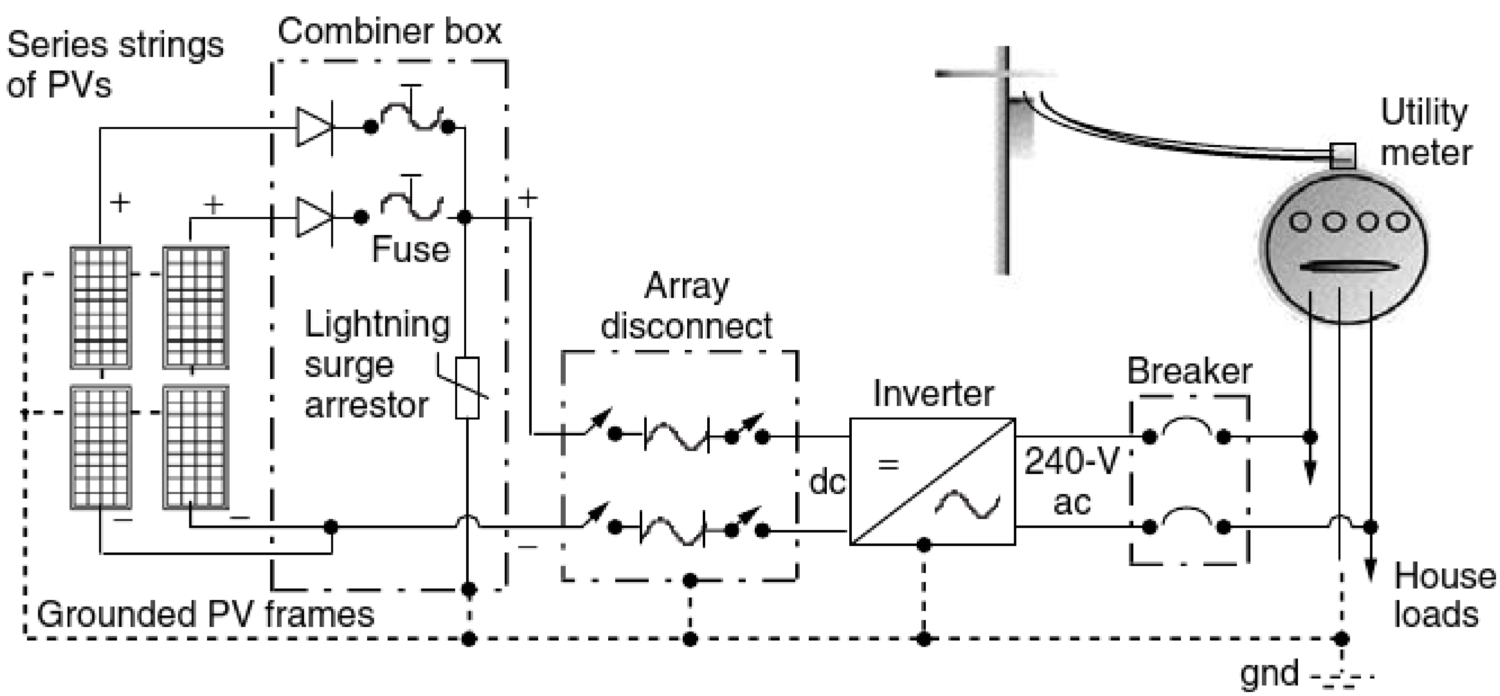
Photovoltaic Systems II

EE 446/646

Components of a grid-connected residential PV system (net meter)

The inverter contains:

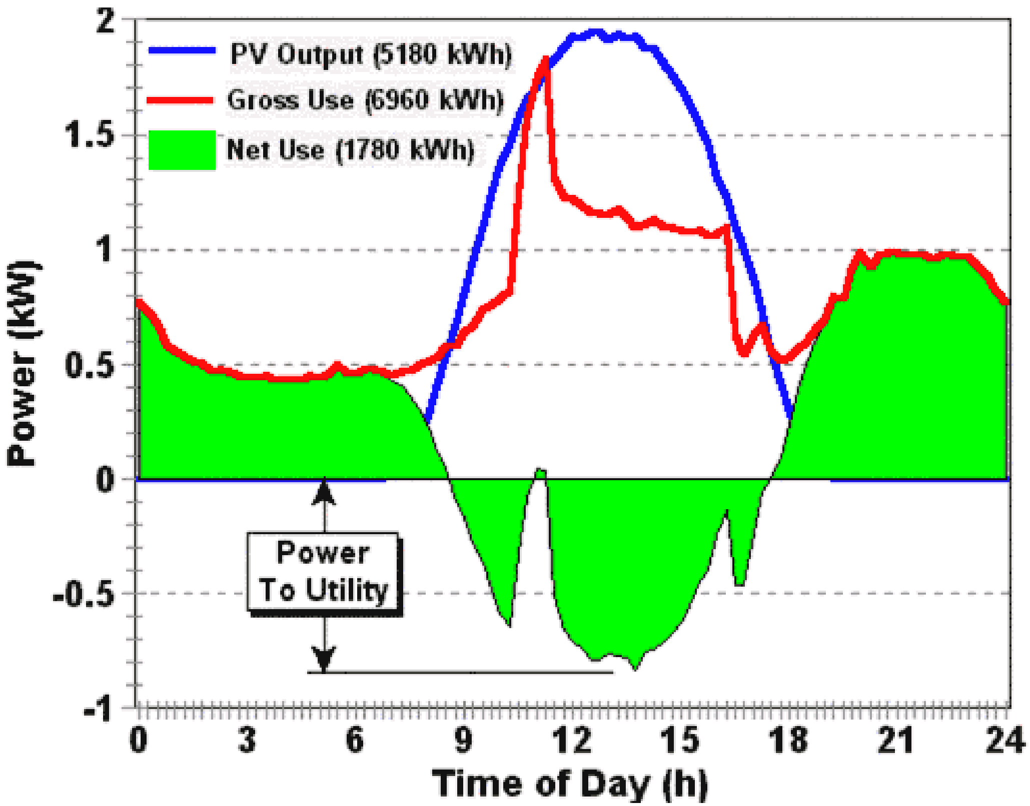
- Ground Fault Circuit Interrupter (GFCI)
- MPPT and Circuitry to disconnect the PV from the grid in case of power loss (built within the inverter).



Today's inverters come with built-in DC and AC disconnects as well as combiner box.

Interfacing with the utility

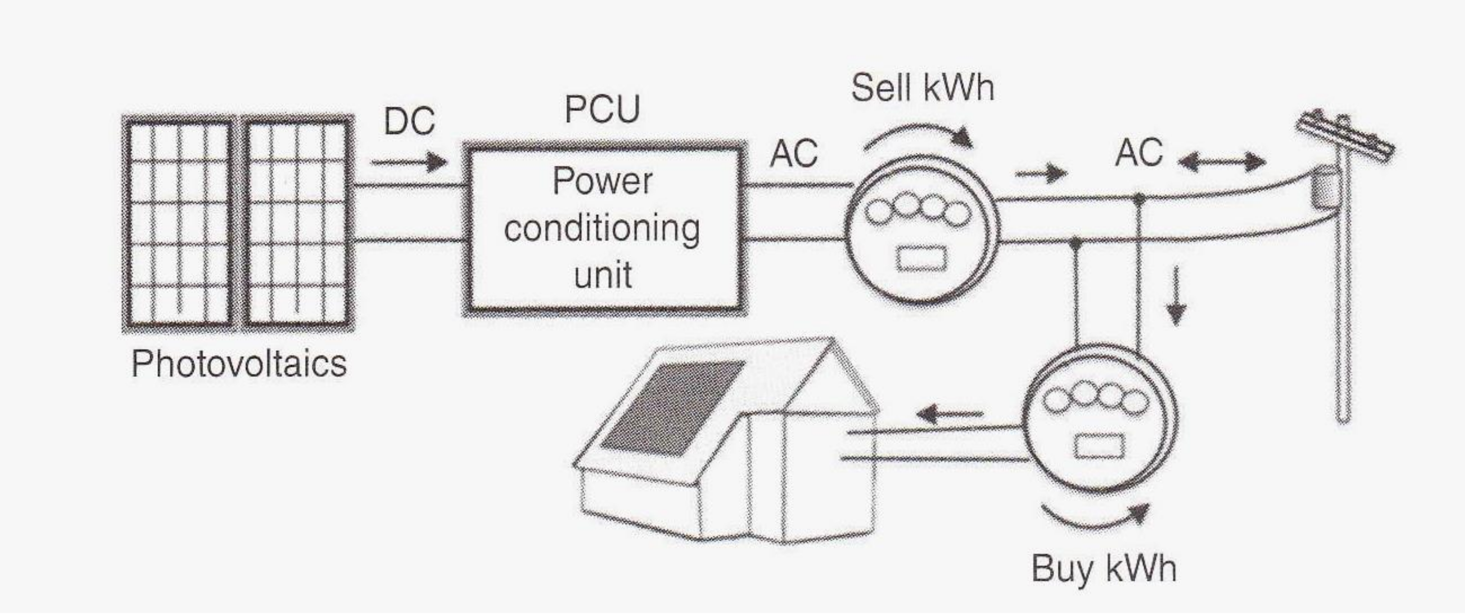
- Whenever the PV system delivers more power than the local demand, the electric meter runs backwards, building up a credit.
- When demand exceeds that supplied by the PV, the grid provides supplementary power. This arrangement is called ***net metering*** billing arrangement (the customer's monthly electric bill is only for that net amount of energy that the PV system is unable to supply).



Smart meters record energy flow in both directions as well as energy used at specific time windows.

