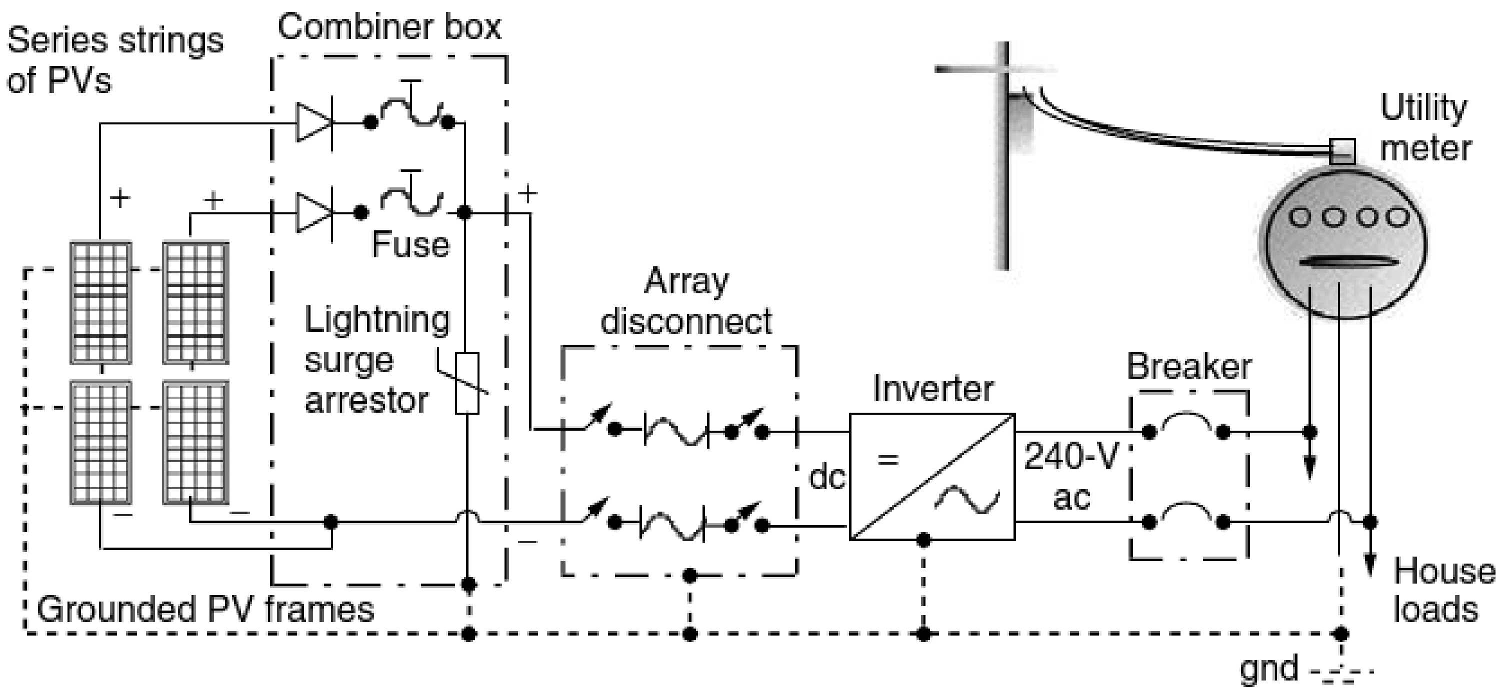
Photovoltaic Systems II

EE 446/646

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

The inverter contains:

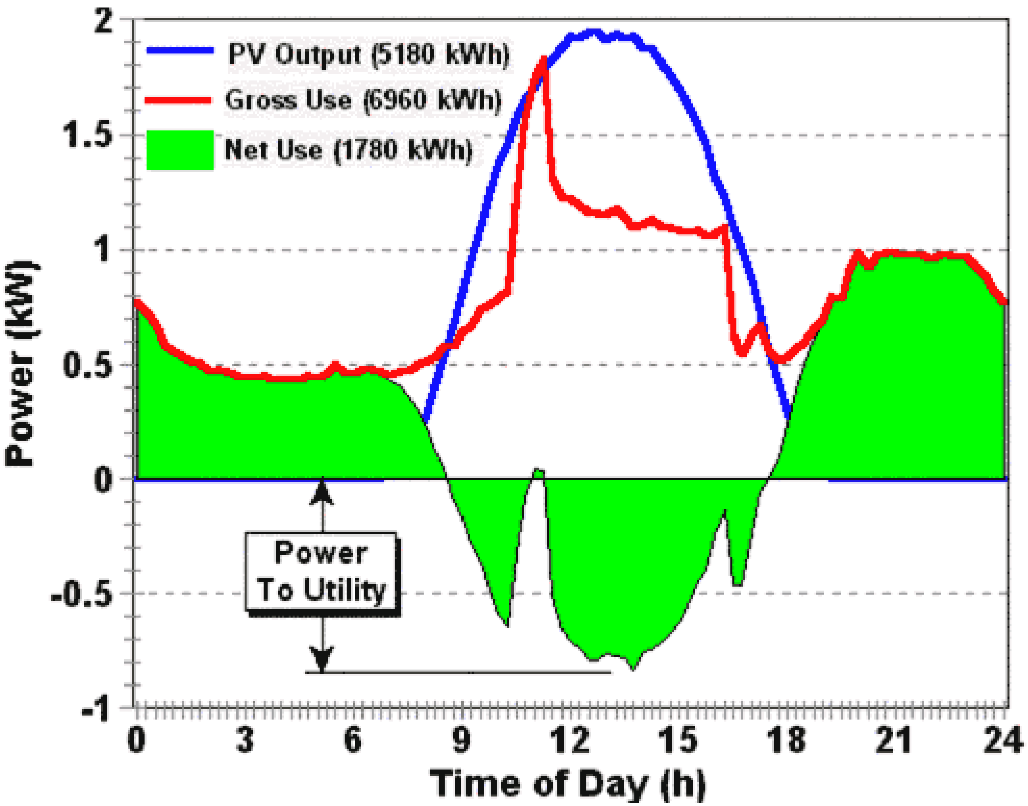
- Ground Fault Circuit Interrupter (GFCI)
- MPPT and Circuitry to disconnect the PV from the grid in case of power loss (built within the inverter).



Today's inverters come with built-in DC and AC disconnects.

Interfacing with the utility

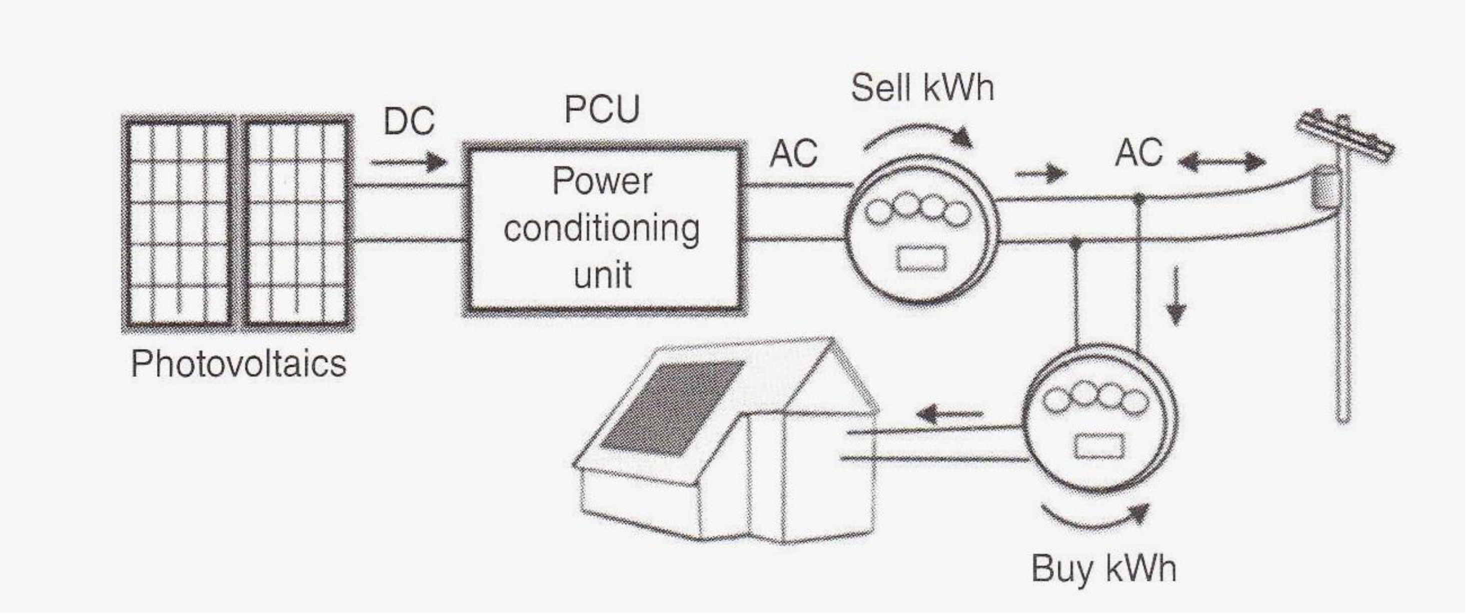
- Whenever the PV system delivers more power than the local demand, the electric meter runs backwards, building up a credit.
- When demand exceeds that supplied by the PV, the grid provides supplementary power. This arrangement is called ***net metering*** billing arrangement (the customer's monthly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

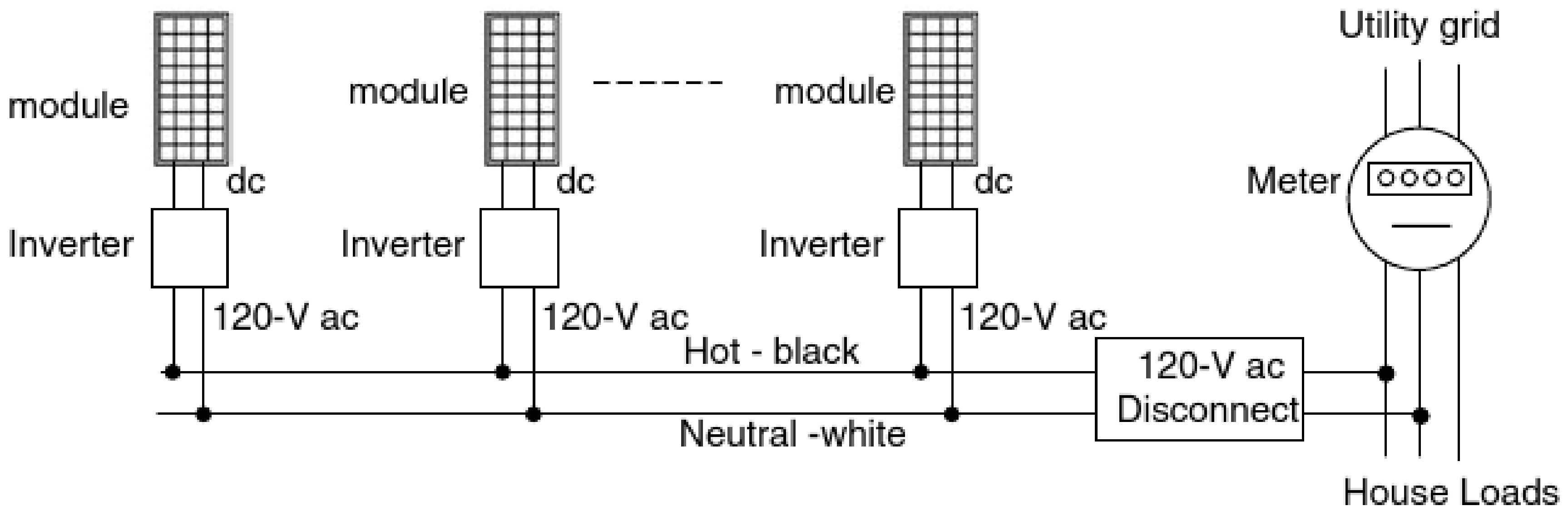
Components of a grid-connected Residential PV system (with two meters)

