Solar PV Lab Manual

Seven hands-on labs for an introductory solar photovoltaic course

Before you start

These labs take you from setting up a PV lab station to measuring modules, siting an array, predicting its output and labelling it to code. Each lab begins with the background you need, then gives the steps and the questions to answer. Work with a partner, and keep everything you produce: together it becomes your course portfolio.

Text in [square brackets] is for your instructor to fill in for your lab.

Safety in every lab

- A PV module produces voltage whenever light falls on it. You cannot switch it off. Cover modules with an opaque sheet when you connect or disconnect them.
- Modules in series add their voltages. A string of eight modules can reach several hundred volts DC, which can kill. Treat every conductor as live until you have measured it.
- DC arcs do not go out on their own the way AC arcs can. Never disconnect a connector or a wire under load.
- Use a meter rated for the voltage you are measuring, with intact leads. Check it on a known source before and after you use it.
- Wear the eye protection and gloves your instructor requires: [your lab's PPE rules].

Your portfolio

Keep a portfolio for the whole course: your station inventory, measurements, results, labels and photos of your work. It helps you learn, it becomes your own reference manual, and it is something to show employers at interviews.

Lab 1: Your lab station

Background

Every PV system is a set of parts that must work together: modules, racking, conductors and connectors, a combiner or junction box, disconnects, overcurrent protection, an inverter, and the point where the system connects to the building's electrical panel. Each part has a manufacturer's datasheet (sometimes called a cut sheet or spec sheet) and an installation manual. Installers rely on these documents: they give the ratings you design with and the instructions an inspector expects you to have followed.

Steps

1. With your partner, list every piece of equipment and hardware at your station. Include the manufacturer and model number of each.

2. Type your inventory neatly and submit it [how your instructor collects work], with your station name and the names of everyone at the station.
3. Find the datasheet and installation manual for each item on the manufacturer's website. Save them in a folder you will use all course.

Questions

1. Which items at your station carry DC, and which carry AC?
2. From a module datasheet, write down its open-circuit voltage (Voc), short-circuit current (Isc), and its voltage and current at maximum power (Vmp, Imp).
3. What is the maximum DC input voltage of your inverter, and why does it matter when you decide how many modules to connect in series?

Lab 2: Measuring modules in series

Background

A solar cell turns light into electricity. Cells are wired together into a module, and modules are wired together into an array.

Two numbers describe a module's output at a given light level:

- Open-circuit voltage (Voc): the voltage across the module's terminals when nothing is connected. It is the highest voltage the module produces.
- Short-circuit current (Isc): the current that flows when the terminals are connected directly through an ammeter. It is the highest current the module produces.

Isc rises and falls almost in step with the light level, so it drops sharply under indoor light or shade. Voc changes much less with light, but it falls as the module gets hotter and rises in the cold. That is why a string's voltage is highest on a cold, bright morning, and why designers check the coldest expected temperature.

When modules are connected in series (positive of one to negative of the next), their voltages add and the current stays about the same as one module. When they are connected in parallel, their currents add and the voltage stays about the same.

Steps

1. Under the lab's ambient light, use your DC multimeter to measure Voc and Isc of one module. Record them in your table.
2. Connect two modules in series. Measure and record Voc and Isc again.
3. Repeat with four modules in series, then with [all the modules at your station] in series.
4. If your instructor allows, repeat one measurement in brighter light, or outdoors, and note the difference.

Results table

Make a table with one row for each test: number of modules in series, Voc measured, Isc measured, and what you expected.

Questions

1. How did Voc change as you added modules in series? How did Isc change? Explain why.
2. Why were your readings lower than the datasheet values? (Datasheet values are measured at standard test conditions: 1,000 watts per square meter of sunlight at a cell temperature of 25 degrees C.)
3. If one module in a series string is shaded, what happens to the current of the whole string?

Lab 3: Grounding and bonding the array

Background

The metal parts of a PV array, such as module frames and racking, could become energized if insulation fails. Grounding and bonding connect all of these parts together and to the building's grounding system, so a fault current has a safe path and trips the overcurrent protection. Bonding must be continuous: removing one module must not break the ground path to the others.

The rules are in the National Electrical Code (NEC): the grounding and bonding requirements in Article 690 for PV systems, and Article 250 for grounding in general. The rules change between editions, so always work from the edition your jurisdiction enforces: [NEC edition used in this course].

Steps

1. Read the grounding and bonding requirements for PV systems in your NEC edition.
2. Install the equipment grounding conductor or the listed bonding hardware at your station, following the racking and module installation manuals.
3. Check continuity from each module frame and rail to the grounding point with your meter.

Questions

1. Why must the ground path stay continuous when a module is removed?
2. Which NEC sections did you apply? List them with your edition's numbering.

Lab 4: Finding true south

Background

In the northern hemisphere, a fixed array usually produces the most energy over a year when it faces true (geographic) south. A compass does not point to true north: it points to magnetic north. The angle between the two is the magnetic declination. It depends on where you are, and it slowly changes over the years.

