ESCI61
Introduction to Photovoltaic Technology

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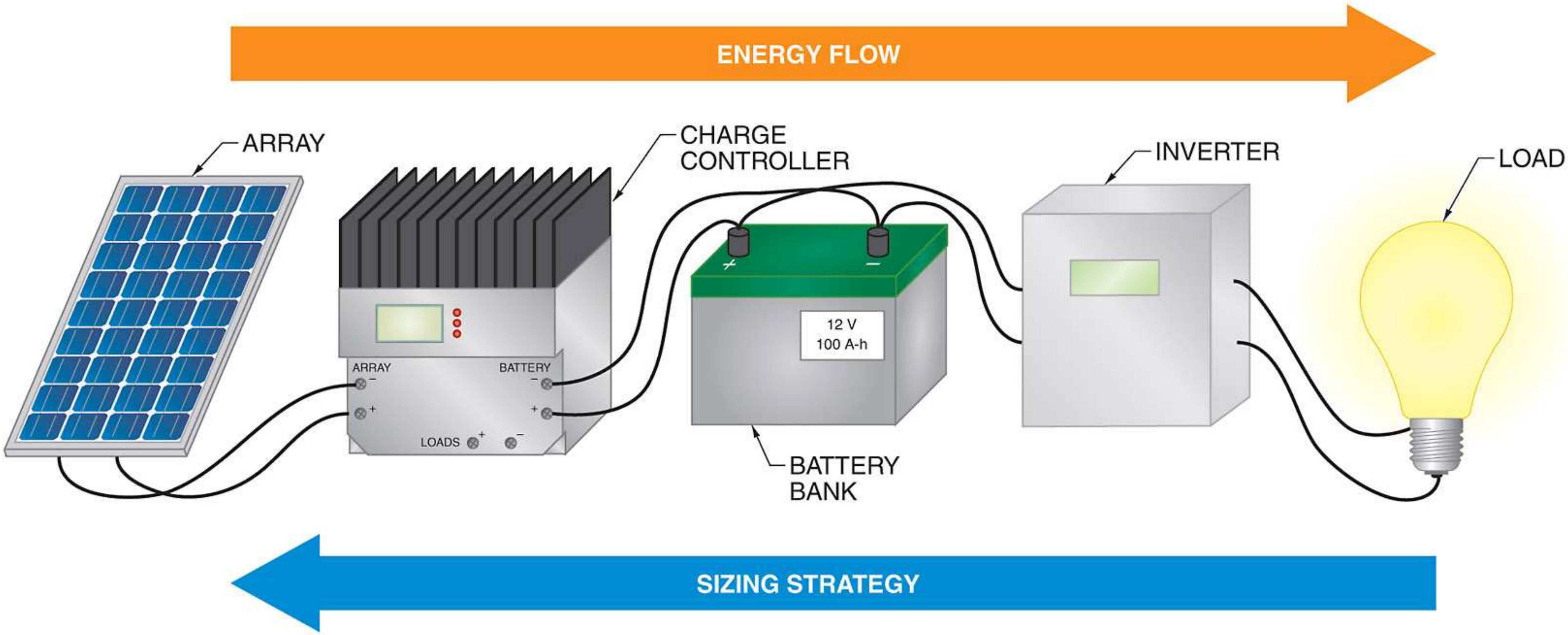
PV System Design and Sizing

Sizing Strategy



Designing PV Systems

- Determine how much energy you want to generate per year (or for specific time periods if off grid)
- Identify physical constraints on system (location, size, orientation, etc)
- Design a system that meets the above criteria, as best as possible.

PV System Design Steps

- PV system design is a convolutional process
- There is no unique list of steps that one must follow to design a PV system
- Multiple factors play an important role in determining the PV system size (budget, roof space, shading, electricity need, …, etc.)

Sample Case Study

- The LeBlanc family would like to have a quote for a PV system for their home.
- LeBlanc are typical laypersons, so they do not know that much how to assess if their house is good for solar or how big would be their PV system
- What questions would you ask them?

Design Assumptions

- You want to design and size a grid tied PV system (as opposed to standalone or bimodal PV systems), so there are no batteries
- You want to use flat plate collectors (as opposed to concentrating collectors)
- You will install the modules at fixed tilt (as opposed to 1- or 2-Axis tracking system)
- You want to optimize the average annual energy output of the PV system
- You're using String Inverter technology (as opposed to micro-inverter one)

Step 1 - Electricity Audit

- Electricity bills for at least the last 12 months, 24 months is better
- Average electricity usage
- Where and how electricity is being used
- Which appliances consume the most of the electricity
- Which appliances are old enough to be replaced in the near future
- If some appliances are too energy inefficient, do not wait until they break to replace them
- Don't wait for light bulbs to break before you replace them with CFLs.
- From the energy audit you can also determine what can you do to reduce your electricity bill.