- 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



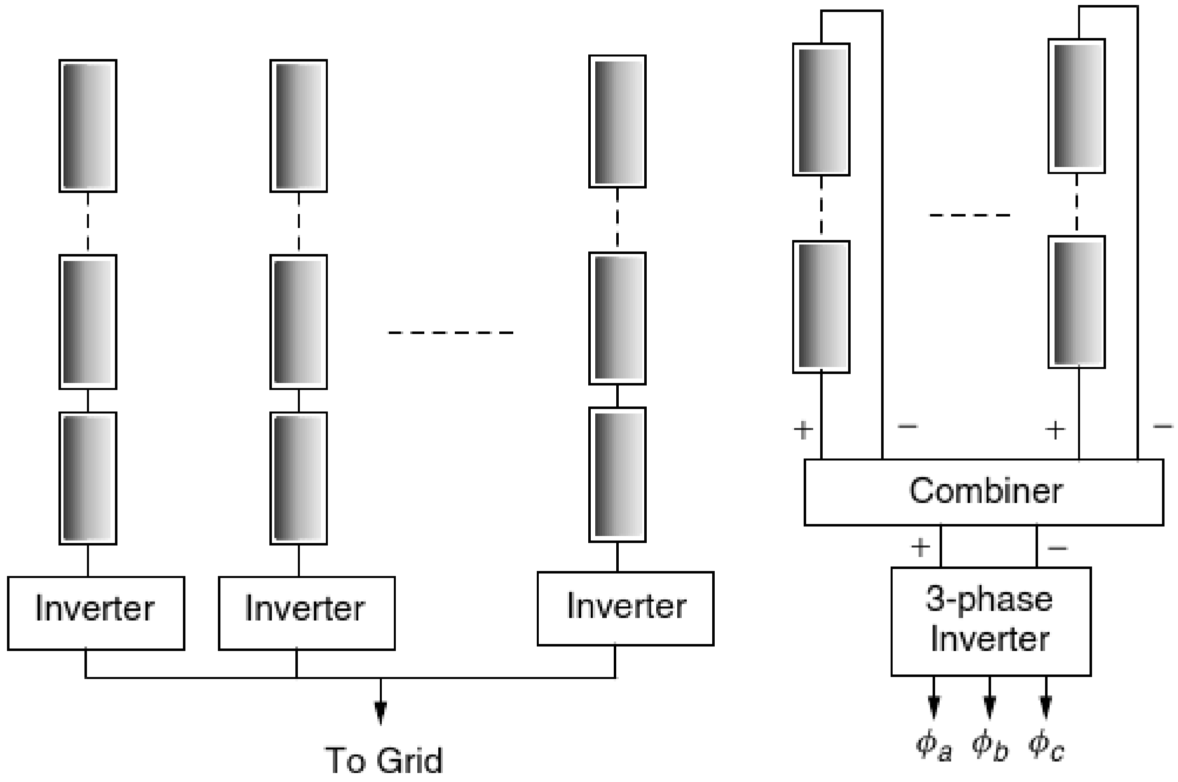
Option of using micro-inverters

- 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

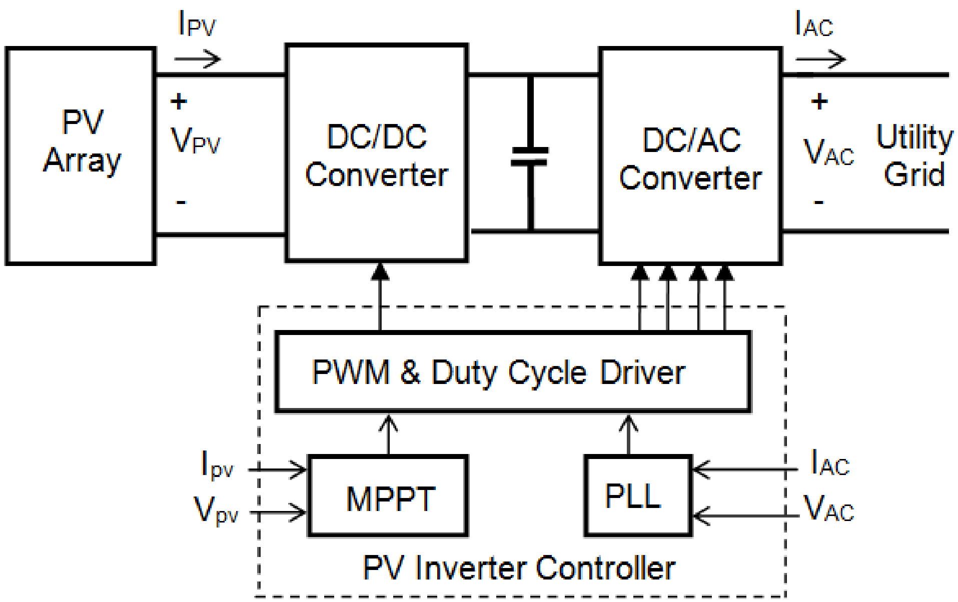
- For large grid-connected systems, strings of PV modules may be tied into inverters in a manner analogous to the individual inverter/module concept. By doing so, the system is modularized.
- Large, central inverter systems providing three-phase power to the grid are also an option.



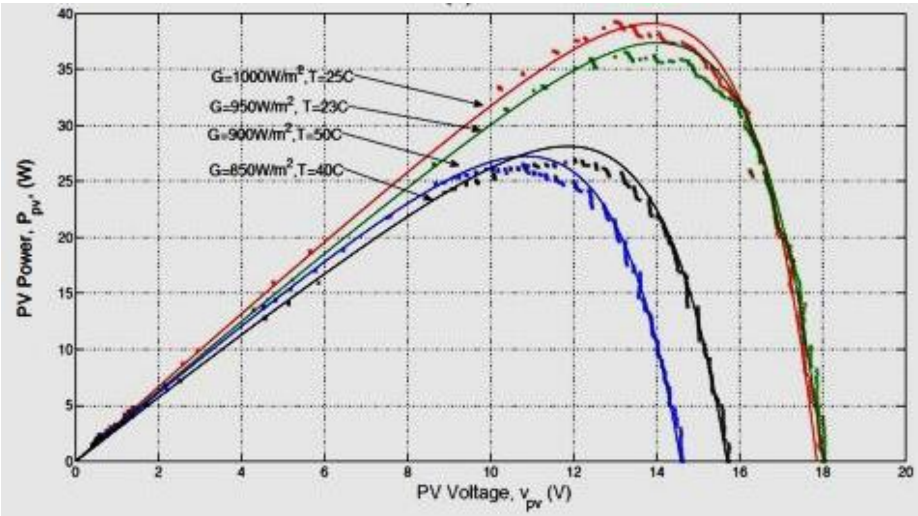
Grid-Tied PV Inverters

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).

