MSCE in Energy Infrastructure

Brief on Solar Energy and Power Production

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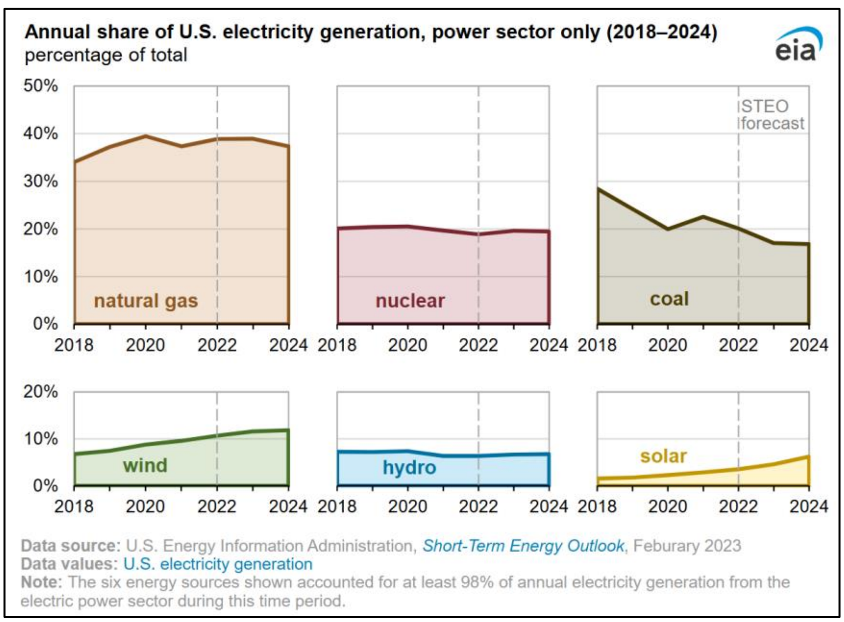
Solar Energy and Power Production

Topics

- Introduction
- Solar Radiation
- PV Cells
- PV Panels
- PV Panel Connections
- Project Orientations
- Example Project
- PV Capacities and the Northwest
- PV Panel Costs and System Sizes
- Useful Websites

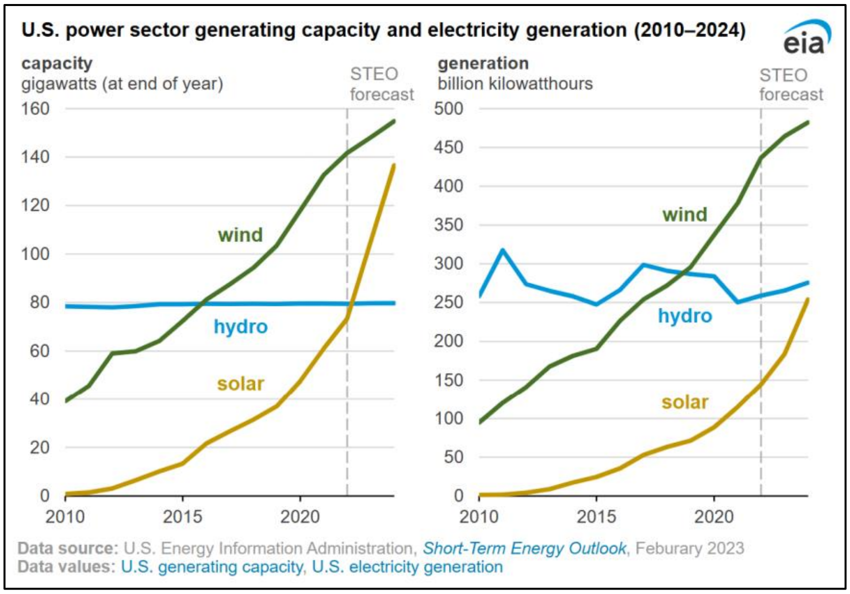
Introduction

This brief will cover the basics associated with solar energy and power production. First, how much utility-scale solar is generating electricity in the US? Two EIA figures are helpful which follow.