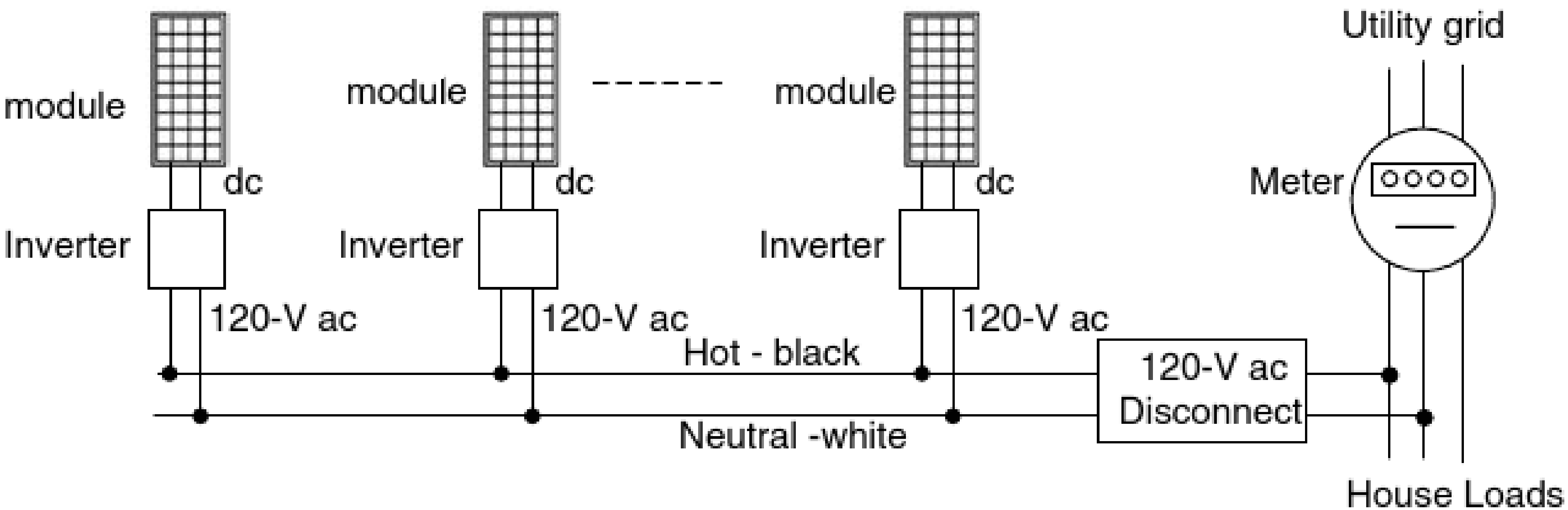
Components of a grid-connected Residential PV system (with two meters)

- A two-meter system allows a ***feed-in tariff*** to provide separate rates for power generated by the PV system and power used by the customer.
- This approach greatly reduces the uncertainty about the value of PV systems.



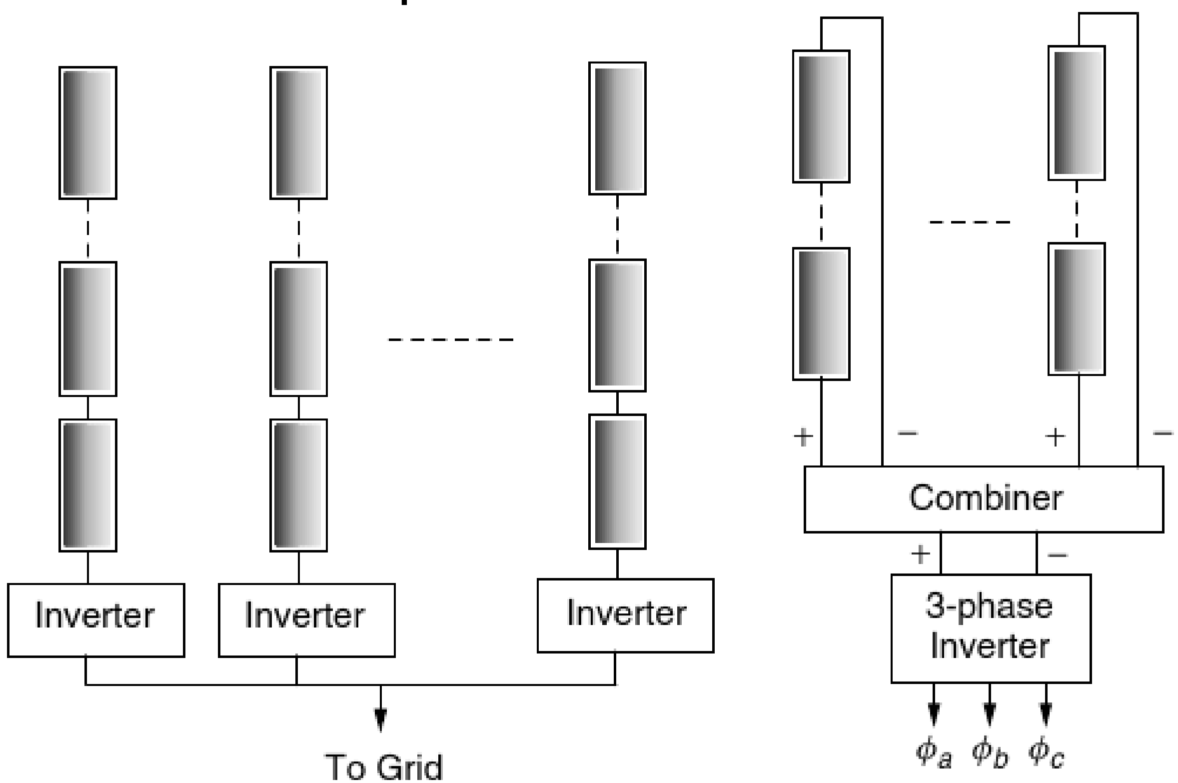
Option of using micro-inverters

- An alternative approach is based on each PV module having its own small inverter (i.e., micro-inverter) mounted directly onto the backside of the panel.
- Now some panels come with built-in micro-inverters.
- These ac modules allow simple expansion of the system, one module at a time, … but at a higher cost.



Modular vs. centralized inverter

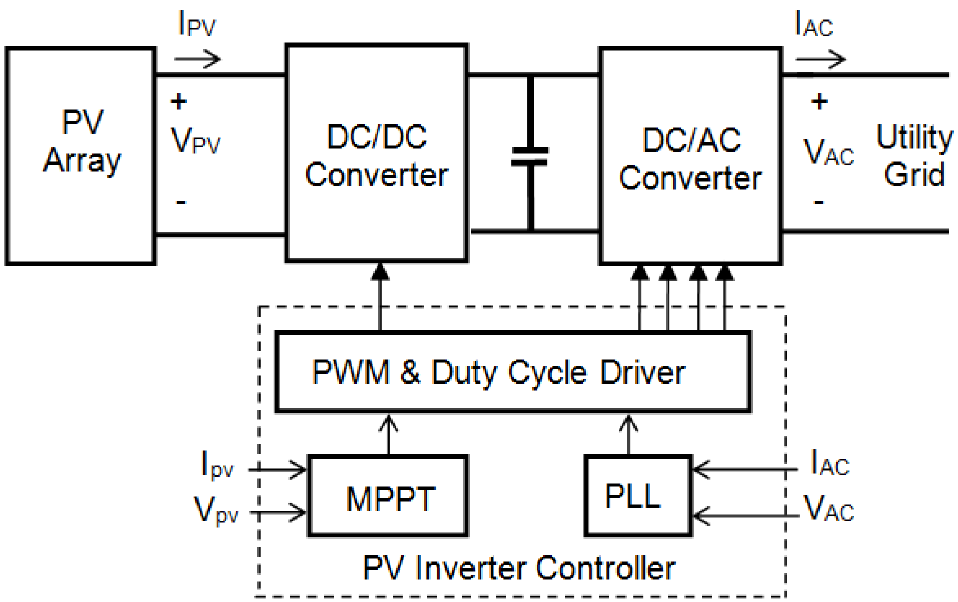
- For large grid-connected systems, strings of PV modules may be tied into inverters in a manner analogous to the individual inverter/module concept. By doing so, the system is modularized.
- Large, central inverter systems providing three-phase power to the grid are also an option.



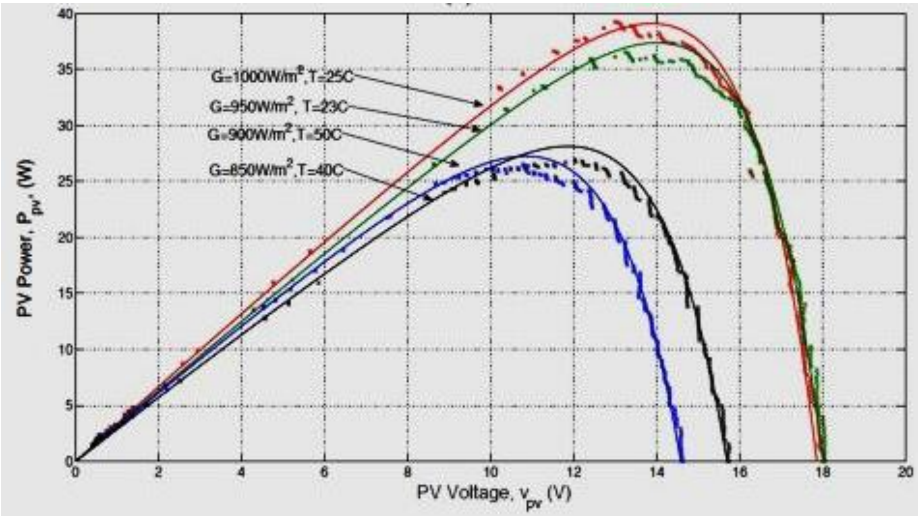
Grid-Tied PV Inverters

Grid-tied inverters are smart power electronic devices:

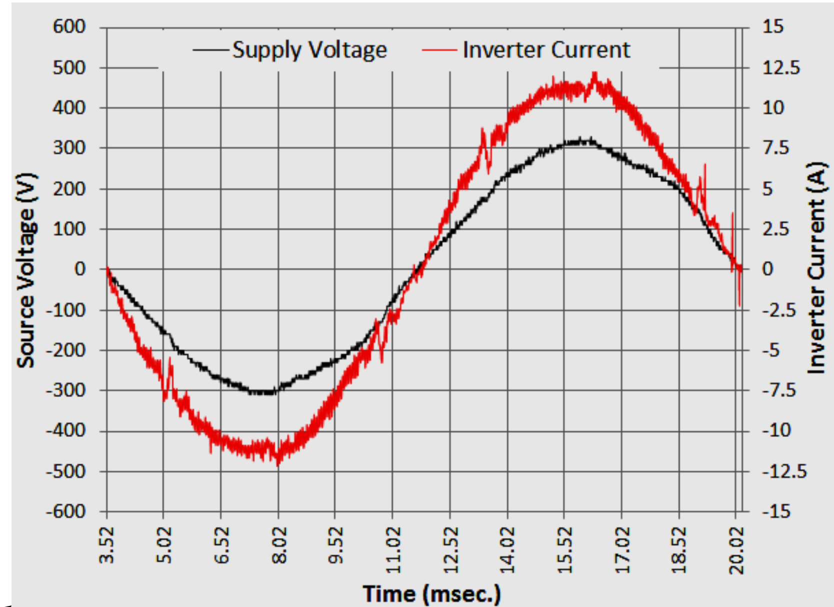
- monitor the PV array, track the maximum power and operate at that point,
- sense the presence of the grid, synchronize to and inject a current in phase with the voltage,
- monitor the grid and disconnect in case of trouble (e.g., swings in voltage or frequency, or power outage).