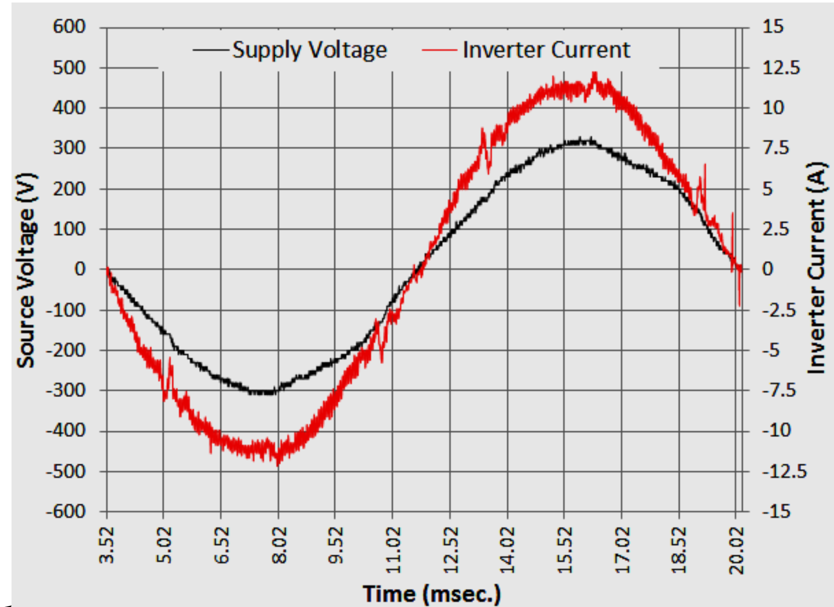


Grid-Tied PV Inverter main Functions

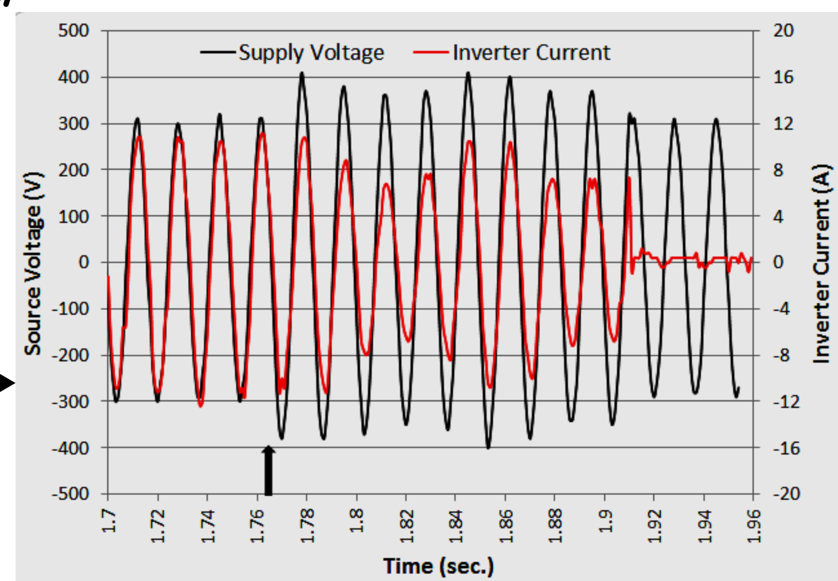


Maximum Power Tracking

Grid synchronization



Grid Monitoring - Disconnect



AC Rated Power of PV System

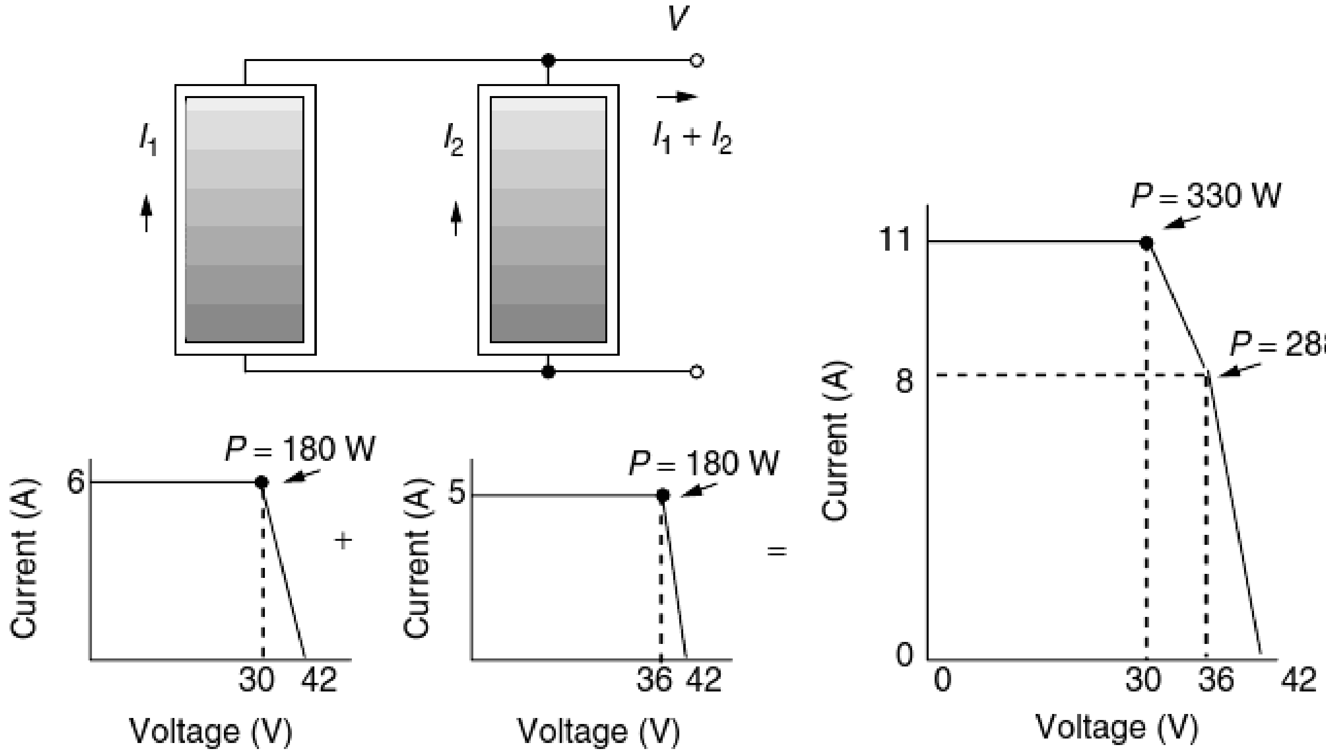
- The AC rated power of a grid-connected PV array is defined as

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

  - 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 25%.

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)*

Impact of Temperature

- 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^{o}C at which they are rated (STC) and we know that as temperature increases, PV power decreases.
- Other PV module rating system:
  - The PVUSA test condition (PTC) is defined as 1-sun irradiance in the plane of the array, ambient temperature of 20°C, and a wind-speed of 1 m/s. California, for example, has chosen to use the PTC rating for its PV rebate program.
    - What is the difference between PTC and NOTC?

      (Ans: different solar irradiances).
    - What is the difference between PTC and STC?

      (Ans: different cell temperatures).

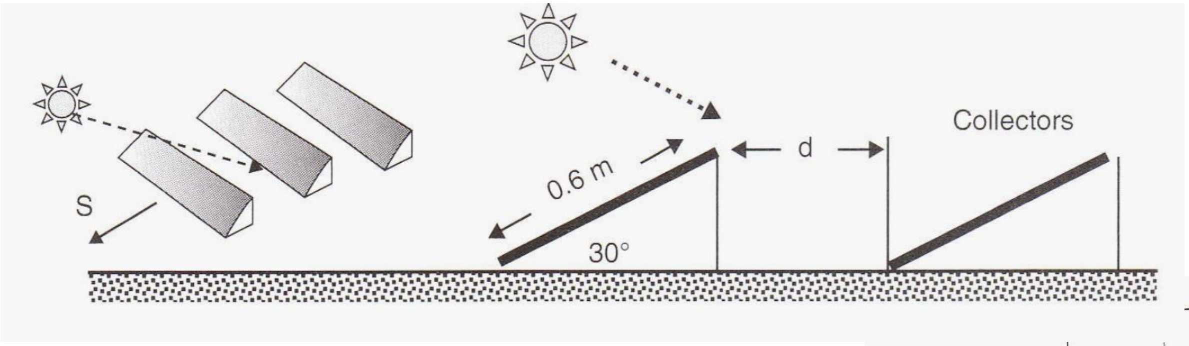
Accuracy when Using PTC

- The PTC rating assumes a nominal ambient of 20^{o}C, which is a pretty good average estimate for many locations in the United States.
- For Las Vegas, NV, we expect PTC to
  - be accurate during for the months of March and November
  - over-predict performance during the months of April-October,
  - under-predict during December-February.

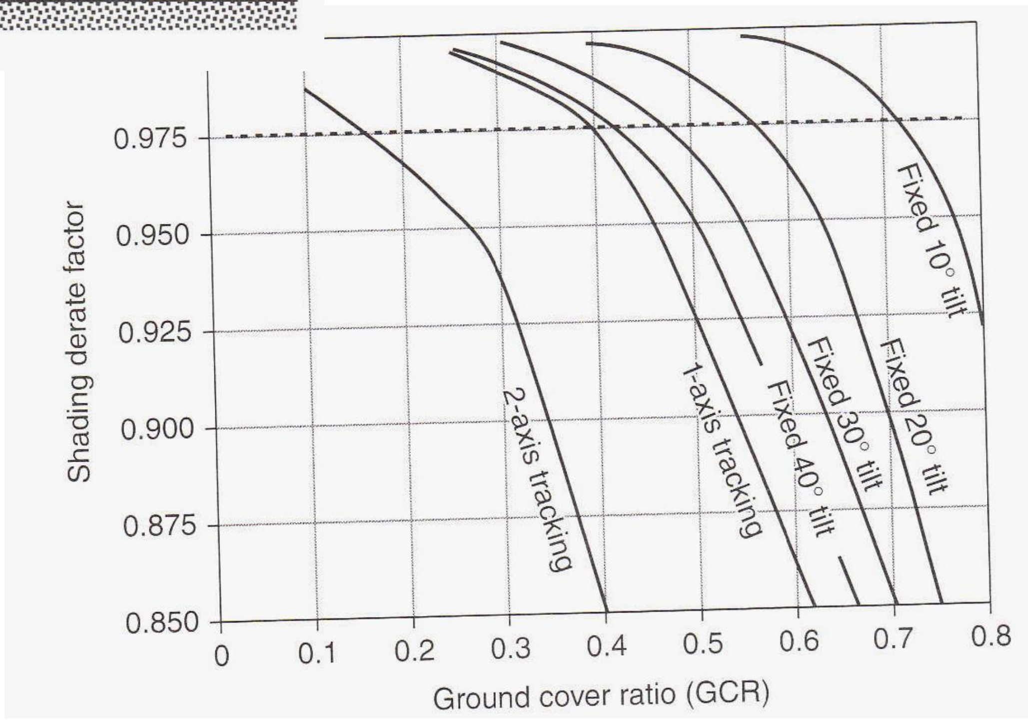
Tilt	LAS Vegas, NV Jan	Feb	Mar	Apr	May	Jun	Latitude 36.08°N July	Aug	Sept	Oct	Nov	Dec	Year
Lat − 15	4.4	5.3	6.4	7.5	7.8	8.1	7.7	7.5	7.1	6.1	4.8	4.2	6.4
Lat	5.1	5.9	6.7	7.4	7.3	7.4	7.1	7.2	7.2	6.6	5.5	4.9	6.5
Lat + 15	5.6	6.1	6.6	6.8	6.5	6.3	6.2	6.5	7.0	6.8	5.9	5.4	6.3
90	5.0	5.1	4.7	3.9	3.0	2.6	2.6	3.4	4.5	5.3	5.2	5.0	4.2
1-Axis (Lat)	6.2	7.3	8.8	10.2	10.6	11.1	10.4	10.3	9.8	8.6	6.7	5.9	8.8
Temp. (°C)	14.1	17.4	20.4	25.3	31.0	37.9	41.1	39.6	34.8	27.8	19.7	14.2	26.9

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.