Step 1 - Electricity Audit

- Experience tells that some people could cut in more than half their electricity usage after upgrading their appliances, light bulbs, …, etc. This is very common.
- Determine if your electricity usage is going to decrease or increase in the near future.
- Get an idea how much of your electricity do you want to generate from a PV system.
- You can first assume that you want to generate 100% of your electricity and restart the process if you realize later on that the PV system is too big to fit on your roof or too expensive to fit in your budget.
- At the end of this step, you know the average number of AC KWh per day, per month and per year that your PV systems must generate.

Step 2 - Available Sun Resources

- if you're going to use PVWatts (recommended) you can skip this step
  - PVWatts already integrates the information about sun resources from the Red Book
  - The advantage of doing this step is that it gives you a hint about the DC Power of your PV system; this is an input to PVWatts tool

Step 2 - Available Sun Resources

- Look at the available sun resources in your area, as reported in the "Red Book"
  - http://rredc.nrel.gov/solar/pubs/redbook/PDFs/CA.PDF, if your site is in California
- The Red Book provides sun resources for a limited number of locations in each state (ten locations for California)
  - chose the location closest to your site in the Red Book
- You can also use Solmetric's Insolation Lookup tool http://www1.solmetric.com/cgi/insolation_lookup/go.cgi

Step 2 - Available Sun Resources

- From the red book you can determine the minimum/average/maximum number of sun hours in your area.
- Most PV system designers, and design tools like PVWatts, use the average number of sun hours for sizing.
- Some de-rating might be necessary if your array is not facing South or is not installed at the tilt angles listed in the Red Book.
- If you use PVWatts (Step 4), it will take care of these derating factors.
- Dividing the average number of KWh per day (Step 1) by the average number of sun hours per day (Step 2), you get the AC rating (W) of your PV system.

Step 2 - Available Sun Resources

- At the end of this step, you know the AC Rating of your PV system (W_{AC}); this is the AC power of the PV system before any de-rating, if the array is installed in your location and in the conditions specified in the Red Book.

Step 3 - Site Survey

- Location of the PV array
- Roof Area & Orientation (Google Earth, Roof Ray)
- Roof slope
- Exact shading
- Roof conditions
- Special mounting system

Step 3 - Site Survey

- At the end of this step, you have an idea if the site is good or not for a PV system.
- You might realize that orientation is too far away from due South, or that your roof is too shaded, or that you do not have enough roof space, or that your roof space is composed of multiple small areas and therefore is more adequate for multiple-inverters or micro-inverter options, …, etc.

Step 3 - Site Survey

- In the following, we assume that site survey conclusions are in favor of a single-array, or at most two-array PV system.
- If you think two arrays are more convenient for your site, you need to decide if you want a single inverter that supports two Maximum Power Point Tracking (MPPT) feature, or if you prefer a design with two inverters.

Step 4 - PV System Sizing

- Use an online tool like PVWatts (www.pvwatt.com) to determine the size of your PV System
  - Version 1 should be sufficient at this step
  - Version 2 to fine tune your design or if you're PV location is outside the US
  - You might need multiple iterations to determine the size of your system because, counter-intuitively, PVWatts starts with the DC Rating of the system and not AC Rating, so you need to determine the DC size of the PV system that generates the annual energy you need, taking into account tilt, azimuth and all other de-rating factors.
  - Some de-rating factors depend on which inverter and which modules you use, because inverters' efficiencies and modules' power tolerances vary per vendor

Step 4 - PV System Sizing

- At the end of this step, you know the DC Rating of your PV system; this is the DC power (W_{DC}) of the PV system under Standard Test Conditions (STC)

Step 5 - Shop for Modules and Inverter

- Now that you know the DC Rating of your system, you can start shopping.
- This can be an iterative process because you may choose a module type that will not fit nicely with the inverter when you start sizing.
- For the inverter, start trying with the one which size is immediately above your DC rating.
- For the modules, there are multiple options based on your preference for efficiency, cost, color, manufacturer, brand, …, etc.

Step 5 - Shop for Modules and Inverter

- The important thing to do is that every time you select a PV module or an inverter, you need to check if they are in the CEC certified equipment list, otherwise, you will not qualify for the CSI rebate; these information are found at the following website www.gosolarcalifornia.ca.gov/equipment

Step 5 - Shop for Modules and Inverter

- Make sure you don’t choose a 3-phase inverter that’s more destined for commercial and industrial use. It is recommended to short list multiple inverters and multiple modules because your first choice might not be the right & final one.

