741 Supplement SA Testing	UL 1741 SA13 Volt-Var	UL 1741 SA Freq-Watt Volt-Watt	Common Smart Inverter Profile Conformance	Description	Maximum Continuous Output Power at Unity Power Factor	Nominal Voltage	Weighted Efficiency	UL 1741 Supplement SA Certification (SA8-SA13)[3]		
SunPower	X-Series: X22-360	Y	Y	Y	N	360 W, 240 Vac, Grid Support Utility Interactive, monocrystalline ACPV Module, white	0.32	240	96	UL	[6/21/2017]	[15732];[16143];[16332]

(c) Local Code 1

UL 1741 SA13 Volt-Var	UL 1741 SA Freq-Watt Volt-Watt	CSIP Certification		Notes	Built-In Meter	Microinverter
10/31/18	[10/03/2017]	No Information Submitted	No Information Submitted	This component is specific to ACPV modules and is not available as an individual unit.	Y	Y

(d) Local Code 2

(e) SREC

Figure 15: Necessary Portions