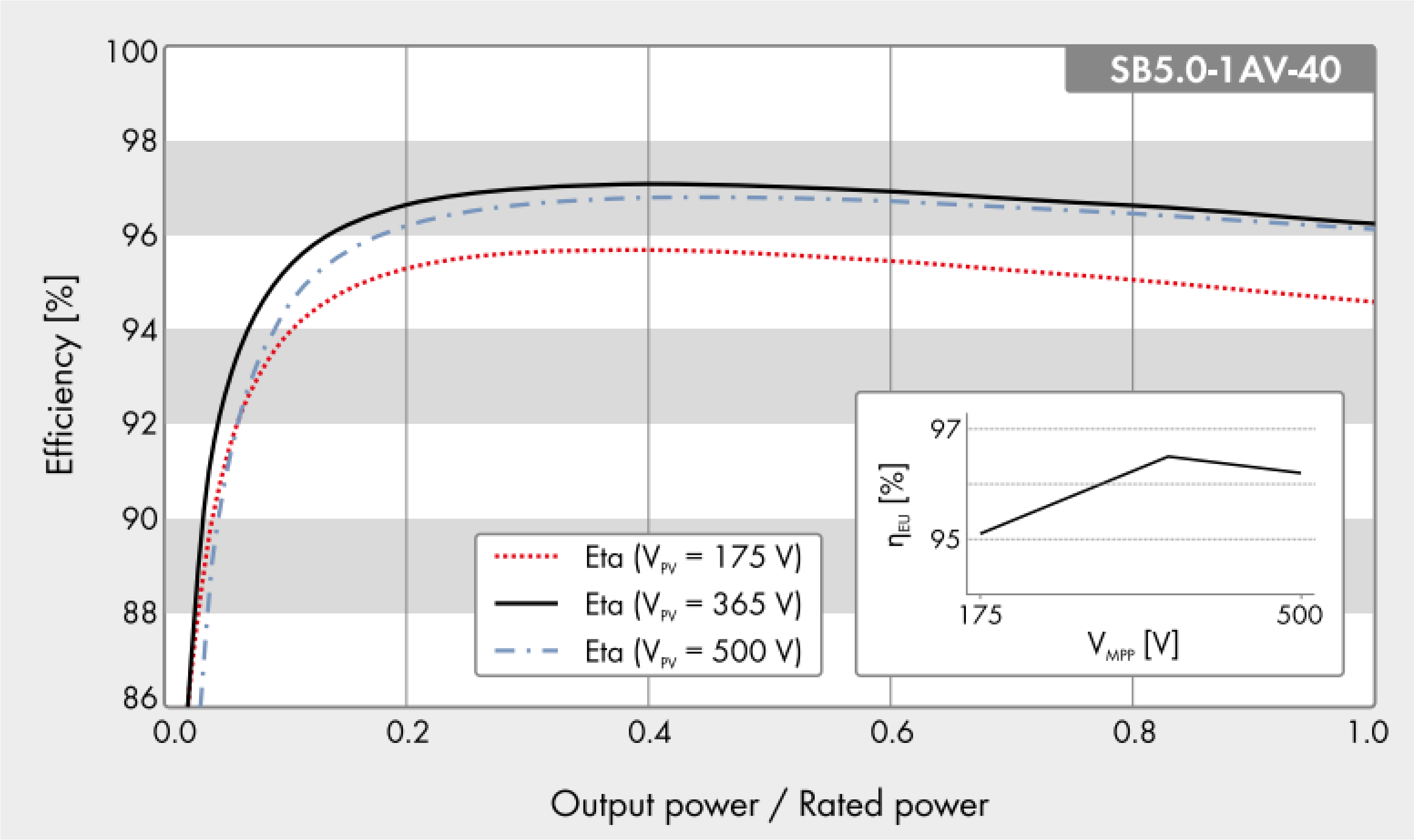


Refer to posted white paper by SunPower for more details.



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

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

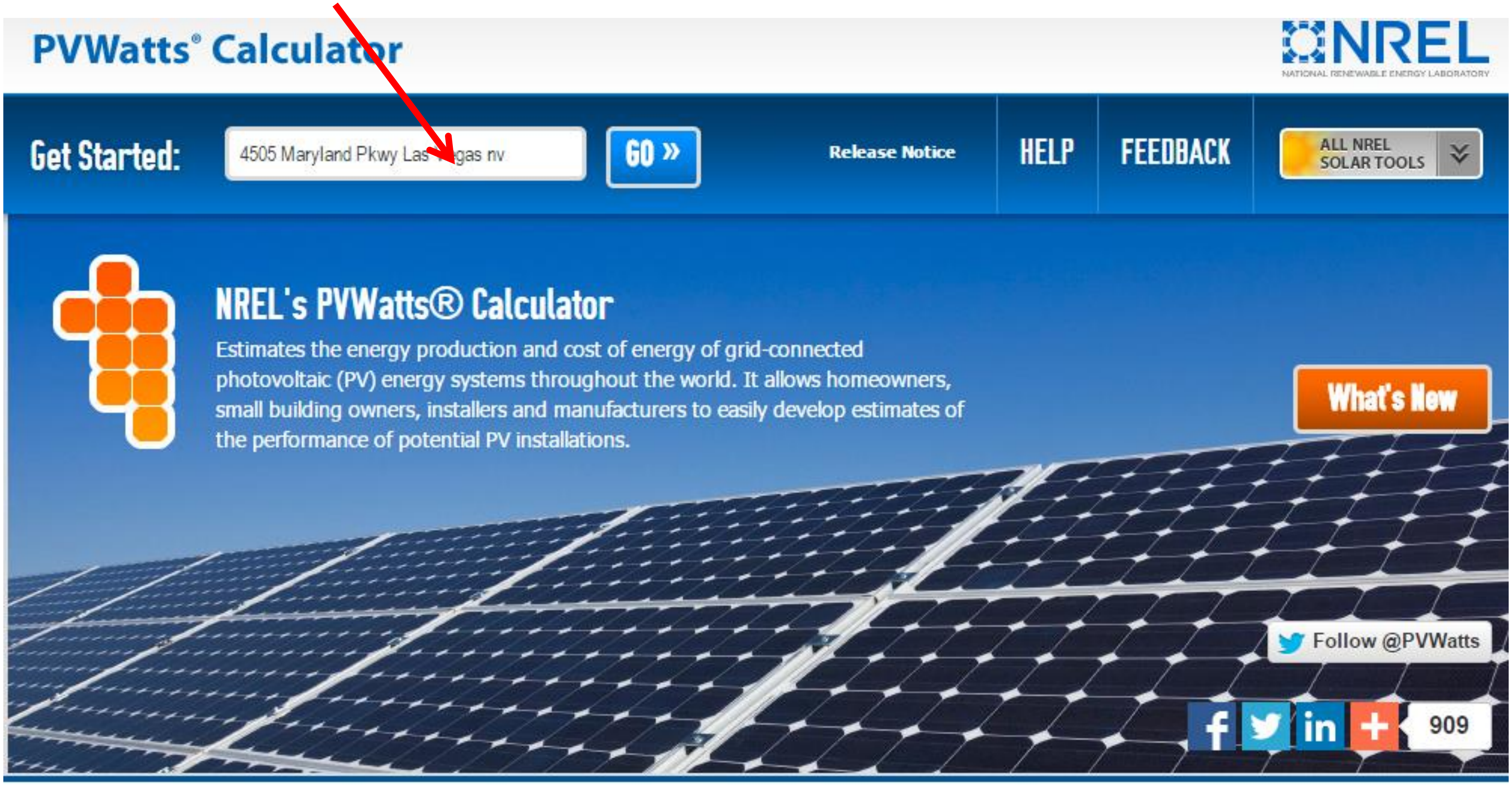
PV Size Tool (for California only)

- http://www.csi-epbb.com/default.aspx
- Used to determine the amount of solar energy of a specific system and amount of incentives from the CSI.
- Try the following:
  - Home in Irvine with Zip Code 92603
  - Module: A10Green Technology:A10J-M60-240
  - # modules: 24
  - Inverter: ABB:PVI-5000-OUTD-S-US-Z [208V]

Useful Tool to Size PV Systems:

http://pvwatts.nrel.gov/

Type address here

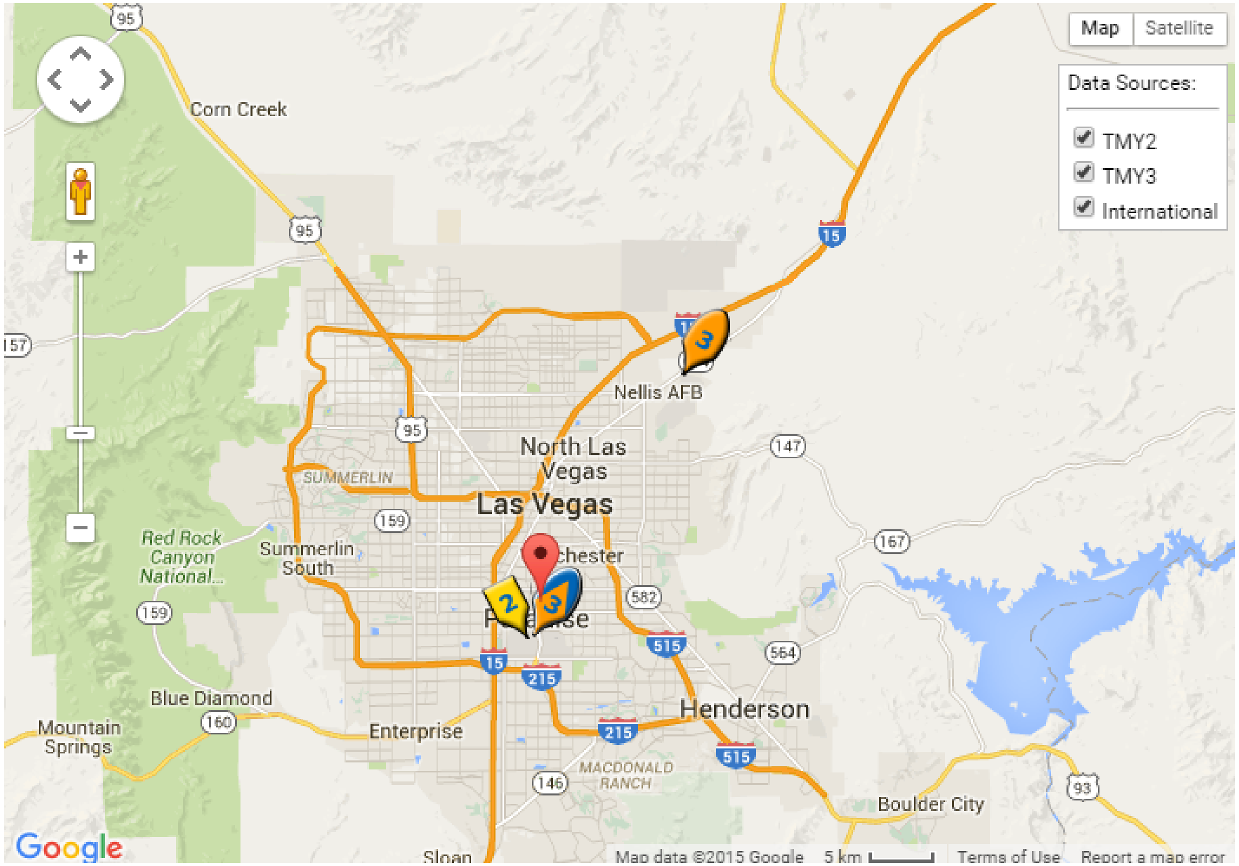


PV-WATTS – Select Weather Data

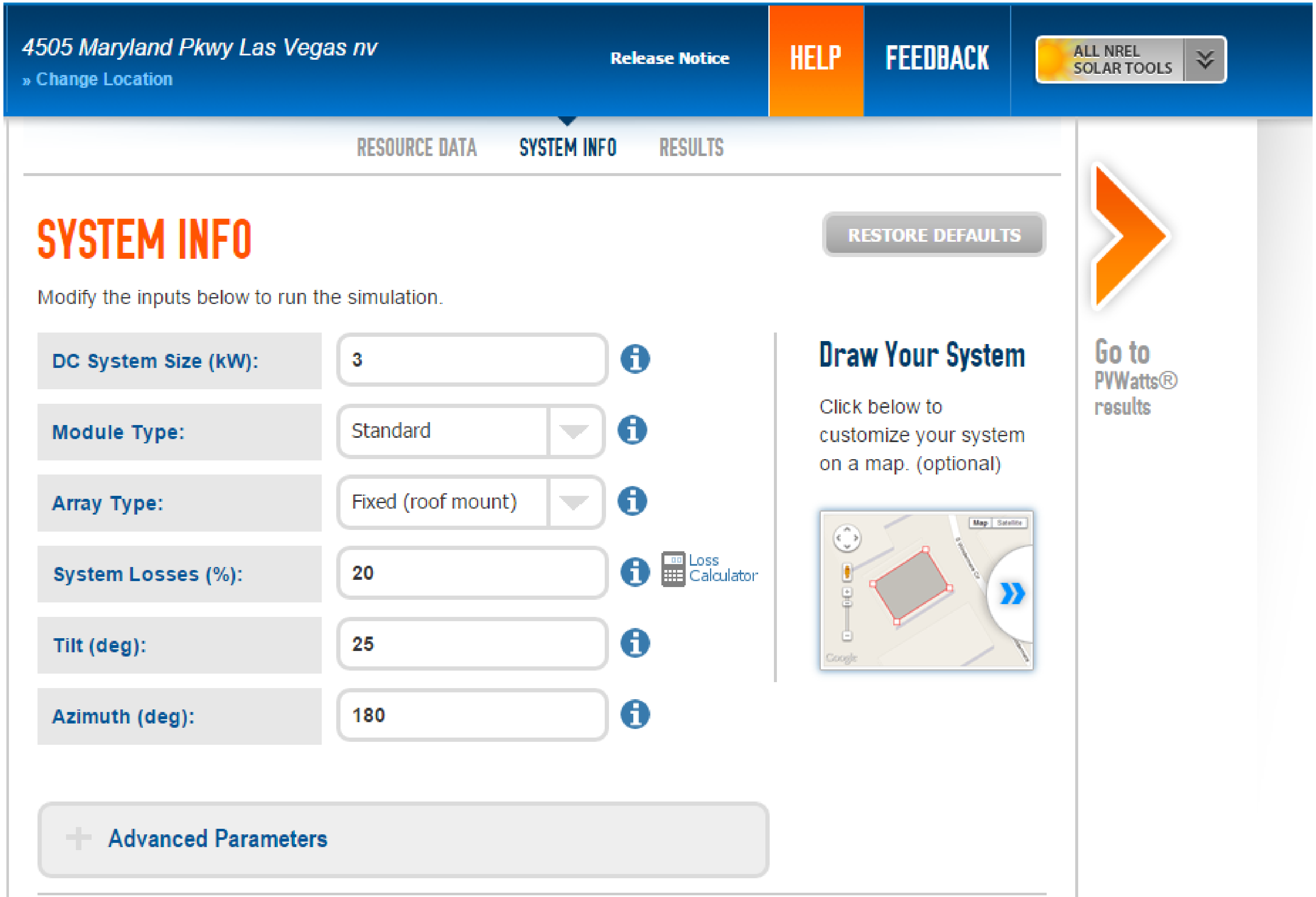
Optionally, Select Different Weather Data

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

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

Examples: Annual Energy Using the Peak-Sun-Hours

Example 1: Estimate the annual energy delivered by the 1-kW (dc, STC) array described in the previous example if it located in Las Vegas, NV, is south-facing, and has a tilt angle L - 15◦. Use an overall derating factor of 72%.

- *Answer: PSH = 6.4 (see Appendix E). De-rated ac power output 1kW x .72 = 0.72 kW. Annual Energy = 0.72 kW × 6.4h/day × 365 day/yr = 1,682 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.

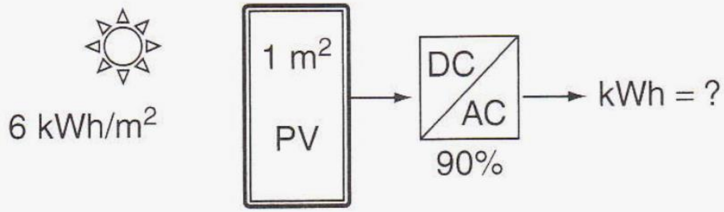


FIGURE P6.1

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.

Ans: a. 150 W
b. 0.73 kWh/day

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.

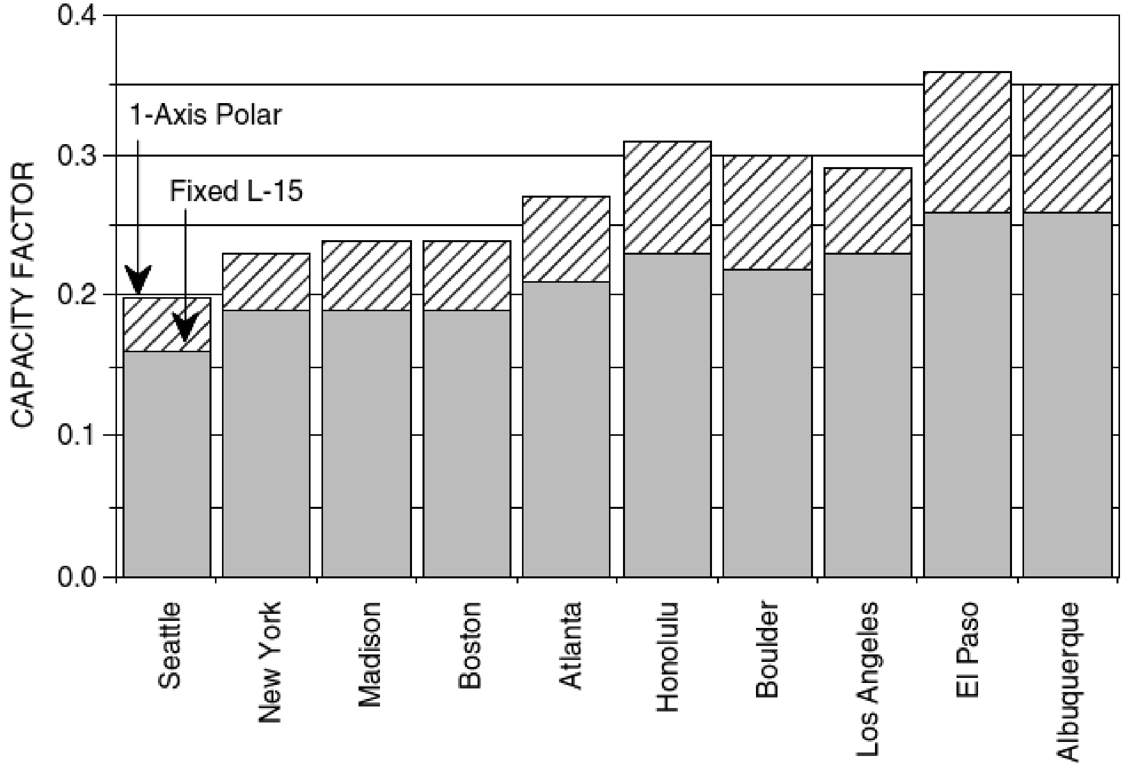
Ans: a) 0.712
b) 0.934
c) ………………..

Capacity Factor (CF)

- Capacity Factor for grid-connected PV systems:

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

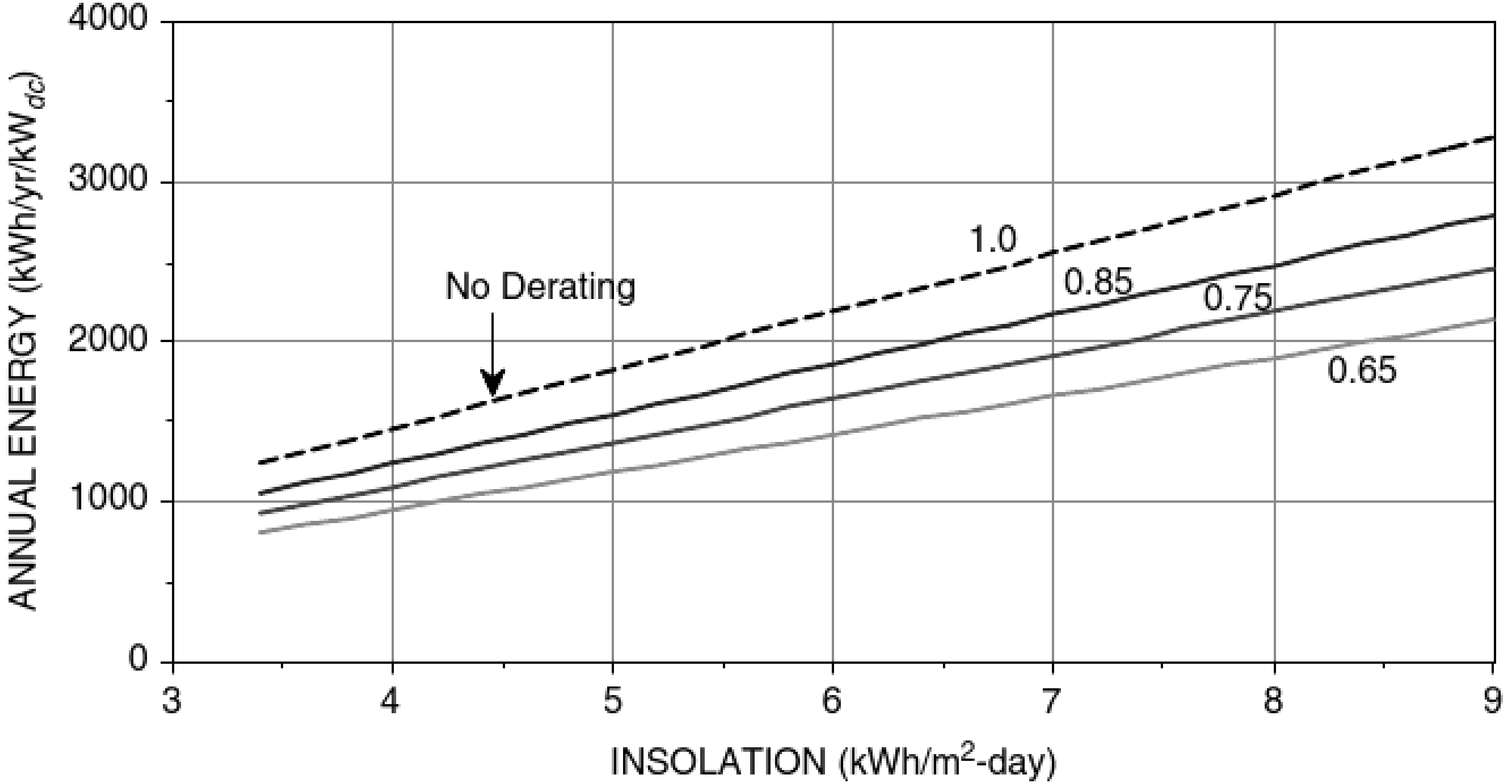
- Example: what is the capacity factor of a fixed PV array in Las Vegas, NV (south facing with tilt = latitude)? *(Ans: 6.4/24 = 0.27)*