This data shows the relative US electricity generation by fuel type over the last 6 years. Natural gas as a percent of the total has been flat for the last 4 years but, by far, the largest, nuclear steady at about 20% of the total, coal is declining, hydro a slight decline and wind and solar growth. Wind and solar generation are about 18% of the total US generation.

Source : EIA, https://www.eia.gov/outlooks/steo/report/BTL/2023/02-genmix/article.php#:~:text=In%20our%20February%20Short-Term%20Energy%20Outlook%2C%20we%20forecast,and%20to%2017%25%20in%20both%202023%20and%202024.



This figure from the same EIA source adds to the prior but shows wind, solar, and hydro changes in capacity (GW) and generation (billion kWh) from 2010 through today. What is apparent is the solar capacity increasing at a high rate, wind less so, and hydro is flat. As to generation, the average national capacity factor for solar is about 20%, wind at 35%, and hydro at 39%. These capacity factors are important since the generation picture for these three types is complicated by intermittency of generation. Compare these values to nuclear plants with capacity factors of 90% or more.

Next, a few basics associated with solar radiation which is fundamental to understanding solar power.

Solar Radiation

There are several terms used to describe solar radiation. Key definitions will be described.

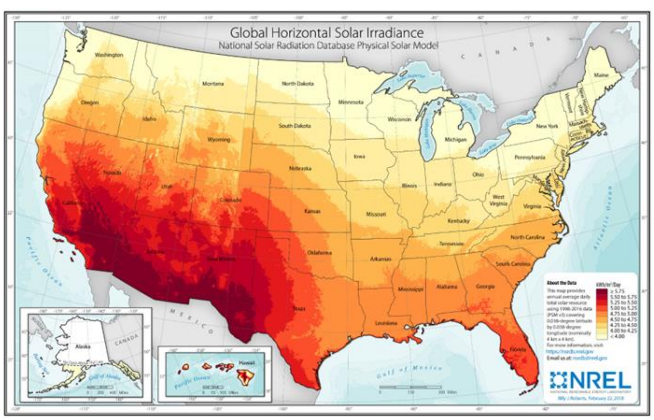
We use solar radiation as the sun's energy that needs to be estimated for PV panel power production (or solar power). Common measurements of solar radiation include **solar insolation** and **solar irradiance**. Additional relevant terms include global horizontal, direct normal, and diffuse horizontal.

For solar power the significant measures are intensity and energy per unit area.

- **Intensity (or solar irradiance)** is defined at a point in time and is analogous to power. It is the sum of all wavelengths within the spectrum in units of W/m^2 for a surface.
- **Energy per unit area (or solar insolation)** is a measure of irradiance on a surface over a period of time and typically expressed as kWh/m^2. **Insolation = Irradiance x Time**
- **Solar constant:** The solar constant is the amount of incoming solar irradiance per unit area that would be incident on a plane perpendicular to the rays at a point just above the earth's atmosphere. The solar constant includes all types of solar radiation, not just the visible light. It is measured by satellite to be 1,367 W/m^2. The solar constant is, in effect, the Sun's power density.
- Sources: NREL and Green Rhino Energy

Instantaneous solar irradiance (16.1 W/m^2) measured at 1630 hours in Seattle on a cloudy, rainy day in February (not much sunshine) via handheld pyranometer.

Instantaneous **solar irradiance** (1038 W/m^2) measured at 1400 hours in Seattle on a sunny day in February via the same handheld pyranometer. A 6X difference between cloudy and sunny.



Solar maps approximate either irradiance or insolation typically by country or state—with one example shown here. The map is for solar irradiance (W/m^2). When such data is presented, it is important to understand how the data was developed (such as—are the data measured or estimated for a horizontal surface or an inclined surface?). This map illustrates well why many utility-scale PV projects are located in the Southwestern US.

Map source: https://atb.nrel.gov/electricity/2021/utility-scale_pv

To recap for solar radiation the significant measures are:

- **Intensity or solar irradiance** (analogous to power) which is typically in terms of W/m^2 and is a point in time (not cumulative such as per hour or per day).