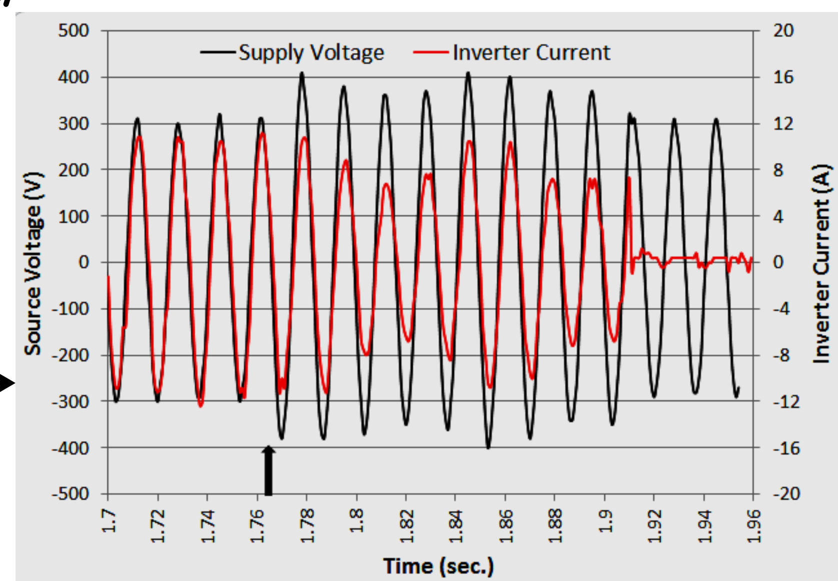
Grid-Tied PV Inverter main Functions



Maximum Power Tracking



Grid synchronization



Grid Monitoring - Disconnect

AC Rated Power of PV System

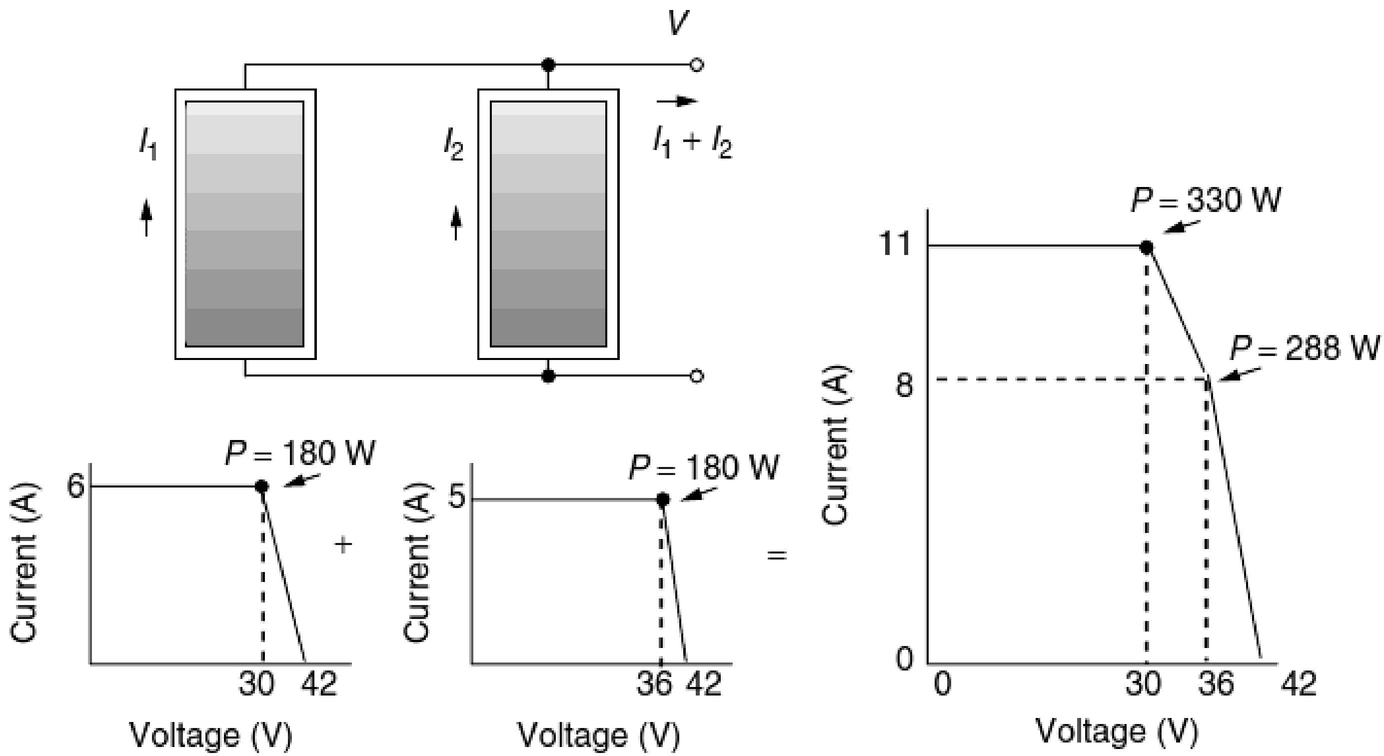
- The AC rated power of a grid-connected PV array is defined as

$$\mathbf{P_{ac} = P_{dc,STC} \times (derate\ factor)}$$

  - where $P_{dc,STC}$ is the dc power of the array obtained by simply adding the individual module ratings under standard test conditions.
  - The derating factor accounts for inverter efficiency, dirty collectors, mismatched modules, and differences in ambient conditions, losses in DC and AC wiring, impact of partial shading, etc.…
  - The derating factor does not include temperature impact.
- Even in full sun, the impact of the above losses can easily derate the power output by 20%.

Mismatched Modules

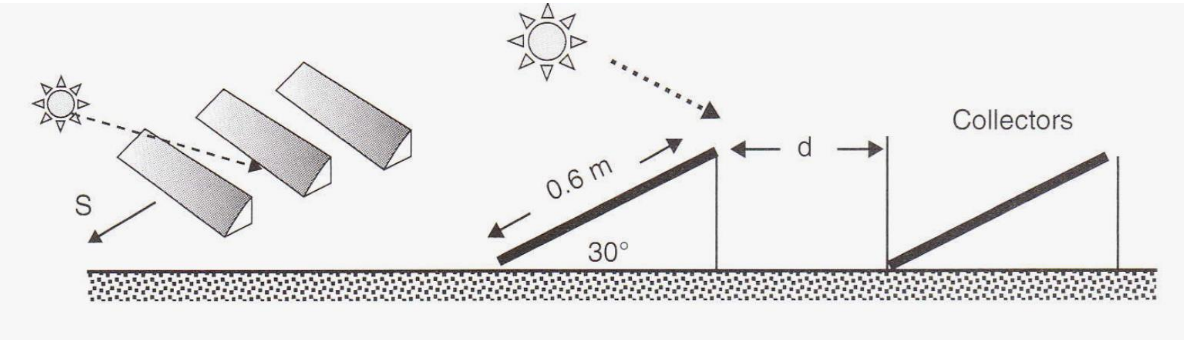
- Not all modules coming off the very same production line will have exactly the same rated output. For example, some 100-W modules may produce 103 W and others 97 W. → Production tolerances can reduce array output as well.



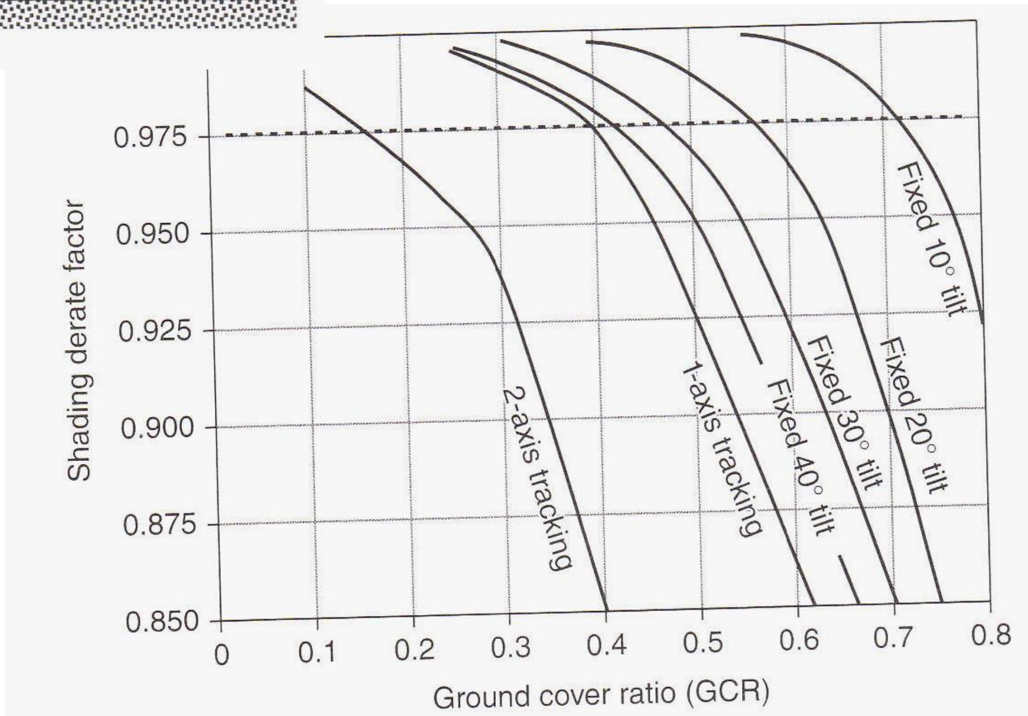
- What is the maximum power of the above modules if connected in series? *(Ans: 340 W)*

Derating due to Shading – Ground Cover Ratio (GCR)

- GCR = ratio of area of PV to total ground area.
- Industry practice: optimize use of space for a 2.5% loss – this corresponds to a shading de-rating factor of 0.975.