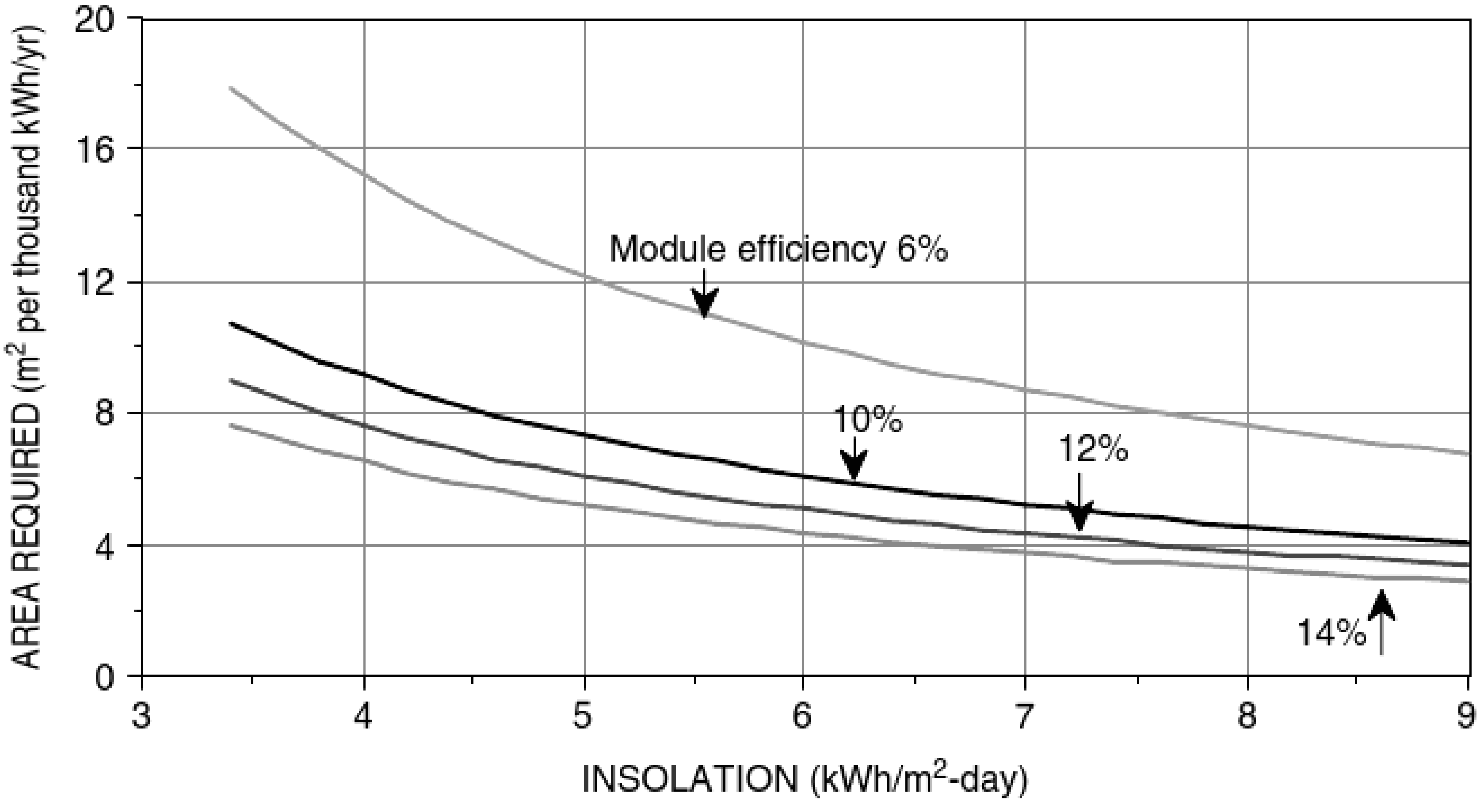
System Sizing – Practical Design Considerations

- **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?
- **Case of house in Fresno, CA:** Desire a rooftop PV array that will annually displace all of the 3,600 kWh/yr 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/m^2/day of annual insolation for L-15,*
  - $P_{ac} = 3600/(5.7 \times 365) = 1.73$ *kW*
  - *Assume derating factor of 75%* $\rightarrow P_{dc,STC} = 1.73/.75 = 2.3$ *kW*
  - *Assume collector efficiency of 12.5%* $\rightarrow$ *Area* $= 2.3/0.125 = 18.4$ *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 & Inverter Selection

Module:	Sharp NE-K125U2	Kyocera KC158G	Shell SP150	Uni-Solar SSR256
Material:	Poly Crystal	Multicrystal	Monocrystal	Triple junction a-Si
Rated power $P_{dc,STC}$:	125 W	158 W	150 W	256 W
Voltage at max power:	26.0 V	23.2 V	34 V	66.0 V
Current at max power:	4.80 A	6.82 A	4.40 A	3.9
Open-circuit voltage V_{OC}:	32.3 V	28.9 V	43.4 V	95.2
Short-circuit current I_{SC}:	5.46 A	7.58 A	4.8 A	4.8
Length:	1.190 m	1.290 m	1.619 m	11.124 m
Width:	0.792 m	0.990 m	0.814 m	0.420 m
Efficiency:	13.3%	12.4%	11.4%	5.5%

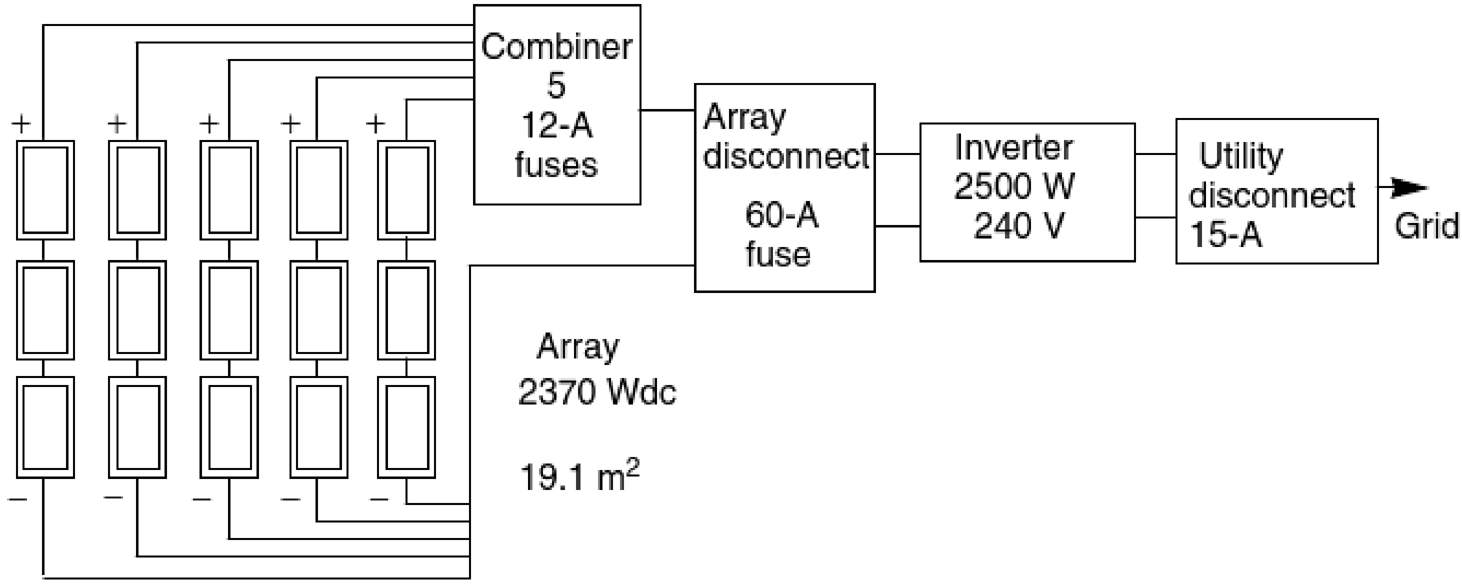
Manufacturer:	Xantrex	Xantrex	Xantrex	Sunny Boy	Sunny Boy
Model:	STXR1500	STXR2500	PV 10	SB2000	SB2500
AC power:	1500 W	2500 W	10,000 W	2000 W	2500 W
AC voltage:	211–264 V	211–264 V	208 V, 3Φ	198–251 V	198–251 V
PV voltage range MPPT:	44–85 V	44–85 V	330–600 V	125–500 V	250–550 V
Max input voltage:	120 V	120 V	600 V	500 V	600 V
Max input current:	—	—	31.9 A	10 A	11 A
Maximum efficiency:	92%	94%	95%	96%	94%

Panel & Inverter Selection

- Number of modules needed: 2300/158 = 14.6 (14 - 15 panels)
- Number of panels per string:
  - 2 panels result in a rated voltage of 46.4 V
  - 3 panels result in a rated voltage of 69.6 V
  - Which of these falls nicely in the MPPT range of the inverter? Ans: 3
- Therefore using 15 panels (5 parallel strings – each with 3 panels) is a nice fit.
- Check that the maximum Voc does not exceed the highest DC voltage of the inverter:
  - 86.7 V < 120 V
  - Check the case for the coldest temperature (recall that Voc increases a colder temperatures)
  - The National Electrical Code (NEC) restricts all voltages in family dwellings to not more than 600 V.

Roof area, energy production and fuses

- Roof area: 15 x 1.29 x 0.99 = 19.1 m^2
- Rated Power (dc, STC): 15 x 158 = 2,370 W
- Rated AC Power (assuming de-rating of 75%): 2.37x.75 = 1.777 kW
- Expected annual energy production: 1.777 x 5.7 x 365 = 3,698 kWh/year → goal is met.
- Combiner fuse > 1.56 (per NEC) x 7.58 = 11.8 A → 12 A
- DC Disconnect fuse > 11.8 x 5 = 59.2 A → 60 A
- AC Disconnect fuse > 1.25 (per NEC) x (2500/240) =13 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: 8S, 2P

Examples

6.3 You are to size a grid-connected PV system to deliver 4000 kWh/yr in a location characterized by 5.5 kWh/m^2-day of insolation on the array.

a. Find the dc, STC rated power of the modules assuming a 0.72 derate factor.