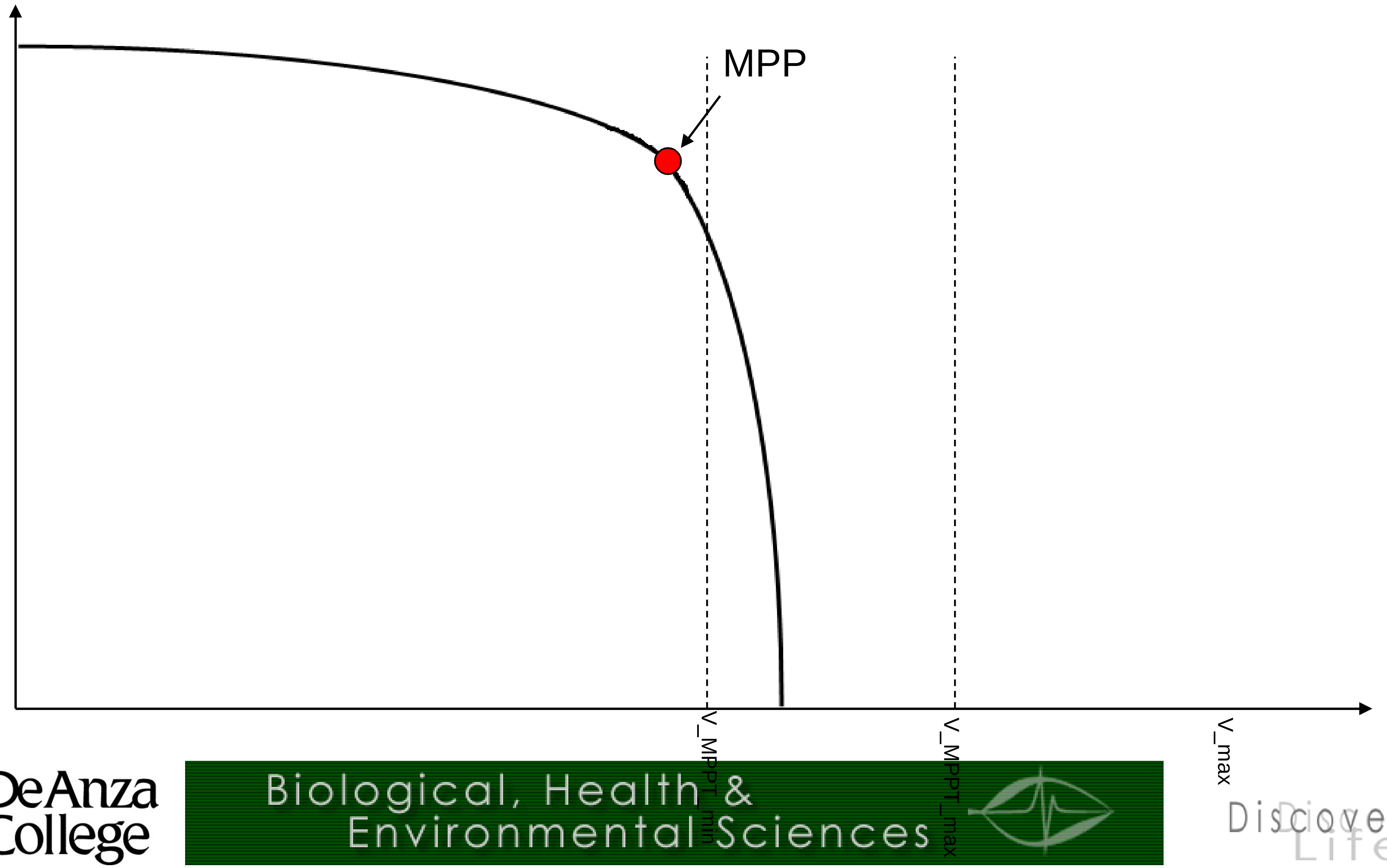
Step 5 - Shop for Modules and Inverter

- You may need multiple iterations of Step 4, Step 5 and Step 6 until you find the right combination of modules and inverter.