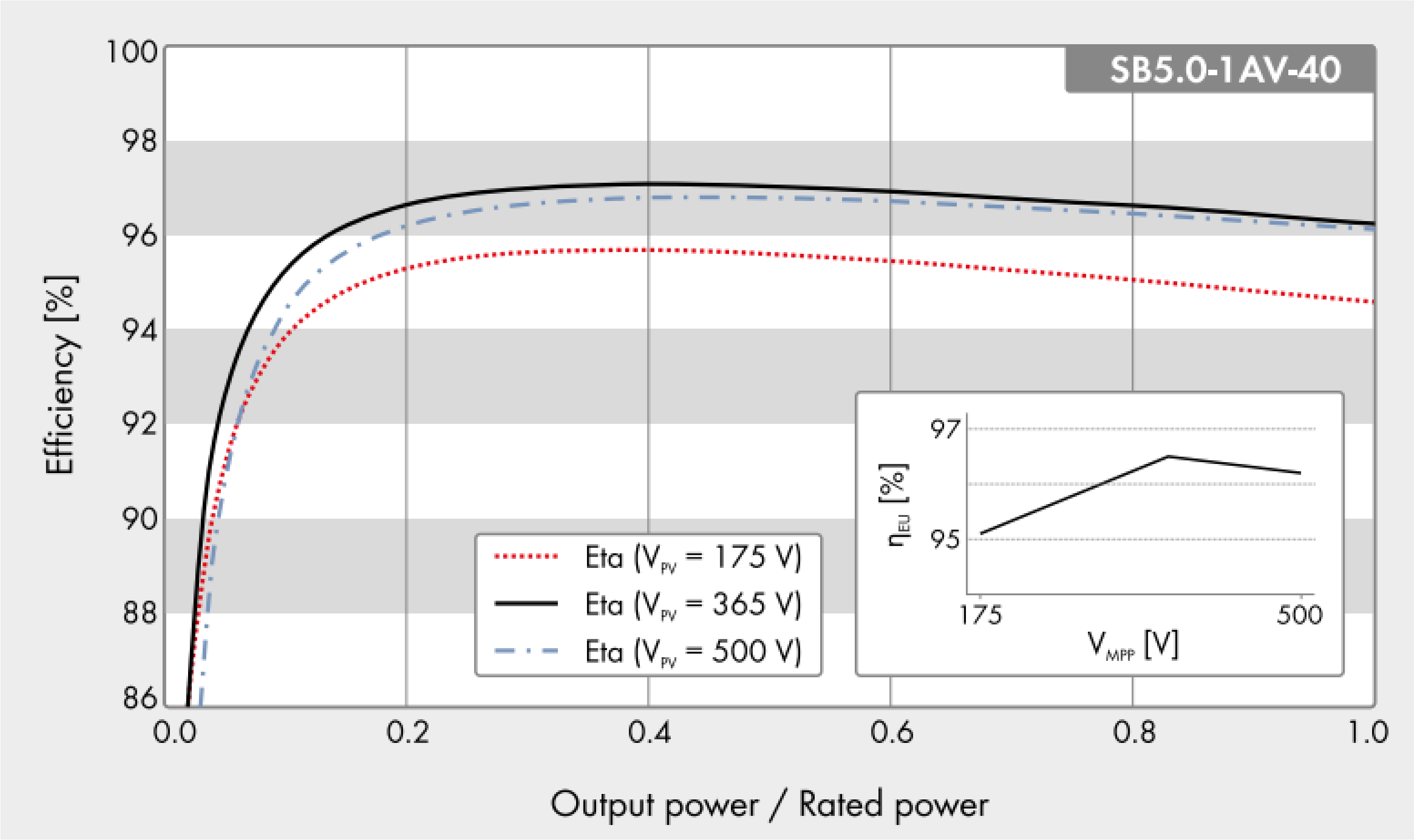


Refer to posted white paper by SunPower for more details.



Inverter Efficiency

- The inverter efficiency (hence power loss) depends on that amount of power it is converting, which in turn depends on the amount of solar irradiance. It also depends on the PV array DC voltage.



Typical Inverter Technical Data

Technical data	Sunny Boy 3.0	Sunny Boy 3.6	Sunny Boy 4.0
Input (DC)			
Max. DC power (at cos φ =1)	3200 W	3880 W	4200 W
Max. input voltage	600 V		
MPP voltage range	110 V to 500 V	130 V to 500 V	140 V to 500 V
Rated input voltage	365 V		
Min. input voltage / initial input voltage	100 V / 125 V		
Max. input current input A / input B	15 A / 15 A		
Max. input current per string input A / input B	15 A / 15 A		
Number of independent MPP inputs / strings per MPP input	2 / A:2; B:2		
Output (AC)			
Rated power (at 230 V, 50 Hz)	3000 W	3680 W	4000 W
Max. apparent power AC	3000 VA	3680 VA	4000 VA
Nominal AC voltage / range	220 V, 230 V, 240 V / 180 V to 280 V		
AC power frequency / range	50 Hz, 60 Hz / −5 Hz to +5 Hz		
Rated power frequency / rated grid voltage	50 Hz / 230 V		
Max. output current	16 A	16 A	22 A[3)]
Power factor at rated power	1		
Adjustable displacement power factor	0.8 overexcited to 0.8 underexcited		
Feed-in phases / connection phases	1 / 1		
Efficiency			
Max. efficiency / European Efficiency	97.0% / 96.4%	97.0% / 96.5%	97.0% / 96.5%

European weighted efficiency

$$\eta_{EU} = 0.03 \cdot \eta_{5\%} + 0.06 \cdot \eta_{10\%} + 0.13 \cdot \eta_{20\%} + 0.10 \cdot \eta_{30\%} + 0.48 \cdot \eta_{50\%} + 0.20 \cdot \eta_{100\%}$$

California Energy Commission (CEC) weighted efficiency

$$\eta_{CEC} = 0.04 . \eta_{10\%} + 0.05 . \eta_{20\%} + 0.12 . \eta_{30\%} + 0.21 \cdot \eta_{50\%} + 0.53 \cdot \eta_{75\%} + 0.05 \cdot \eta_{100\%}$$

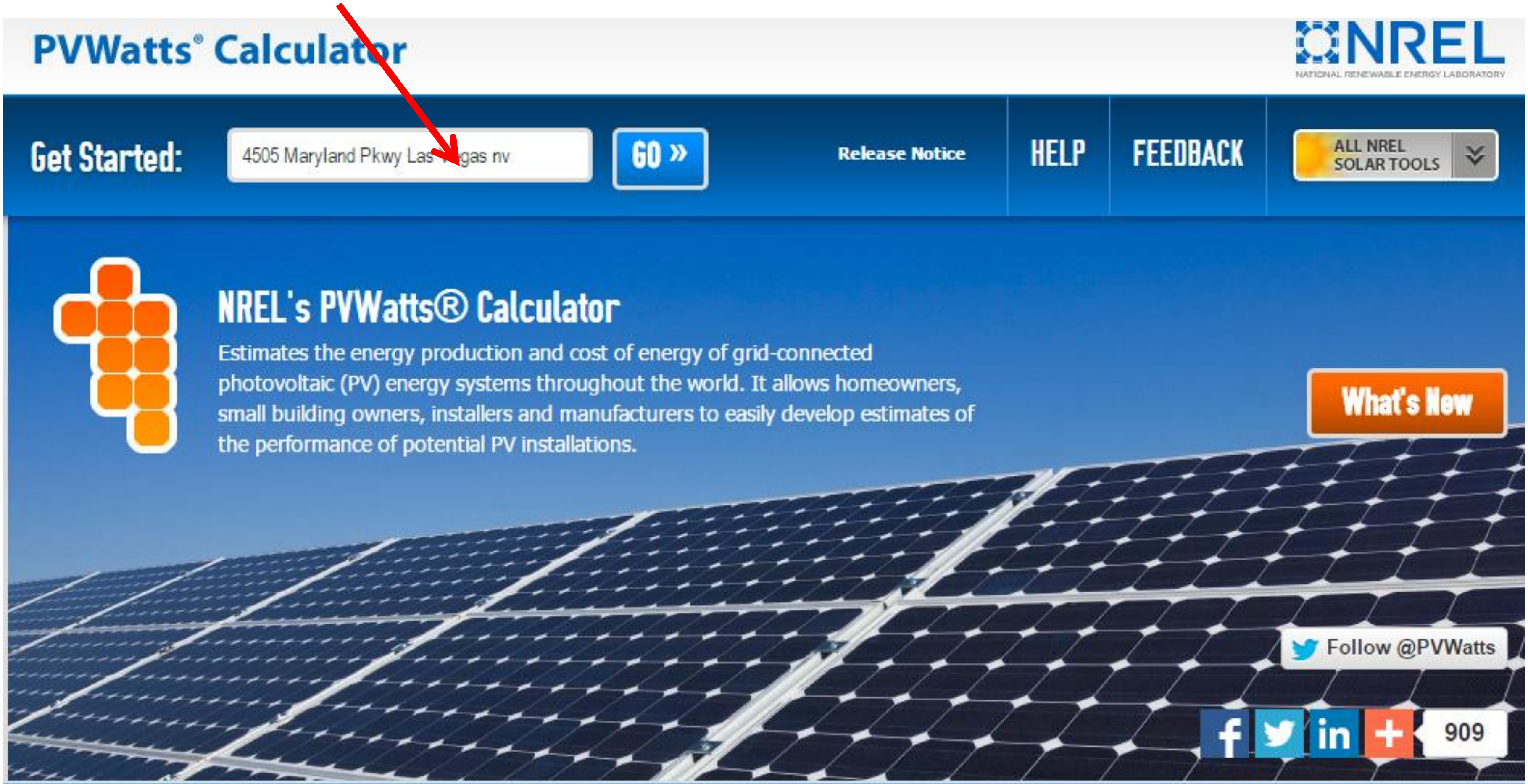
Temperature-Related Derating

- An even more important factor that reduces module power below the rated value is cell temperature. In the field, the cells are likely to be much hotter than the 25°C at which they are rated (STC) and we know that as temperature increases, PV power decreases.
- $$T_{\text{cell}} = T_{\text{amb}} + \left(\frac{\text{NOCT} - 20^\circ}{0.8} \right) \cdot S$$
- **Example:** Determine the NOCT derate factor of a PV module that is receiving 753 W/m^2 under an ambient temperature of 25.6 °C. The module NOCT is 45 °C and its temperature coefficient is -0.38%/°C.
- Answer: T_{cell} = 25.6+(45-25)*.753/0.8 = 49.1°C.
- Decrease in power: 0.38%*(49.1-25) = 9.16%.
- Temperature derate factor: 1 – 0.0916 = 0.908
- this translates into a 9.08% decrease in performance.