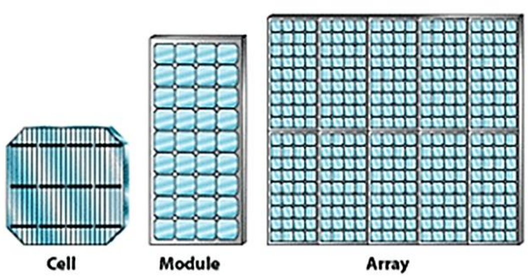
- **Energy per unit area or solar insolation** in terms of kWh/m^2 measured on a surface over a period of time.
- Other measures are available and used in various applications but the two above are most common. Further, we should pay attention to the "surface" of measurement…is it horizontal or tilted?

PV Cells

- **Flexible solar cells** typically convert about 8 to 17% of the solar radiation to electricity. Made of amorphous silicon or organic polymers. Conversion percentages are increasing.
  - Positive: flexible cells are cheaper to manufacture and require far less materials—a reduction of 100X in some cases. Potential for improvements is high.
  - Negative: Efficiencies are lower.
- **Crystalline silicon cells** can have typical conversion efficiencies about 22% with up to 26% conversion efficiency.
  - Negative: these cells are more expensive to manufacture than flexible.
  - Efficiencies are higher.
  - Durability is high…product lives of 25 to 35 years readily obtainable.
- **Thin film** is a rather different construction as illustrated by companies such as First Solar with high conversion efficiencies and longevity.

PV Cells and Panels

PV cells are arranged to create a PV module and modules are arranged to create an array. A PV cell typically produces 1 to 2 watts of power. The cells are connected in series so that the voltages are additive.



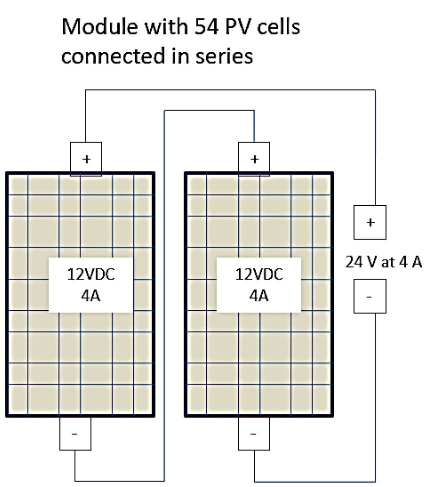
Source: DOE, Solar Energy Technologies Program, http://www1.eere.energy.gov/solar/pv_systems.html

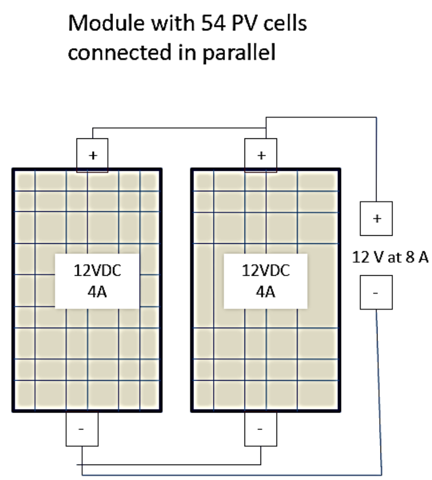
This straightforward comparison shown in the table below reveals how PV panels have changed over a span of about 15 years. The Sharp panel was installed at a Washington State project in 2007. More recent panels (First Solar, SunPower and Risen) illustrate how panel power has changed by 2X to 4X.

Manufacturer	Model	Year	Panel Efficiency (STC)	Power	Panel Weight and Size
Sharp	ND-187U1F	2007	12.7%	187W	17 kg 1.73 m^2
First Solar (thin film)	Series 6	2020	18.2%	450W	34.5 kg 2.47 m^2
SunPower	Maxeon 3	2020	22.6%	400W	19 kg 1.77 m^2
Risen Energy	NewT@N	2021	22.5%	700W	To be announced but the panel size is not expected to increase in size

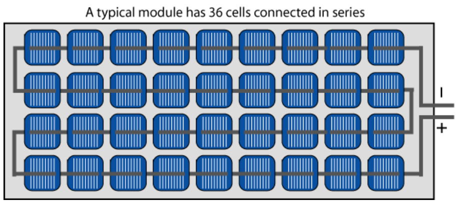
PV Panel Connections

PV panels (or modules) can be connected in series or parallel as shown below. “Series” panel connections, voltages add; for “parallel” panel connections, the currents add.