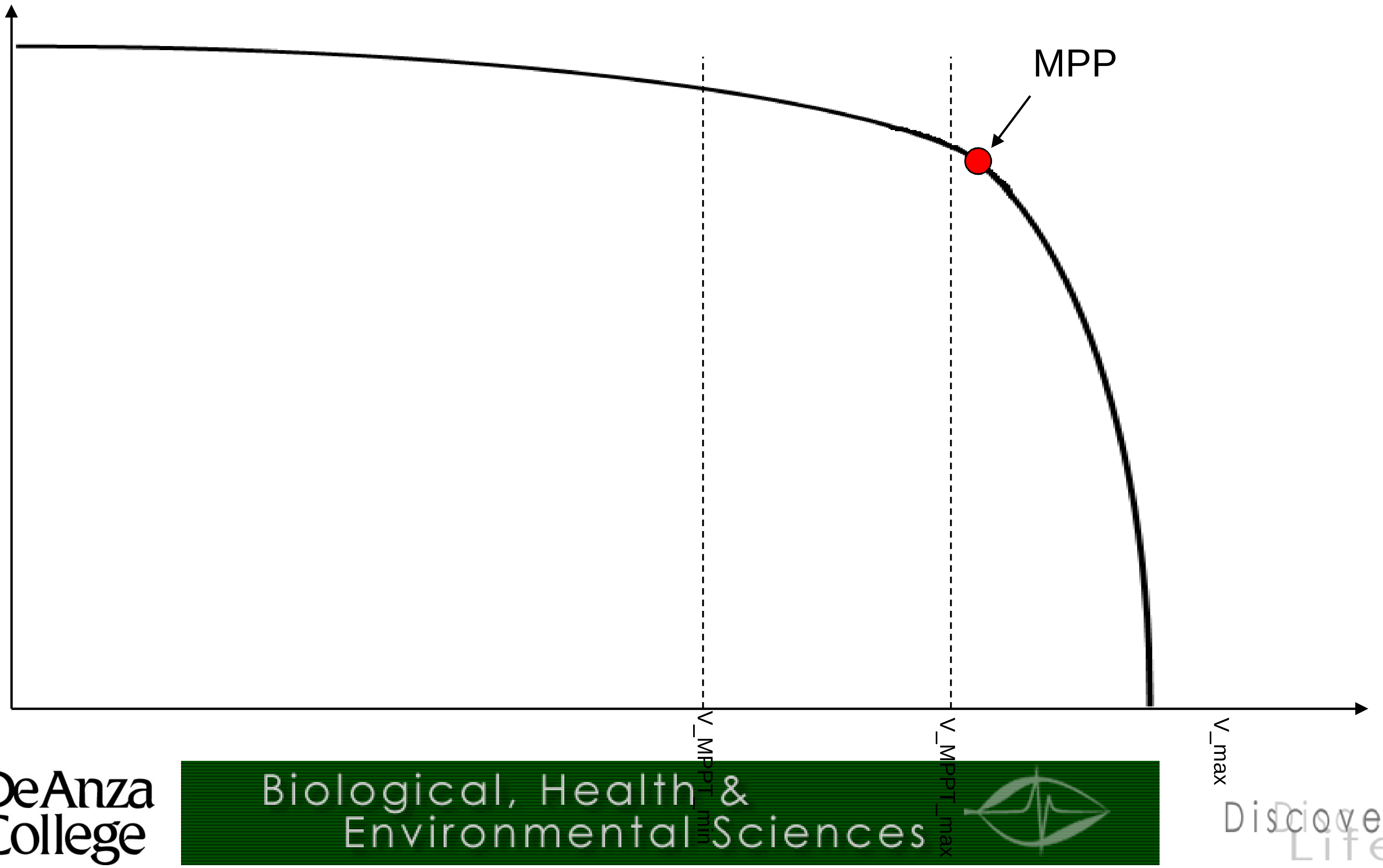
Step 6 - String Sizing

- You can either do this work manually or use an online tool; most inverters' vendors have a web based string sizing tool.
- Before using their tool, determine weather condition of your location; you can get these info, for example from www.weather.com or from ASHRAE database ($)
- Weather conditions are important because :
  - record low temperature determines the highest Voc of the array, and therefore the maximum number of modules per string not to exceed the inverter's max input voltage
  - record low temperature determines the highest Vmp of the array, and therefore the maximum number of modules per string not to exceed the inverter's maximum MPPT voltage
  - Average/Record high temperature will determine the lowest Vmp and therefore the minimum number of modules per string not to fall below the inverter's minimum MPPT voltage