Useful Tool to Size PV Systems:

http://pvwatts.nrel.gov/

Type address here

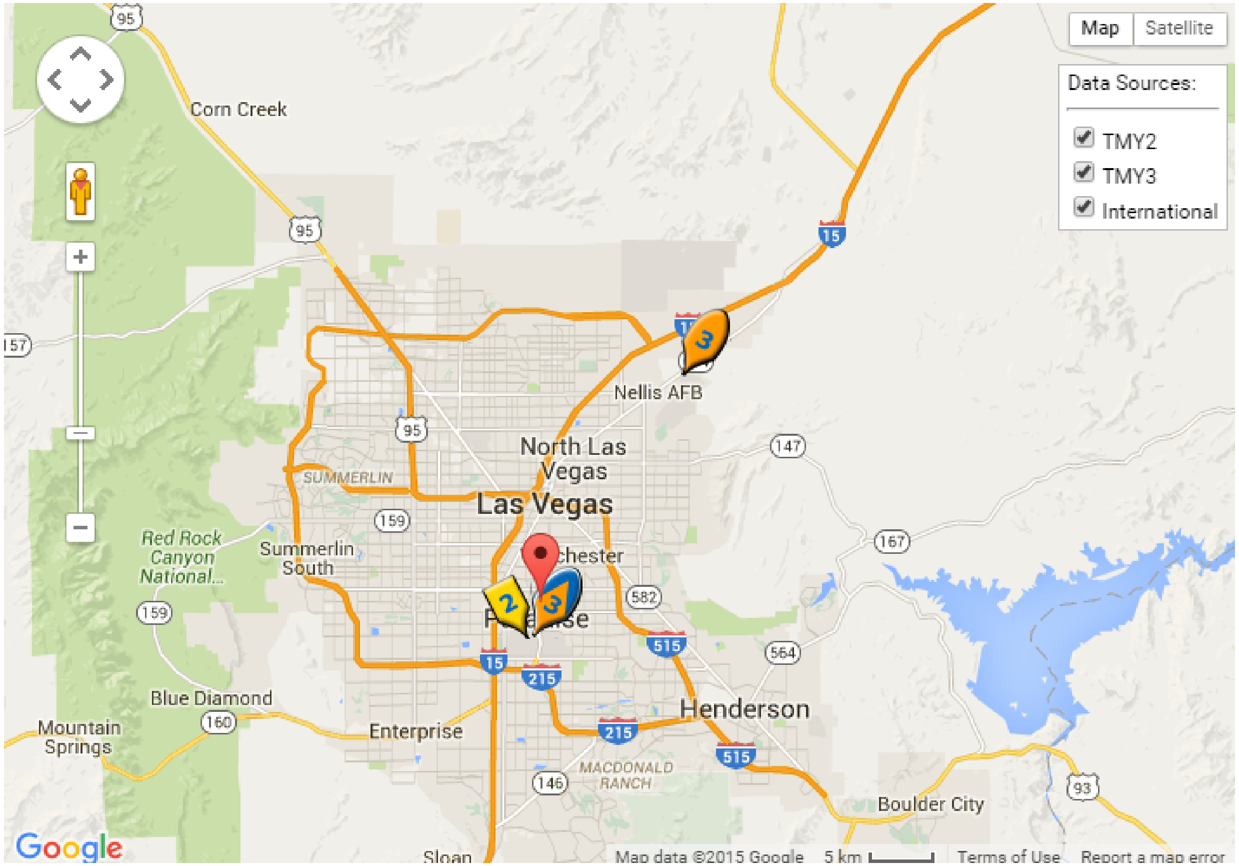


PV-WATTS – Select Weather Data

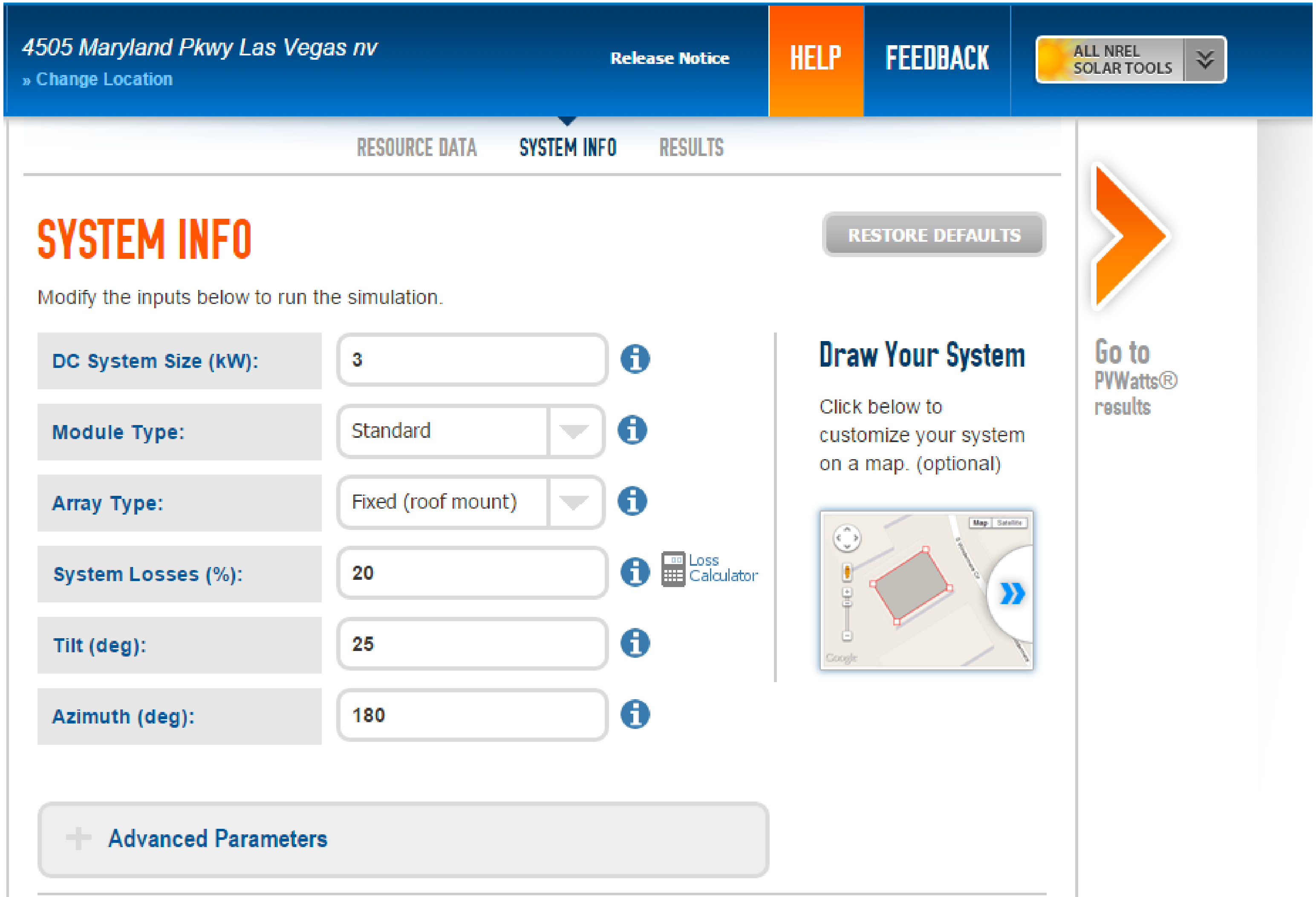
Optionally, Select Different Weather Data

Currently, PVWatts® defaults to the closest TMY2 weather file (or international file). This will be the standard for the foreseeable future. We also offer the TMY3 locations and a 10 km gridded data set from SolarAnywhere®. We will not be including the older 40 km gridded data from PVWatts Version 2 as the other datasets are superior. The selected weather source pin is wrapped with a blue background. Click a different pin to select that source. If you enable SolarAnywhere® data for the continental US, then **double-click** anywhere on the map to select that grid cell (it must be enabled for each location). Refer to **Help** for more detailed information.

Enable SolarAnywhere® Gridded Data



PV-WATTS – System information



Temperature effect and inverter losses are already included in the tool.

PV-WATTS - RESULTS

RESULTS

Print Results

4,806 kWh per Year *

Month	Solar Radiation (kWh / m^2 / day)	AC Energy (kWh)	Energy Value ($)
January	4.51	308	37
February	5.27	324	39
March	6.05	410	50
April	7.46	471	57
May	7.53	476	58
June	7.66	453	55
July	7.57	449	55
August	7.53	453	55
September	7.22	424	51
October	6.17	395	48
November	5.23	338	41
December	4.51	305	37
Annual	6.39	4,806	$ 583

PV-WATTS - RESULTS

The tool allows you to download the monthly as well as hourly data.

Go to
system info

December	4.32	444	49
Annual	**6.45**	**7,123**	**$ 785**

User Comments

Type here to add optional comments to printout.

Download Results: Monthly | Hourly

Find A Local Installer

* **Caution:** The PVWatts® energy estimate is based on an hourly performance simulation using a typical-year weather file that represents a multi-year historical period for Las Vegas, NV for a Fixed (roof mount) photovoltaic system. The kWh range is based on analysis of a nearby data site described here.

The estimate for the value of this energy is the product of the AC energy and the average retail electricity rate. This value is useful for basic comparisons but does not account for financial considerations in a cash flow-based analysis. All of these results are based on assumptions described in Help that may not accurately represent technical or economic characteristics of the project you are modeling.

‘‘Peak-Hours’’ Approach to Estimating PV Performance

- Predicting performance is a matter of combining the characteristics of the PV system (including the inverter) with local insolation and temperature data.
- Since 1-sun of insolation is defined as 1 kW/m^2 , we can think of an insolation of say 5.6 kWh/m^2/day as being the same as 5.6 h/day of 1-sun, or 5.6 “peak sun hours” (PSH). So, if we know the ac power delivered by an array under 1-sun insolation (P_{ac}), and assume that the system efficiency remains constant, then the daily energy collected would be equal to

$$\textbf{Energy (kWh/day)} = \mathbf{P_{ac}\ (kW) \cdot (PSH)}$$

Examples: Annual Energy Using the Peak-Sun-Hours

Example 1: Estimate the annual energy delivered by the 1-kW (dc, STC) array that is located in Las Vegas, NV, is south-facing, and has a tilt angle L - 15°. Use an overall derating factor of 80%.