Declination is given as east or west. To turn a compass bearing into a true bearing, add an east declination or subtract a west declination. For example, with a declination of 10 degrees east, a compass reading of 170 degrees is a true bearing of 180 degrees: true south.

You can look up the declination for any place with the U.S. National Oceanic and Atmospheric Administration's (NOAA) online magnetic field calculator. A site assessment tool, such as a sun path viewer, usually has a compass and a way to adjust for declination.

Steps

1. Look up the magnetic declination for San Francisco, California. Set your site assessment tool or compass for that declination, level it, and sight along true south as if you were there. Note what object in the room lies true south of you.
2. Repeat for your own location: [your school or training site].
3. Repeat for New York City.

Questions

1. What was the declination at each place, and was it east or west?
2. How far apart were the three "true south" directions you found in the room? Why?
3. What would happen to an array's output if it were aimed using a compass with no correction for declination?

Lab 5: Predicting a system's output

Background

Before a system is built, installers estimate how much energy it will produce in a year. The estimate depends on the site's sunlight, the array's tilt and direction, shading, temperature, and losses in wiring and the inverter.

The National Renewable Energy Laboratory's free PVWatts calculator makes this estimate for any address, using weather data for that location. As a rule of thumb, a fixed array tilted at about the site's latitude produces close to the most energy over a whole year. A steeper tilt favors winter, when the sun is low, and a flatter tilt favors summer. A tracking array, which follows the sun, produces more energy than a fixed one, but it costs more and needs maintenance.

Steps

1. Open PVWatts and enter [your school's address, or another site your instructor gives].
2. Set up a 1 kW system with a fixed (open rack) array, facing true south, tilted at the site's latitude. Accept the default losses. Enter your local electricity price: [price per kWh].
3. Run the calculation and save the results.
4. Run it five more times, changing one thing each time: tilt of latitude plus 7 degrees, latitude plus 15 degrees, latitude minus 7 degrees, latitude minus 15 degrees, and a 2-axis tracking array.

Questions

1. Which setup produced the most energy over the year? Which was second?
2. Of the fixed arrays, which produced the most in summer? Which in winter? Explain why.
3. How much more energy did the tracking array produce than the best fixed array, as a percentage? Would that be worth its extra cost and upkeep for a home? For a large solar farm?

Lab 6: Labels and markings to code

Background

The NEC requires labels on a PV system so that anyone who works on it later, including firefighters, can see what it is, where its power comes from, how to shut it down, and what voltages and currents to expect. Required labels include, for example, the maximum DC voltage and current of the PV circuits, warnings at disconnects that both sides may be energized, the identification of every power source at the service equipment, and the rapid shutdown label. The exact wording, size, color and location are set by your NEC edition and your local inspector.

Steps

1. Read the labelling and marking requirements for PV systems in your NEC edition, in Article 690 and Article 705 for interconnected systems.
2. Make every required label for your lab system and fix each one in the correct place.
3. Then go through your whole system, from each module to the point where it connects to the panel. At each place where you met a code requirement, attach a small tag with the NEC section number.
4. For each tag, write two or three sentences in your portfolio: what the section requires, and how your installation meets it. Add a photo if you can.

Example portfolio entry

"Junction box where the module leads join the building wiring. The conductors here can get hotter than in the rest of the building, so we used conductors and connectors with a 90 degree C rating, as the code requires for this location. [NEC section in your edition]."

Questions

1. Who are labels for, and what could go wrong if a required label is missing?
2. Which label tells a firefighter how to shut the array down?

Lab 7: Unit conversions for PV work

Background

Datasheets, weather data and building plans do not always use the same units. Convert by multiplying by a fraction equal to one, so the old unit cancels out.

Conversion factors

- Length: 1 inch = 2.54 cm; 1 m = 100 cm; 1 m = 3.28 feet
- Area: 1 square meter = 10.76 square feet; 1 square foot = 929.03 square cm
- Temperature: degrees C = (degrees F - 32) x 0.56; degrees F = (1.80 x degrees C) + 32
- Sunlight (irradiation): 1 langley = 1 calorie per square cm = 41,840 joules per square meter = 11.62 watt-hours per square meter
- Energy: 1 kilowatt-hour (kWh) = 1,000 watt-hours

Worked examples

- 23.5 m in feet: 23.5 m x (3.28 feet / 1 m) = 77.08 feet
- 14.2 square meters in square feet: 14.2 x 10.76 = 152.79 square feet
- 78.0 degrees F in degrees C: (78.0 - 32) x 0.56 = 25.76 degrees C
- -4.5 degrees C in degrees F: (1.80 x -4.5) + 32 = 23.9 degrees F

Questions

1. A roof section is 6.5 m by 4.0 m. What is its area in square feet?
2. A module datasheet gives a temperature coefficient for 25 degrees C. What is 25 degrees C in degrees F?
3. A site receives 450 langleys of sunlight on an average day. How many watt-hours per square meter is that?