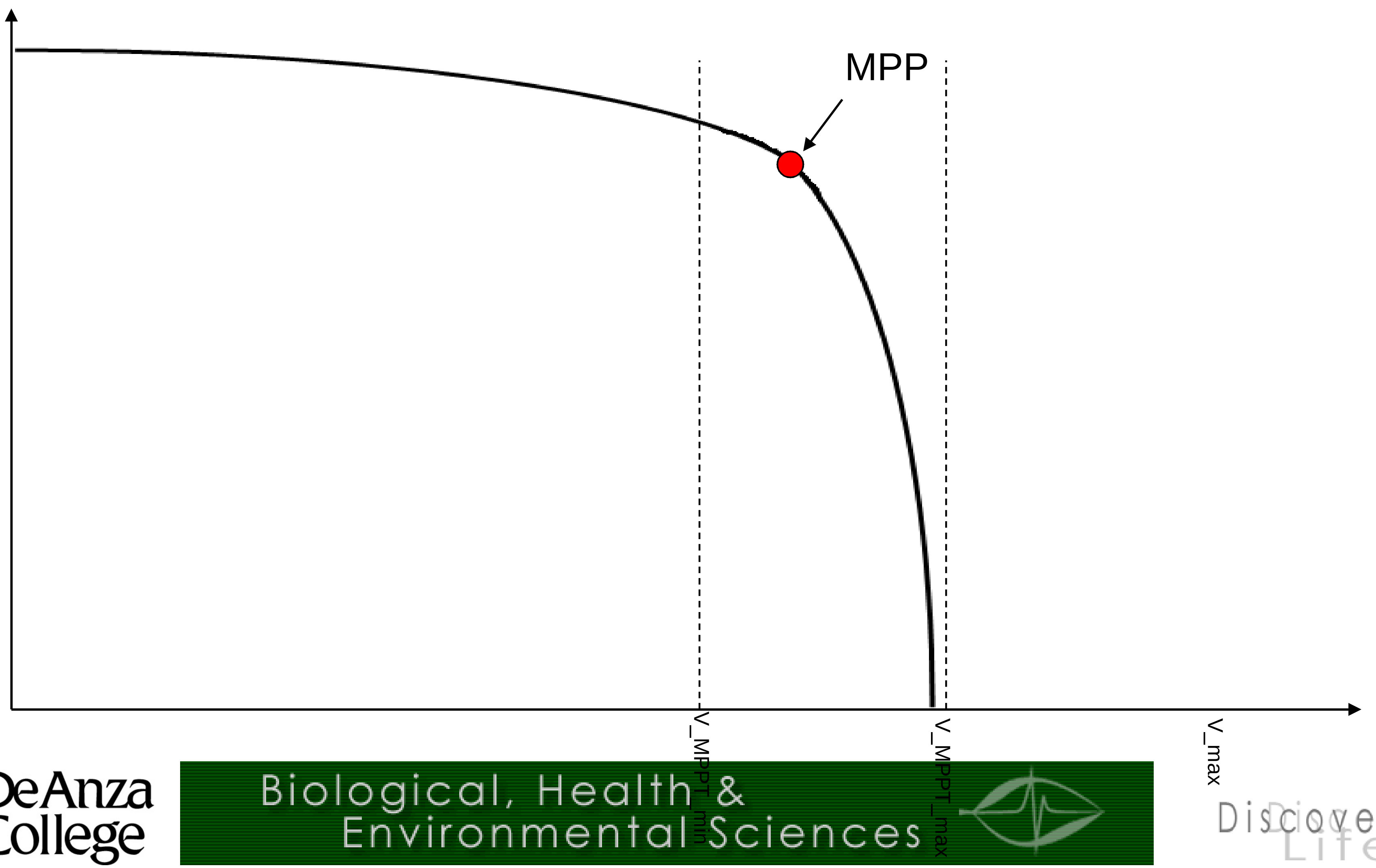
Undersized String



Oversized String



Well Sized String



Absolute Maximum Number of Modules per String

- String Voc must not exceed the maximum input voltage of the inverter
  - If maximum input voltage of the inverter is exceeded, the inverter can be damaged
  - Maximum string Voc is determined at record low temperature of the PV system location
  - Record low temperatures usually occur a few hours before sunrise (very low irradiance)
  - PV cell temperature can be as much as 10℃ lower than ambient temperature