- *Answer: PSH = 6.4 (see Appendix E). De-rated ac power output 1kW x .80 = 0.8 kW. Annual Energy = 0.8 kW × 6.4h/day × 365 day/yr = 1,869 kWh*

Problem 6.1:

A clean, 1 m^2, 15%-efficient module (STC), has its own 90%-efficient inverter. Its NOCT is 45°C and its rated power degrades by 0.5%/°C above the 25°C STC.

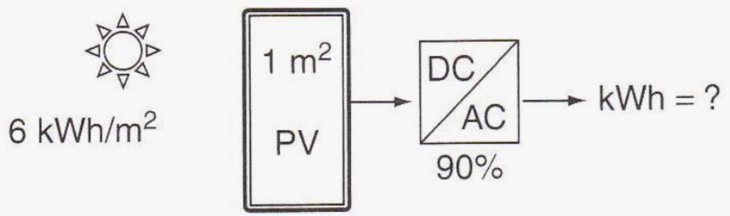


FIGURE P6.1

Ans: a. ………

b. ………

a. What is the STC rated power of the module?

b. For a day with 6 kWh/m^2 of insolation, find the kWh that it would deliver if it operates at its NOCT temperature. Assume the only deratings are due to temperature and inverter efficiency.

Examples:

- **Problem 6.2:**

NREL's PVWATTS website predicts that 5.56 $kWh/m^2/d$ of insolation on a south-facing, 40° tilt array in Boulder, CO, will deliver 1459 kWh/yr of AC energy per $kW_{DC,STC}$ of PV modules.

a. Using the "peak-hours" approach to performance estimation, what overall derate factor (including temperature effects) would yield the same annual energy delivered?

b. Since PVWATTS' derate value of 0.77 includes everything but temperature impacts, what temperature-induced derating needs to be included to make the peak-hours approach predict the same annual energy?

(Overall derate = PVWATTS derate × Temperature derate).

c. Use the PVWATTS website to find the overall annual temperature derate factors for a cold place (Bismarck, ND) and a hot place (Houston, TX). Use the same south-facing, 40° tilt array.

Ans: a) ………………..

b) ………………..

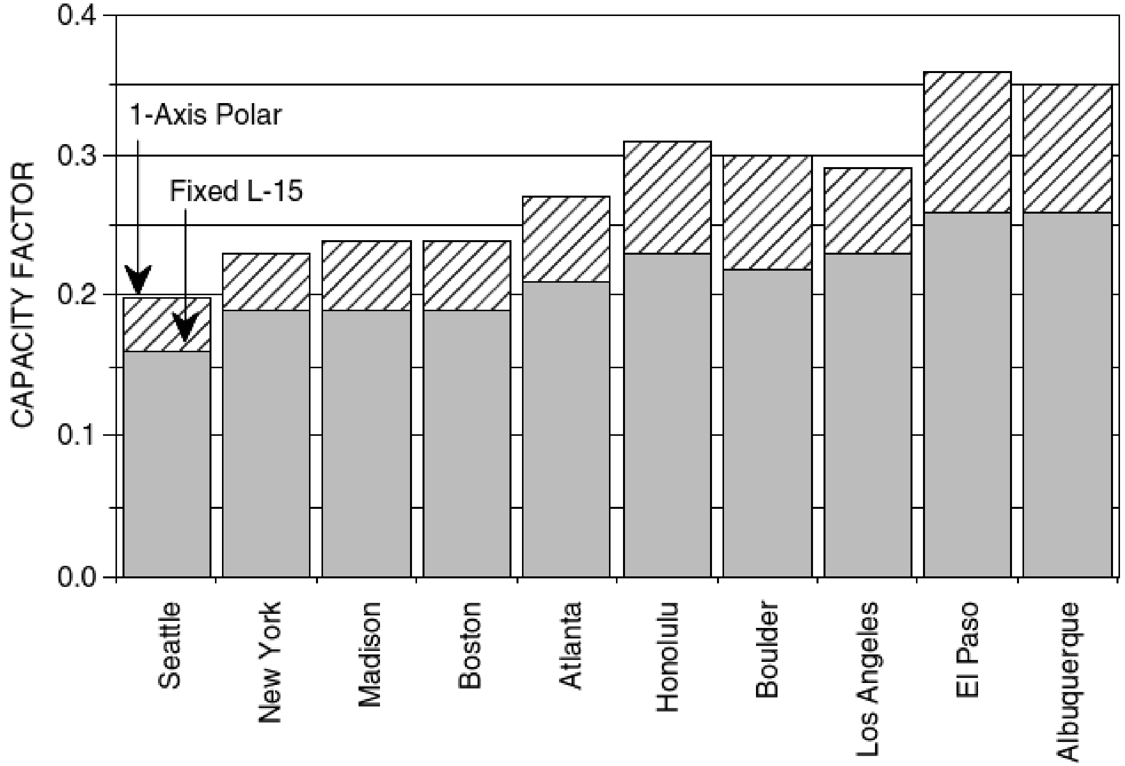
c) ………………..

Capacity Factor (CF)

- Capacity Factor for grid-connected PV systems:

$$\text{Capacity factor (CF)} = \frac{\text{(h/day of “peak sun”)}}{\text{24 h/day}}$$

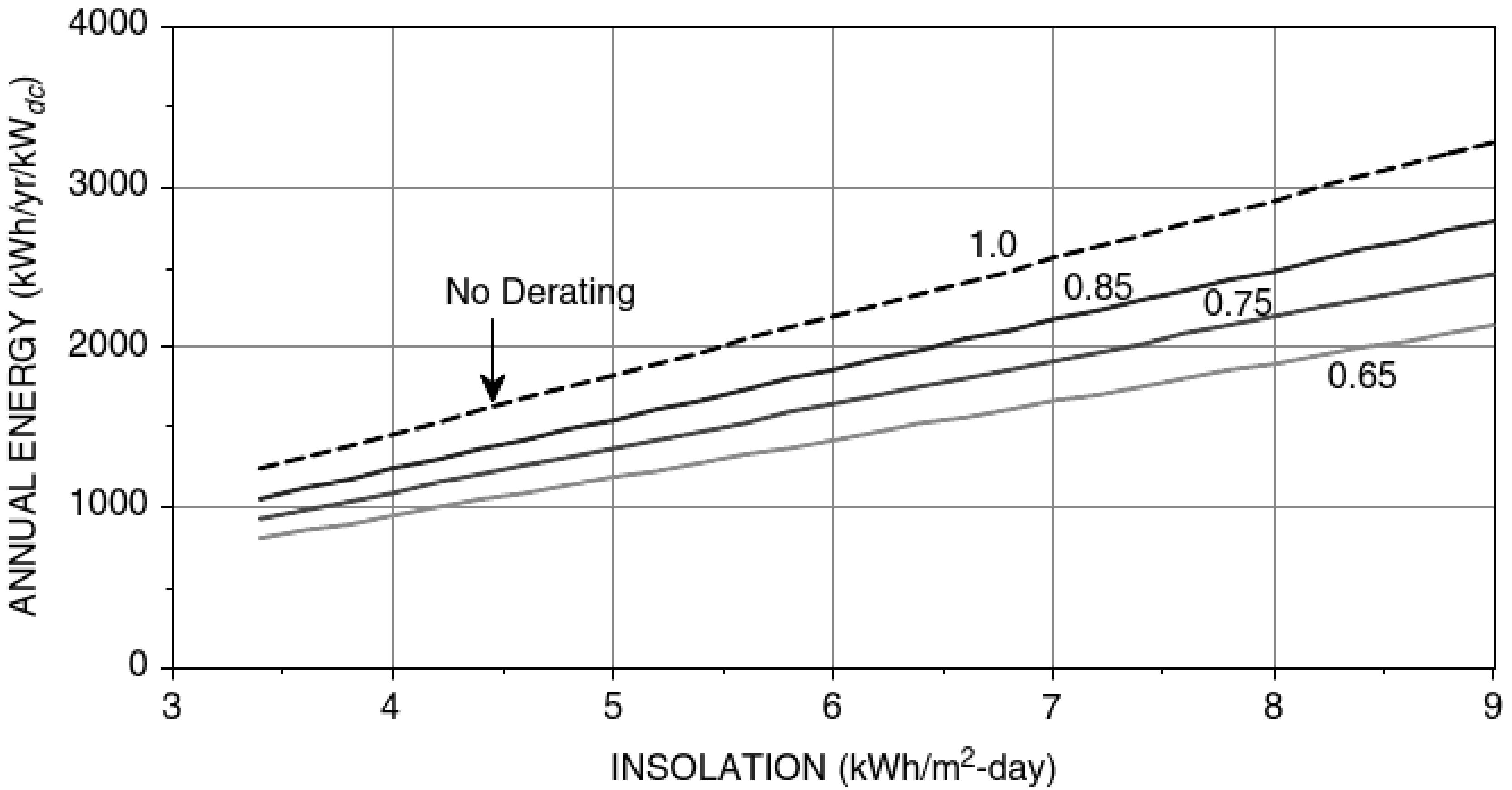
- **Example 2**: what is the capacity factor of a fixed PV array in Las Vegas, NV (south facing with tilt = latitude)? *(Ans: 6.4/24 = 0.27)*