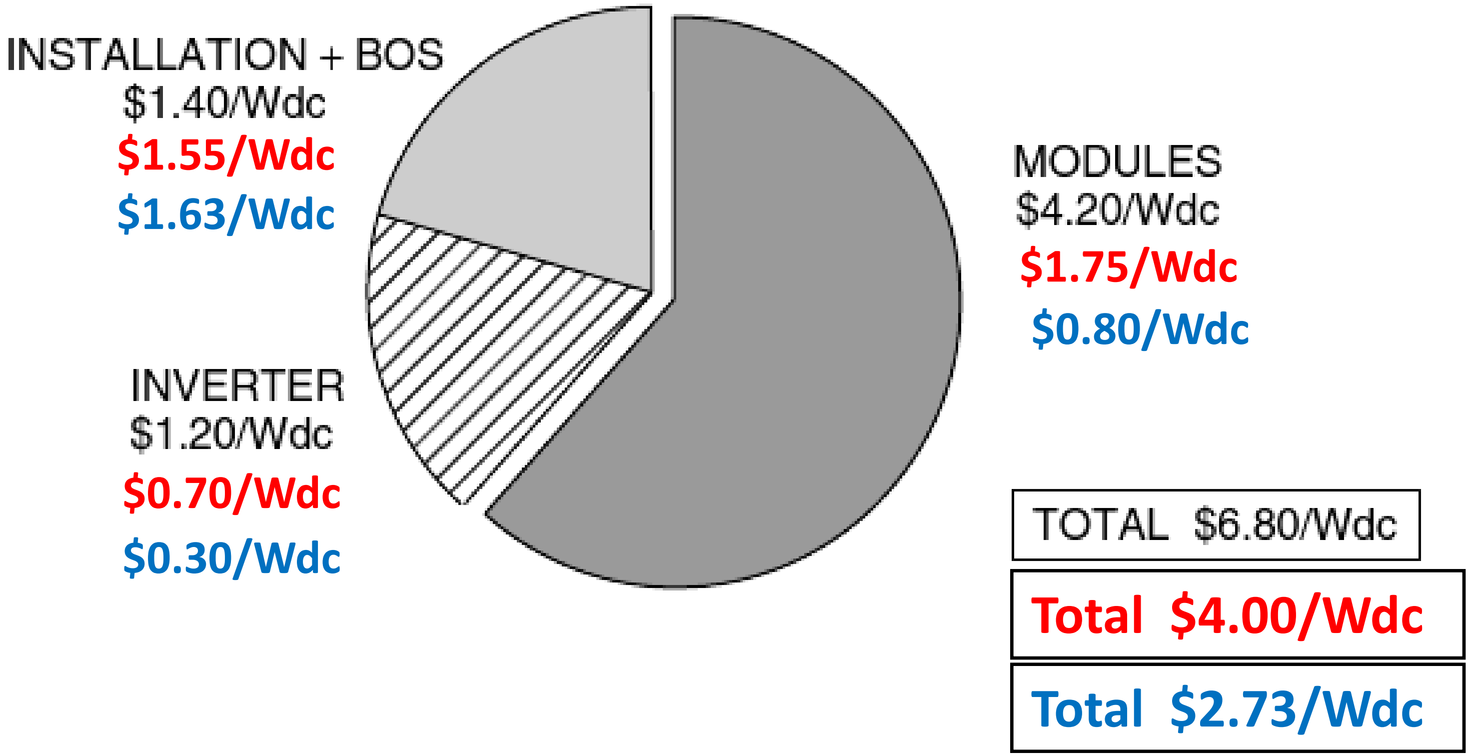
b. Find the PV collector area required if, under standard test conditions, these are 18%-efficient modules.

Ans: a) 2.77 kW
b) 15.4 m^2

Grid-connected PV System Economics: Economic Viability

- Whether the system is economically viable or not depends on many factors:
  - the initial cost of the system,
  - the amount of energy it will deliver each year.
  - Local utility rate structure
  - Net-metering rate
  - whether there are any tax credits or other economic incentives,
  - how the system is to be paid for.
- A detailed economic analysis will include:
  - estimates of operation and maintenance costs;
  - future costs of utility electricity;
  - loan terms and income tax implications if the money is to be borrowed, or personal discount rates if the owner purchases it outright;
  - system lifetime;
  - costs or residual value when the system is ultimately removed.
- Commercial and utility systems differ from residential systems
  - Economies-of-scale
  - Differences in economic incentives

Average Installed cost of residential PV Systems



– 2000 prices, – 2012 prices - 2018 prices

(*) https://www.solarreviews.com/solar-panels/solar-panel-cost/cost-of-solar-panels-in-nevada/solar-panels-cost-in-clark-county/las-vegas/

Example

- Assume a 5 kW PV system costs $15,000 to purchase and install locally. It is expected to produce 9,500 kWh/year.
  - Cost of panels(*) (16 x 300 W @ $180/piece) = $2,880, that is $0.60/W
  - Cost of 5 kW inverter (**): $1,551, that is $0.31/W
  - Cost of BOS: $2.11/W (assumed)
- Nevada has a rebate program funded by utility ratepayers that offers a $0.20/Wdc (as of 2018). Then the price drops down to $14,000.
- Furthermore, the federal government provides a 30% tax credit. Hence, the price drops further down to $9,800.

(**) https://www.solar-electric.com/fronius-primo-5000-watt-grid-tie-inverter.html?gclid=EAIaIQobChMIy8KVzdLy3gIVXR-tBh2l2ATrEAQYASABEgIiZPD_BwE

(*) https://webosolar.com/store/en/grid-tie-solar-panels/2138-canadian-solar-cs6k-300ms-300w-monocrystalline-perc-superpower-panel.html?gmc_currency=2&gclid=EAIaIQobChMI_aS3ptHy3gIVFCCtBh14vwJLEAQYBCABEgJq1_D_BwE

Energy Economics – Simple Payback Period

- **Simple payback period = (system cost)/(annual savings)**
  - Simplest to understand of all economic measures
  - Surveys show very short payback (order of only few years) in order to consider such energy investment
  - Misleading measure since it does not include the longevity of the system
- Example: suppose the cost of electricity (whether imported or exported) is $0.11/kWh, then the customer of the 5 kW system in the previous slide would save 9500x0.11=$1,045/year. Therefore,
  - Simple payback period = 9,800/1,045 = 9.38 years!
  - → most people will think that this is too long, and will choose to put their money elsewhere!

Energy Economics – Simple Payback Period

- Example: suppose the cost of electricity is purchased at $0.11/kWh, and sold at $0.09/kWh. Further assume that only 60% of the energy generated by the PV system is self-consumed. Then the new energy savings would by 9500x0.6x0.11 + 9500x0.4x0.99 = $969/year. Therefore,
  - Simple payback period = 9,800/969 = 10.11 years!
- What if the local utility decides to cancel net metering (i.e., the excess solar energy has no value)? Then the new energy savings will reduce to 9500x.6x.11 = $627/year
  - Simple payback period = 9800/627 = 15.63 years!
- What if the customer stores the excess energy in an ideal battery (that costs $2,000) and use it in the evenings? Then the energy savings are back to $1,045/year
  - Simple payback period = 11,800/1045 = 11.33 years!

Energy Economics – Time Value of Money

- Today's Dollar is worth more than a Dollar years from now.

$$P = F/(1+i)^n$$

where F = future value, P = present value, i = discount rate, and n = number of years.

- Example: The $1,045 yearly savings in the previous slide on the n = 9th year, assuming a discount rate of i = 6%, would have a present worth P of
  - $P = 1045/(1+.06)^9 = \$618.53$
- The Net Present Value (NPV) of the investment over n yeas, present value the sum of the savings over n years, is calculated by

$$NPV = SxPVF(i,n) - C, \qquad where \quad PVF(i,n) = \frac{(1+i)^n - 1}{i(1+i)^n}.$$

where S = yearly savings, PVF = present value function, and C = system cost.

Energy Economics – Time Value of Money

- Example (previous slide),
  - S = $1,045 yearly savings,
  - Discount rate i = 6%,
  - Syste cost S = $9,800.
  - NPV over a 20-year period = $2,186.
- If the PV-savings of $11,986 is borrowed from a bank a in interest rate of i = 6% over n = 20 years, then the annual loan payment is $1.045/year
- Use $9,800 of the borrowed money to pay for the system, and put the rest (i.e., $2,186) in your pocket on day 1.

Year	PV-Savings	Project NPV
0	$ -	$ (9,800.00)
1	$ 985.85	$ (8,814.15)
2	$ 1,915.90	$ (7,884.10)
3	$ 2,793.30	$ (7,006.70)
4	$ 3,621.04	$ (6,178.96)
5	$ 4,401.92	$ (5,398.08)
6	$ 5,138.60	$ (4,661.40)
7	$ 5,833.59	$ (3,966.41)
8	$ 6,489.23	$ (3,310.77)
9	$ 7,107.77	$ (2,692.23)
10	$ 7,691.29	$ (2,108.71)
11	$ 8,241.78	$ (1,558.22)
12	$ 8,761.12	$ (1,038.88)
13	$ 9,251.05	$ (548.95)
14	$ 9,713.26	$ (86.74)
15	$10,149.30	$ 349.30
16	$10,560.66	$ 760.66
17	$10,948.74	$ 1,148.74
18	$11,314.85	$ 1,514.85
19	$11,660.23	$ 1,860.23
20	$11,986.07	$ 2,186.07

Energy Economics - Amortizing Cost

- If an amount of money, or principal, C ($), is borrowed over a period of n (years) at an interest rate of i (decimal fraction/yr), then the annual loan payments, A($/yr), is expressed in terms of the Capital Recovery Factor (CRF) as

$$A = C x CRC(i,n), \qquad where \quad CRC(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} = \frac{1}{PVF(i,n)}$$

- Example: Suppose the 5 kW system cost is financed at a rate of 6% for 15 years, then the annual loan payment is
  - A=9800x0.1030 = $1,009.40
  - So the system saves 1,045 - 1,009.4 = $35.60/year
  - The cost of electricity generated by the system is 1009.4/9500=$0.106/kWh (slightly less that the utility rate)
  - As the utility rates rise, the investment will look even better over time.

Most expensive states with residential electricity rates(*)

Rank	State	August 2018 Electric Rate
1	Hawaii	32.40
2	Alaska	22.73
3	Connecticut	21.28
4	Massachusetts	20.86
5	California	20.56
6	New Hampshire	19.28
7	New York	19.03
8	Rhode Island	18.70
9	Vermont	17.93
10	Maine	16.28

Check net-metering rules and utility rate structure in your State before making a decision.