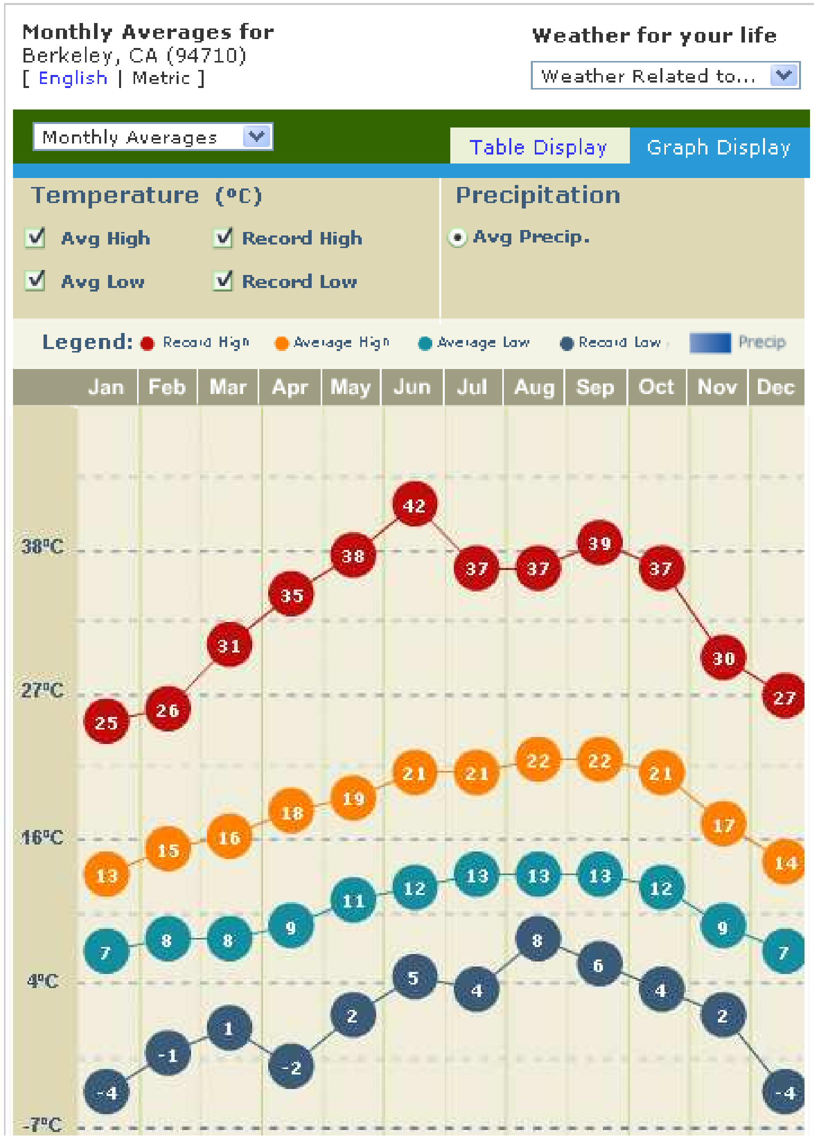
Maximum Number of Modules per String

- String Vmp should not exceed the maximum voltage of the inverter's MPPT window
  - If maximum MPPT voltage of the inverter is exceeded, it will adjust to its high MPPT voltage and that results in performance loss
  - Maximum string Vmp is determined at average low temperature of the PV system location
  - String Vmp might be higher than the inverter's high MPPT voltage when record low temperature occurs, but that's not important because that's likely to happen when irradiance is very low (a few hours before sunrise)
  - PV <u>cell temperature</u> can be as much as 10℃ lower than <u>ambient temperature</u>

Minimum Number of Modules per String

- String Vmp must not go below the inverter's low MPPT voltage
  - This determines the minimum number of modules in series per string
  - If that happens, the inverter will adjust to its low MPPT voltage resulting in power loss
  - Lowest Vmp voltage happens at record high temperature of the location
  - PV <u>cell temperature</u> can be as much as 30℃ higher than the highest <u>ambient temperature</u> and 10℃ lower than the lowest <u>ambient temperature</u>

Step 6 - String Sizing



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Step 6 - String Sizing

- if data is not provided by the PV module vendor, then use NEC book 2008 to determine temperature correction factors for your location

Step 6 - String Sizing

NEC Table 690.7 Voltage Correction Factors for Crystalline and Multicrystalline Silicon Modules

Correction Factors for Ambient Temperatures Below 25°C (77°F) (Multiply the rated open circuit voltage by the appropriate correction factor shown below.)		
Ambient Temperature (°C)	**Factor**	**Ambient Temperature (°F)**
24 to 20	1.02	76 to 68
19 to 15	1.04	67 to 59
14 to 10	1.06	58 to 50
9 to 5	1.08	49 to 41
4 to 0	1.10	40 to 32
-1 to -5	1.12	31 to 23
-6 to -10	1.14	22 to 14
-11 to -15	1.16	13 to 5
-16 to -20	1.18	4 to -4
-21 to -25	1.20	-5 to -13
-26 to -30	1.21	-14 to -22
-31 to -35	1.23	-23 to -31
-36 to -40	1.25	-32 to -40