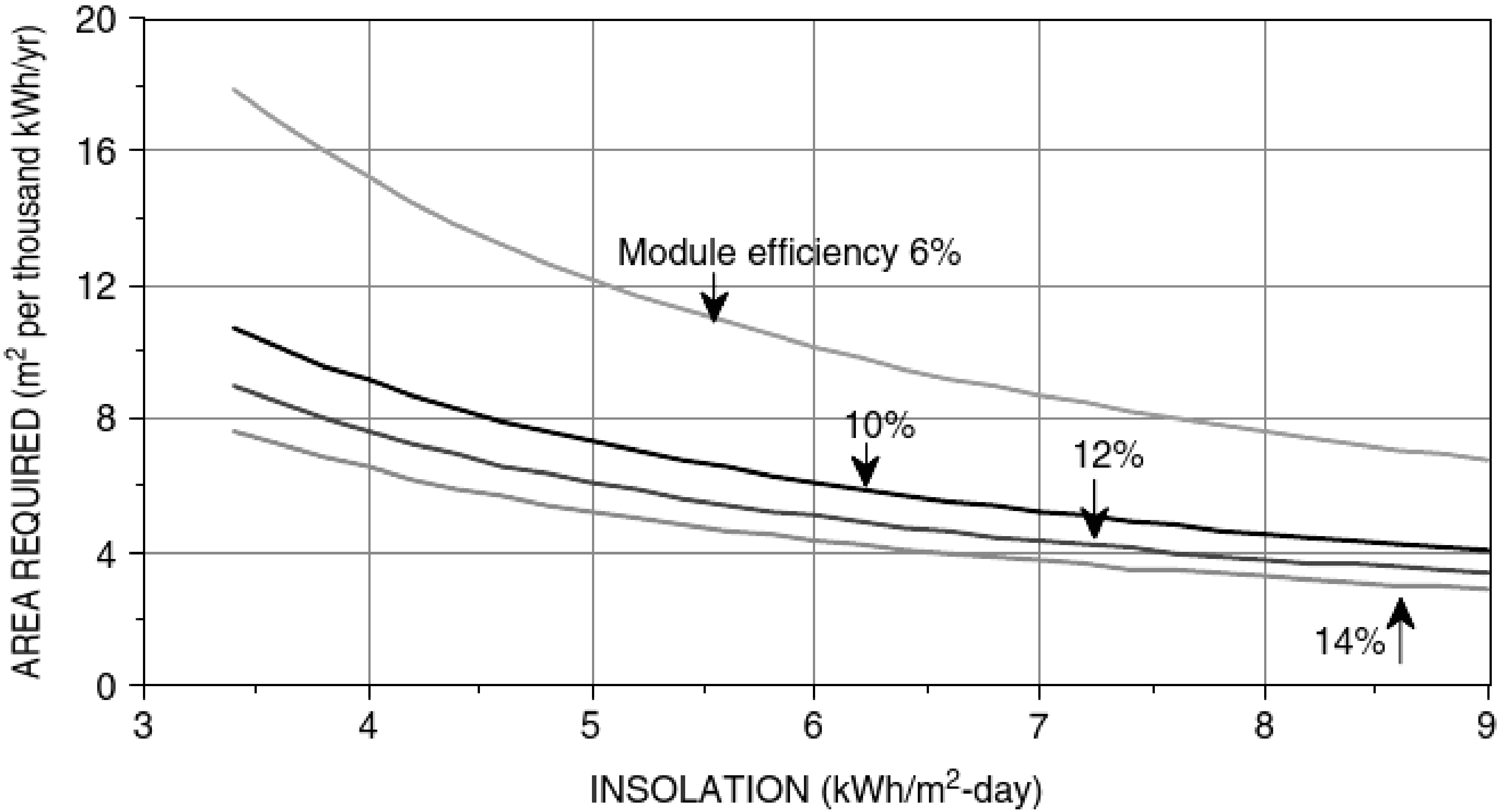
System Sizing – Practical Design Considerations

- **System sizing (First Cut):** How many kWh/year are required? How many peak watts of dc PV power are needed to provide that amount? How much area will that system require?
- **Example 4: Case of house in Fresno, CA:** Desire a rooftop PV array that will annually displace all of the 5,600 kWh/year of electricity that the home uses. How many kW (dc, STC) of panels will be required and what area will be needed? Make assumptions as needed.
- *Answer:*
  - *For Fresno, CA (Appendix G): 5.7 kWh/m²/day of annual insolation for L-15,*
  - $P_{ac} = 5600/(5.7x365) = 2.69$ *kW*
  - *Assume derating factor of 80%* → $P_{dc,STC} = 2.69/.8 = 3.36$ *kW*
  - *Assume collector efficiency of 17.5%* → *Area* $= 3.36/0.175 = 19.2\ m^2$

Annual Energy delivered by 1 kW (dc, STC) PV array



Area required to deliver 1 MWh/year (with dc-to-ac derating of 75%)



Panel (AstroHalo) Selection

ELECTRICAL SPECIFICATIONS				
STC rated output (P_{mpp})*	340 Wp	345 Wp	350 Wp	355 Wp
Rated voltage (V_{mpp}) at STC	37.33 V	37.38 V	37.48 V	37.55 V
Rated current (I_{mpp}) at STC	9.11 A	9.23 A	9.34 A	9.46 A
Open circuit voltage (V_{oc}) at STC	46.16 V	46.37 V	46.57 V	46.70 V
Short circuit current (I_{sc}) at STC	9.62 A	9.67 A	9.72 A	9.78 A
Module efficiency	17.5%	17.7%	18.0%	18.3%
Rated output (P_{mpp}) at NOCT	237.4 Wp	240.9 Wp	244.4 Wp	247.9 Wp
Rated voltage (V_{mpp}) at NOCT	34.10 V	34.15 V	34.24 V	34.29 V
Rated current (I_{mpp}) at NOCT	6.96 A	7.05 A	7.14 A	7.23 A
Open circuit voltage (V_{oc}) at NOCT	42.36 V	42.55 V	42.73 V	42.85 V
Short circuit current (I_{sc}) at NOCT	7.44 A	7.48 A	7.52 A	7.56 A
Temperature coefficient (P_{mpp})	- 0.408%/°C			
Temperature coefficient (I_{sc})	+0.050%/°C			
Temperature coefficient (V_{oc})	- 0.311%/°C			
Normal operating cell temperature (NOCT)	46±2°C			
Maximum system voltage (IEC/UL)	$1000V_{DC}$ or $1500V_{DC}$			
Number of diodes	3			
Junction box IP rating	IP 67			
Maximum series fuse rating	20 A			

Inverter Selection - (Sunny Boy)

Technical data	Sunny Boy 3.0-US		Sunny Boy 3.8-US		Sunny Boy 5.0-US	
	208 V	240 V	208 V	240 V	208 V	240 V
Input (DC)						
Max. PV power	4800 Wp		6144 Wp		8000 Wp	
Max. DC voltage	600 V					
Rated MPP voltage range	155 - 480 V		195 - 480 V		220 – 480 V	
MPPT operating voltage range	100 – 550 V					
Min. DC voltage / start voltage	100 V / 125 V					
Max. operating input current per MPPT	10 A					
Max. short circuit current per MPPT	18 A					
Number of MPPT tracker / string per MPPT tracker	2/1				3 / 1	
Output (AC)						
AC nominal power	3000 W	3000 W	3330 W	3840 W	5000 W	5000 W
Max. AC apparent power	3000 VA	3000 VA	3330 VA	3840 VA	5000 VA	5000 VA
Nominal voltage / adjustable	208 V / ●	240 V / ●	208 V / ●	240 V / ●	208 V / ●	240 V / ●
AC voltage range	183 – 229 V	211 – 264 V	183 – 229 V	211 – 264 V	183 – 229 V	211 – 264 V
AC grid frequency	60 Hz / 50 Hz					
Max. output current	14.5 A	12.5 A	16.0 A	16.0 A	24.0 A	24.0 A
Power factor (cos ϕ)	1					
Output phases / line connections	1 / 2					
Harmonics	< 4 %					
Efficiency						
Max. efficiency	97.2 %	97.6 %	97.3 %	97.6 %	97.3 %	97.6 %
CEC efficiency	96.2 %	96.3 %	96.4 %	96.7 %	96.7 %	96.9 %

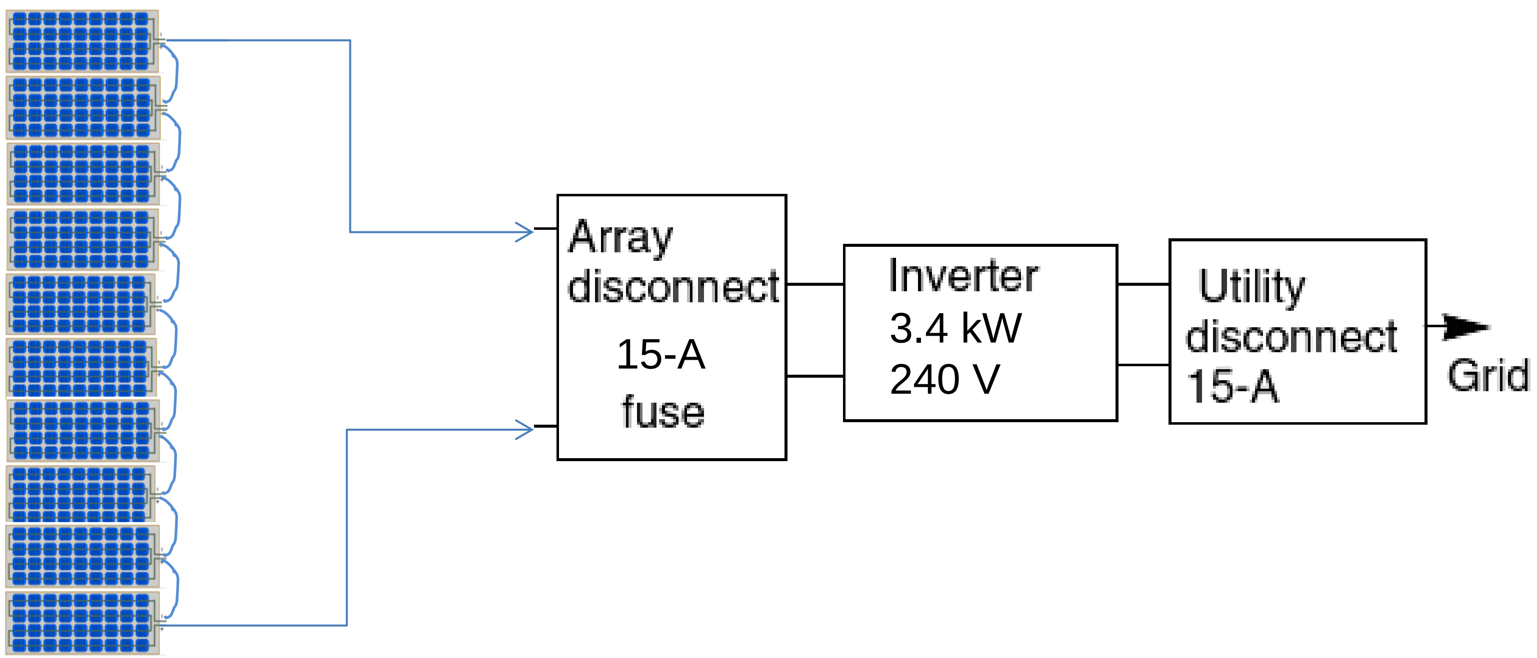
Basic Design/Verification

Example 4 (continued)

- Number of modules needed: 3,360/340 = 9.88 → 10 panels
- Number of strings = 1:
  - Inverter maximum DC Voltage: 600 V (the National Electrical Code (NEC) restricts all voltages in family dwellings to not more than 600 V)
  - Array Open Circuit voltage: 46.16x10 = 416.6 V → good fit
  - Array voltage at maximum power: 37.77x10 = 377.7 V →
  - Inverter MPPT voltage range: 195 V – 480 V good fit
  - Inverter max operating current and short-circuit currents: 10A & 18A
  - Array max operating current and short-circuit currents: 9.11A & 9.62A

Roof area, energy production and fuses

- Roof area: nearly 20 m^2
- Rated Power (dc, STC): = 3.4 kW
- Rated AC Power (assuming de-rating of 80%): 3.4 x.8 = 2.72 kW
- Expected annual energy production: 2.72 x 5.7 x 365 = 5,660 kWh/year → goal is met.
- DC Disconnect fuse > 1.56 (per NEC) x 9.62 = 15 A
- AC Disconnect fuse > 1.25 (per NEC) x (2690/240) =11.2 A → 15 A



Examples

- **Problem 6.6:**

A grid-connected PV array consisting of sixteen 150-W modules can be arranged in a number of series and parallel combinations: (16S, 1P), (8S, 2P), (4S, 4P), (2S, 8P), (1S, 16P). The array delivers power to a 2500-W inverter. The key characteristics of modules and inverter are given below.