In California,

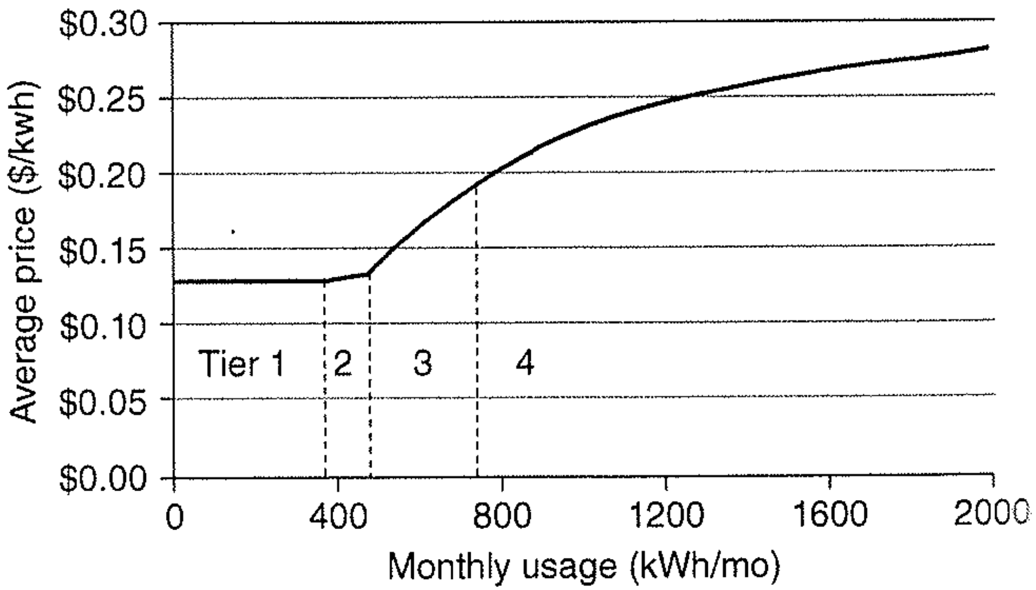
- net-metering is very simple: for every kilowatt-hour (kWh) of solar electricity you feed into the grid, you get a bill credit for one kWh of utility-generated electricity.
- Every property owner who installs a solar energy system will automatically be switched to TOU rates for their electric bills.

(*) https://www.chooseenergy.com/electricity-rates-by-state/

Utility Rate Structures

- **Flat Rate** - all usage during a given period of time (e.g., 30-day billing cycle) is charged the same rate; or
- **Tiered Rate** - typically charge a different price based on blocks of usage during a given period of time (e.g., 30-day billing cycle).

Tier 1 baseline	Tier 2 (101–130% of baseline)	Tier 3 (131–200% of baseline)	Tier 4 (Over 200% of baseline)
e.g. 1st 365 kWh	366–475	475–730	>731 kWh/mo
$0.1285	$0.1460	$0.2956	$0.3356



Utility Rate Structures

- **Time-of-Use (ToU) rate** – discourages high energy used during high demand period.
- **Critical Peak Pricing (CPP) rate** – when utilities observe or anticipate high wholesale market prices or power system emergency conditions, they may call critical events during a specified time period (e.g., 3 p.m.—6 p.m. on a hot summer weekday), the price for electricity during these time periods is substantially raised – customers will be notified a day ahead of a CPP event.
- Refer to link below for local rate options

https://www.nvenergy.com/about-nvenergy/rates-regulatory

Example

6.9 The summer TOU rate structure shown in Table 6.7 includes an off-peak energy charge of \$0.0846/kWh for usage up to 700 kWh/mo and \$0.166/kWh for usage above that base. During the peak demand period it is a flat \$0.27/kWh.

a. What will the customer's bill be for 1000 kWh used off peak and 800 kWh on peak?

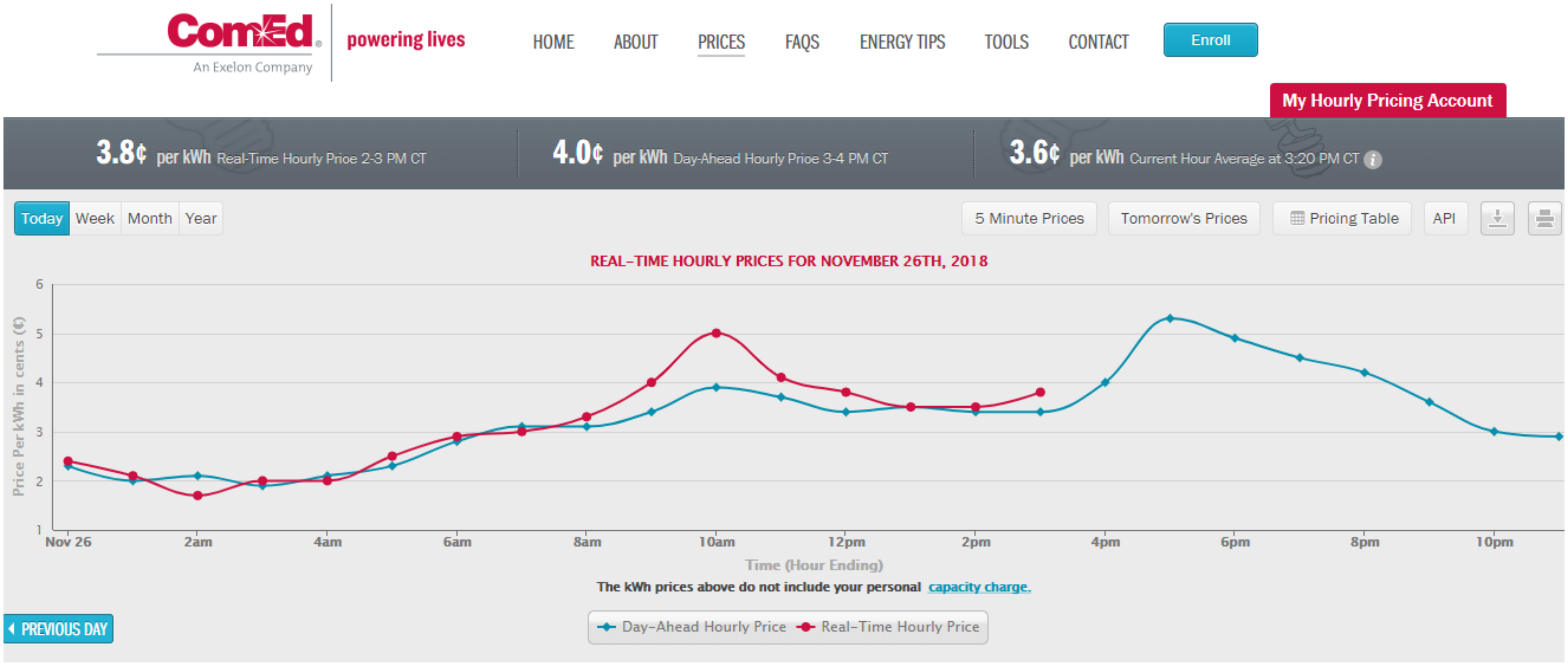
b. Suppose the customer signs up for the TOU + CPP rate structure. During three days, a critical peak pricing period is announced during which time electricity costs \$0.75/kWh. If they use 100 of their 800 peak period kilowatt-hours during that time, what will their bill be that month.

c. Suppose the customer shuts off their power during those CPP periods, what would now be the utility bill?

Ans. a) \$325/mo
b) \$357/mo
c) \$282/mo

Utility Rate Structures

- **Real-Time Pricing (RTP) rate** – varies hourly following the wholesale electricity marked conditions.



https://hourlypricing.comed.com/live-prices/

Commercial and Industrial Rate Structure

- The rate structures include a monthly demand charge ($/kW) (based on the highest amount of power used by the facility), in addition to energy charge ($/kWh).

TABLE 6.8 Electricity Rate Structure Including Monthly Demand Charges

Energy ($/kWh)	Off Peak	Partial Peak	Peak
Summer	$0.0698	$0.0950	$0.1336
Winter	$0.0727	$0.0899	
Demand ($/kW/mo)	**Maximum**	**Partial peak**	**Peak**
Summer	$11.85	$3.41	$14.59
Winter	$11.85	$0.21	

Example

6.10 A small office building that uses 40,000 kWh/month during the summer has a peak demand of 100 kW. An 80-kW photovoltaic system is being proposed that will provide 20,000 kWh/mo. The before and after demand curves are shown in Figure P 6.10.

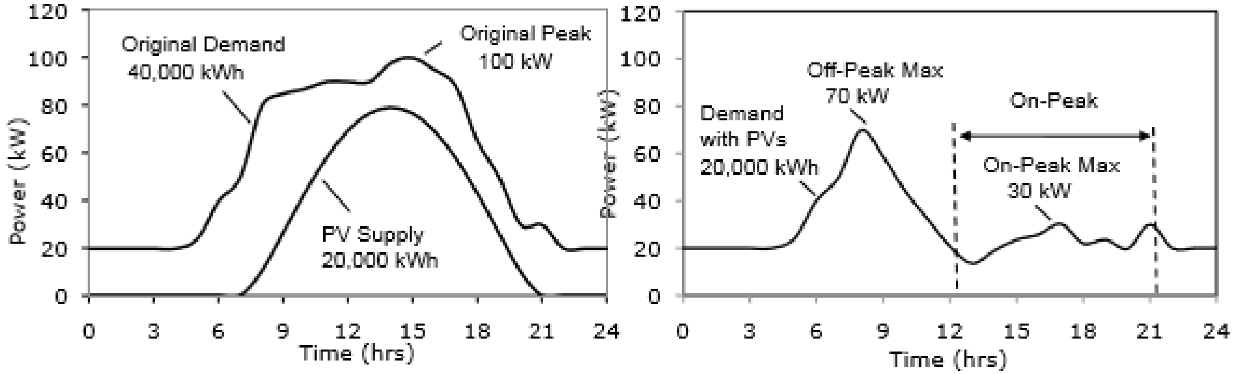


Figure P 6.10

The utility rate schedule includes demand charges that vary depending on whether the customer has signed up for time-of-use rates or not. And the TOU rates have a demand charge that varies with on or off peak periods.

	Non TOU Rates		TOU Rates		
Energy Charge ($/kWh)	$	0.06	$	0.05	
Demand Charge ($/mo/kWp)	$	12.00	$	14.00	on peak
			$	5.00	off peak

Table P 6.10

a. What would be the utility bill without the PVs when the non-TOU rate schedule has been chosen?

b. Which rate structure would be the best for the customer if they install the PVs. How much money would the PVs save with that rate structure?

Ans: a) $3,600/mo
b) $1,770/mo

Utility-Scale Photovoltaics

- These large systems have economies-of-scale advantages over smaller systems, but they have to compete in the wholesale electricity market.
- Power Purchase Agreements (PPA) are common where the utility in now a customer.
- Time-of-Delivery (ToD) factors are often used in the agreement to account for the variable value of electricity sold during different times of the day and.
- Since afternoon power is worth more than morning power, large arrays are often oriented slightly to the west.