Step 6 - String Sizing

- Sizing tools may suggest array sizes that do not match exactly your needs so you may need to run multiple iterations by using a different inverter or different modules until you hit your optimal size.
- If the inverter's vendor does not provide a web based string sizing tool, try www.pvselect.com or you'll need to do all this work manually, by taking into account vendors' specs.
- The main important parameters to take into account for manual sizing are the highest Voc of the array including temperature correction, the inverter's maximum input current and maximum input voltage, and the inverter's MPPT voltage range

Step 6 - String Sizing

- Also, don’t forget to take into account the roof area needed for your PV system: you may need to use more efficient modules to reduce roof space.

Step 6 - Array to Inverter Matching

- With too few modules in series an inverter cannot maintain an array's MPP under high temperature conditions for the site, sacrificing energy harvest.
- Too many modules in series results in voltages above 600 Vdc, which can damage equipment, violate the NEC and void the manufacturer's warranty.

Sample Inverter Specs - Fronius

Fronius IG 2000 / 3000 / 2500LV

Zoom

The reliable PV inverter series.

The Fronius IG series has proven itself to be powerful, user-friendly and highly reliable. Equipped for every size of PV system, especially for smaller systems (e.g. on the roof of a one-family home). The combination of different types available for selection is limitless. The ingenious processor control combined with the powerful HF transformer extracts the maximum energy yield from all types of modules.

Operating Manual

- Technical Data
- Equipment features

Technical Data

Fronius IG	IG 2000	IG 3000	IG 2500-LV
DC Input Data			
Recommend PV power	1500 - 2500 Wp	2500 - 3300 Wp	1800 - 3000 Wp
Max. DC input voltage	500 V	500 V	500 V
Operating DC voltage range	150 - 450 V	150 - 450 V	150 - 450 V
Max. usable DC input current	13.6 A	13.6 A	13.6 A
AC Output Data			
Max. Output power @ 40°C	2000 W	2700 W	2350 W
Nominal AC output voltage	240 V	240 V	208 V
Utility AC voltage range	212 - 264 V (240 V + 10% / -12%)		183 - 227 V
Maximum AC current	8.35 A	11.25 A	11.25 A

Sample Inverter Specs - SMA

Overview | **Technical Data** | Downloads

Input Data (DC)	Sunny Boy 3000US	Sunny Boy 4000US
Recommended Max. PV Power (Module STC)	3750 W	4375 W @ 208 V / 5000 W @ 240 V
Max. DC Voltage	500 V	600 V
Peak Power Tracking Voltage	175 V – 400 V @ 208 V, 200 V – 400 V @ 240 V	220 V – 480 V @ 208 V, 250 V – 480 V @ 240 V
DC Max. Input Current	17 A	18 A
Number of Fused String Inputs	2 (inverter), 4 x 15 A (DC disconnect)	2 (inverter), 4 x 15 A (DC disconnect)
PV Start Voltage (adjustable)	228 V	285 V

Output Data (AC)		
AC Nominal Power	3000 W	3500 W @ 208 V / 4000 W @ 240 V
AC Maximum Output Power	3000 W	3500 W @ 208 V / 4000 W @ 240 V
AC Maximum Output Current	15 A @ 208 V, 13 A @ 240 V	17 A
AC Nominal Voltage / Range	183 – 229 V @ 208 V, 211 – 264 V @ 240 V	183 – 229 V @ 208 V 211 – 264 V @ 240 V
211 – 264 V @ 240 V, AC Frequency / Range	60 Hz / 59.3 Hz – 60.5 Hz	60 Hz / 59.3 Hz – 60.5 Hz
Power Factor	0.99 @ nominal power	0.99 @ nominal power

Sample PV Module Specs

MITSUBISHI ELECTRIC PHOTOVOLTAIC MODULE

SPECIFICATION SHEET

Manufacturer	MITSUBISHI ELECTRIC		
Model name	PV-MF185TD4	PV-MF180TD4	PV-MF175TD4
Cell type	Polycristaline silicon, 156 x 156 mm square, Solder-coa		
Number of cells	50 cells in a series		
Maximum power rating(Pmax)	185W	180W	175W
Warranted minimum Pmax	175.8W	171.0W	166.3W
Open circuit voltage (Voc)	30.6V	30.4V	30.2V
Short circuit current (Isc)	8.13A	8.03A	7.93A
Maximum power voltage (Vmp)	24.4V	24.2V	23.9V
Maximum power current (Imp)	7.58A	7.45A	7.32A
Maximum system voltage	DC 780V		
Fuse rating	15A		
Output terminal	(+) 800mm/(-) 1250mm with MC connector		
Dimensions	1658x834x46mm(65.3x32.6x1.81inch)		
Weight	19.5kg(43.0lbs)		
Module efficiency	13.4%	13.0%	12.7%
Packing condition	2 pcs - 1 carton		
Certificate	IEC 61215, TÜV Safety Class 780 VDC		