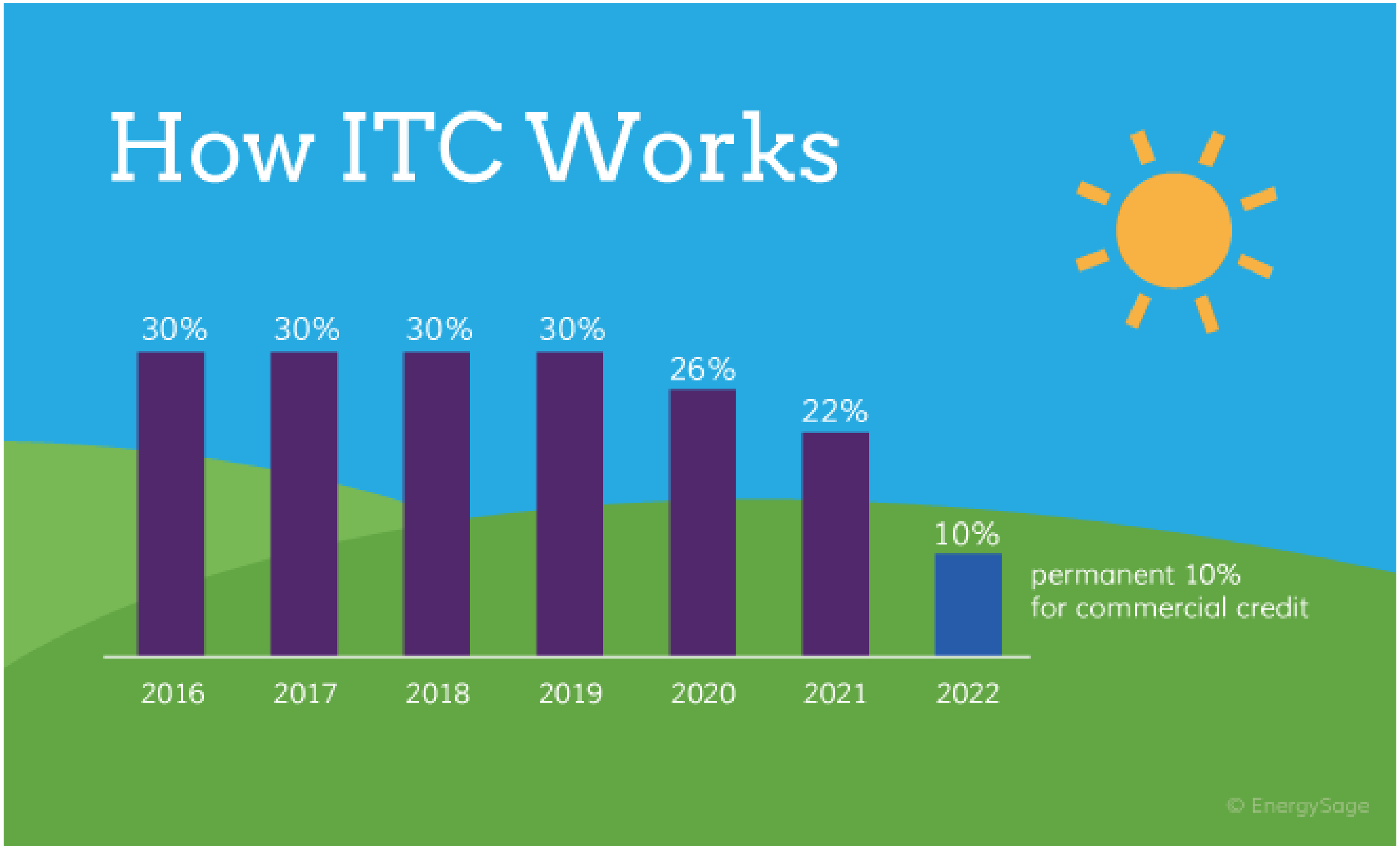
Inverter		Module	
Maximum AC power	2500 W	Rated power $P_{DC,STC}$	150 W
Input voltage range for MPP	250–550 V	Voltage at MPP	34 V
Maximum input voltage	600 V	Open-circuit voltage	43.4 V
Maximum input current	11 A	Current at MPP	4.40 A
		Short-circuit current	4.8 A

Using the input voltage range of the inverter MPPT and the maximum input voltage of the inverter as design constraints, what series/parallel combination of modules would best match the PVs to the inverter? Check the result to see whether the inverter maximum input current is satisfied. For this simple check, you do not need to worry about temperatures.

Ans: ………………..

PV System Economics

- Federal Investment Tax Credit (ITC)



PV System Economics

- NV Energy - Clean Energy Incentive Program

http://www.Nvenergy.com/renewablegenerations

State:	Nevada
Incentive Type:	Rebate Program
Web Site:	http://www.Nvenergy.com/renewablegenerations
Administrator:	NV Energy
Budget:	PV: $255,700,000; Wind and Hydro: $40,000,000
Expiration Date:	12/31/2021 (PBI payments may continue to be paid through 12/31/2026)
Utilities:	Nevada Power Co, Sierra Pacific Power Co
Eligible Renewable/Other Technologies:	Solar Photovoltaics, Wind (All), Wind (Small), Hydroelectric (Small)
Applicable Sectors:	Commercial, Industrial, Local Government, Nonprofit, Residential, Schools, State Government, Tribal Government, Agricultural, Low Income Residential
Incentive Amount:	**Solar (As of 9/24/18):** Residential/Commercial/Industrial (25 kW or smaller): $0.20 / watt-AC Low Income/Nonprofit/Public Entity (25 kW or smaller): $0.45 / watt-AC

PV System Economics

- Local net-metering rates

https://www.nvenergy.com/account-services/energy-pricing-plans/net-metering/nmr-405

Tiers & Capacity

The NMR-405 Rider is made up of four tiers, which are assigned based on the date of the customer's net metering application. Your tier determines your Excess Energy Credit rate.

Tiers 1 and 2 are at capacity. Applications are currently being accepted for Tier 3. Click to view current solar capacity numbers.

	Capacity	Credit	Credit Period	Status
Tier 1	80 megawatts of solar capacity applied for	95% of the retail volumetric electricity rate, excluding public policy charges	20 years	Full
Tier 2	80 megawatts of solar capacity applied for	88% of the retail volumetric electricity rate, excluding public policy charges	20 years	Full
Tier 3	80 megawatts of solar capacity applied for	81% of the retail volumetric electricity rate, excluding public policy charges	20 years	Open - view current capacity
Tier 4	All solar capacity applied for following the closure of Tier 3	75% of the retail volumetric electricity rate, excluding public policy charges	20 years	Not yet open

PV System Economics

- **Amortizing Costs**
- Let ***P*** be an amount of money that is borrowed for ***n*** years at an interest rate of ***i***. Then the annual loan payment ***A*** will be

$$A = P.CRF(i,n)$$

- Where the capital recovery factor is calculated by

$$CRF(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1}$$

- **Example 5:** Consider the 3.4 kW (DC) system of the previous example. Assume the LV homeowner paid $3.25/W for the system.
  - A) what is his final cost (after federal and local incentives).
  - B) What is his annual loan payment if the net cost is borrowed for period of 15 years at a rate of 4%.
  - Answers: A) $7,259. B) $652.58

PV System Economics

- **Example 6:** continuing with the previous example, assume utility rates are as follows: net metering rate = \$0.09/kWh, retail electricity rate = \$0.111/kWh. Further assume that 35% of the expected annual solar energy produced (i.e., 5,660 kWh) is net-metered, while 65% is self-consumed.
  - A) Computer the resulting yearly energy cost savings. *(Answer: \$586.66, net cash flow = \$586.66 – \$652.58 = -\$65.92)*
  - B) Suppose the utility rates increase by 2% per year while the PV performance degradation is 0.5% per year. Determine the year where the net cash flow turns positive. *(Answer: next slide)*

PV System Economics

Example 6 (continued)

Year	Loan Payment	PV Energy (kWh)	Cost Savings	Cash Flow
1	$ 652.58	5,660	$ 586.66	$ (65.92)
2	$ 652.58	5,632	$ 595.40	$ (57.18)
3	$ 652.58	5,604	$ 604.27	$ (48.31)
4	$ 652.58	5,576	$ 613.28	$ (39.30)
5	$ 652.58	5,548	$ 622.41	$ (30.17)
6	$ 652.58	5,520	$ 631.69	$ (20.89)
7	$ 652.58	5,492	$ 641.10	$ (11.48)
8	$ 652.58	5,465	$ 650.65	$ (1.93)
9	$ 652.58	5,438	$ 660.35	$ 7.77
10	$ 652.58	5,410	$ 670.19	$ 17.61
11	$ 652.58	5,383	$ 680.17	$ 27.59
12	$ 652.58	5,356	$ 690.31	$ 37.73
13	$ 652.58	5,330	$ 700.59	$ 48.01
14	$ 652.58	5,303	$ 711.03	$ 58.45
15	$ 652.58	5,276	$ 721.63	$ 69.05
16	$ -	5,250	$ 732.38	$ 732.38