Step 6 - String Sizing

- At the end of this step, you know exactly what inverter, what modules and how many you're using, and how your array is designed (number of strings x number of modules per string)

FRONIUS IG 4000 / 5100 / 4500-LV

Input data	IG 4000	IG 5100	IG 4500-LV
Recommended PV power	3000-5400 Wp	4000-6300 Wp	3600-5500 Wp
MPP-voltage range		150 - 400 V	
Max. input voltage (at 1000 W/m² / 14 °F in no-load operation)		500 V	
Nominal input voltage		270 V	
Nominal input current	16.3 A	20.8 A	18.3 A
Maximum usable input current	26.1 A	33.2 A	29.3 A
Maximum array short circuit	40 A	40 A	40 A

Output data	IG 4000	IG 5100	IG 4500-LV
Nominal output power (P_{nom})	4.0 kW	5.1 kW *	4.5 kW *
P_{nom} at +122 °F (50 °C)	4.0 kW	4.2 kW	4.2 kW
Maximum output power	4.0 kW	5.1 kW	4.5 kW
Nominal AC output voltage	240 V	240 V	208 V
Operating AC voltage range	212 - 264 V	212 - 264 V	183 - 227 V
Nominal output current	16.7 A	21.3 A	21.6 A
Maximum output current	16.7 A	21.3 A	21.6 A
Maximum utility backfeed current **		0 A	
Maximum output fault current		35.2 A	
Maximum output overcurrent protection		30 A	
Nominal output frequency		60 Hz	
Operating frequency range		59.3 - 60.5 Hz	
Total harmonic distortion		< 5 %	
Power factor		1	

Step 7 - Finances

- You can now use the CSI calculator to finalize your design and calculate your rebate (www.csi-epbb.com)
- Don't forget about PBI option, it may be more interesting on the long term; you can also estimate the Federal Investment Tax Credit and the overall net cost of your system
- You may want to use online tools for financial analysis like https://tools.cleanpowerfinance.com/ or http://www.ongrid.net.
- Websites like www.findsolar.com have simple calculators that can give you a very rough approximation of the net cost of your system

Step 8 - Decision

- This is where you need to answer questions like:
  - Is this PV system OK for you?
  - Is it a good investment for you?
  - Can you afford it?
  - Do you want to reduce the size and restart the process from Step 4
  - Are you going to install it yourself or look for an installer? If you're going to do it yourself, you need to shop for the other system components, aka BOS (mounting system, wires, disconnects, …, etc.)

Group Exercise

String Sizing Example

PV Module

- SPR-305-WHT
- Rated Power : 305 W
- Power Tolerance : +/- 5%
- Voltage at Rated Power : 54.7 V
- Current at Rated Power : 5.58 A
- Open Circuit Voltage : 64.2 V
- Short Circuit Current : 5.96 A
- Voltage Temperature Coefficient : -176.2 mV/℃
- Current Temperature Coefficient : 3.5 mA/℃
- Power Temperature Coefficient : -0.38%/℃

String Sizing Example

Inverter

- SPR-4000m (240V US)
- Peak Inverter Efficiency : 96.8%
- CEC Weighted Efficiency : 96.0%
- Recommended Array Input Power (DC @ STC) : 4800 W
- DC Input Voltage Range : 250-600 V
- Peak Power Point Tracking Voltage : 250-480 V
- DC Maximum Input Current : 18 A

String Sizing Example

Location

- Sacramento, CA (for example, zip code 94203)
- Latitude : 38.52°N
- Longitude : 121.50°W
- On average, the warmest month is July
- Average High Temperature : 34.0° C
- Recorded high Temperature was 46.1°C in 1925
- On average, the coolest month is December
- Average Low Temperature : 3.2°C
- Recorded low Temperature was -7.8°C in 1932

Useful Resources

- www.pvwatt.com
- www.csi-epbb.com
- www.roofray.com
- www.delicious.com/deanzapv
- www.pvselect.com
- https://tools.cleanpowerfinance.com
- www.ongrid.net
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- Array to Inverter Matching - Mastering Manual Design Calculations, By John Berdner, SolarPro Magazine, Dec-Jan 2009