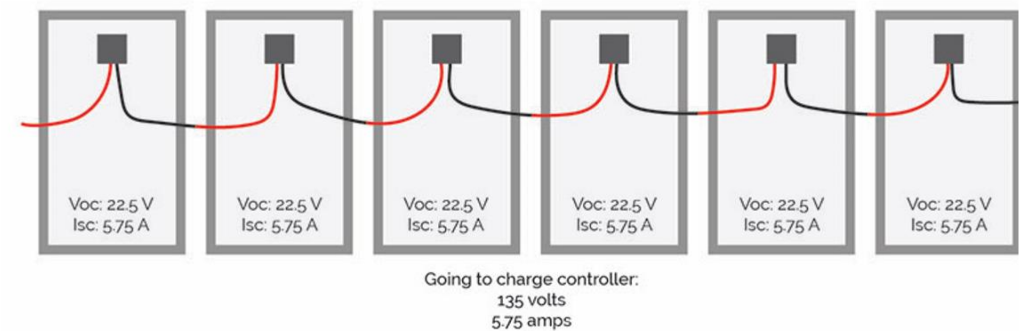




More connection illustrations follow on the next page.



This sketch shows one PV panel with all cells connected in series



This sketch show 6 PV panels in connected in series.

Project Orientations

Two basic and common types of PV panel orientations:

- Fixed angle (non-tracking)
- Tracking

The simplest mounting is a fixed angle orientation. Generally, the panels face south (or west) in northern hemisphere (i.e., face toward the equator), and they face north in the southern hemisphere.

This is a fixed angle arrangement with the PV panels face south for a project located in Washington State.

The backside of the PV array illustrates the tilt angle for this fixed array. It is set at 47° which is the same as the latitude for the project. The angle is measured from the horizontal.

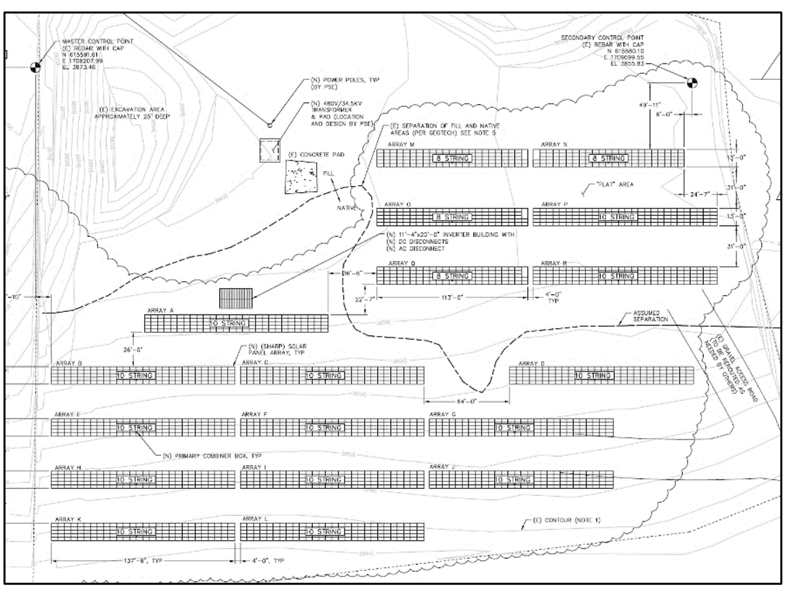
Example Project

We will briefly overview a PV project built in Eastern Washington, It is owned by Puget Sound Energy and much of the data presented was provided by them. The project is the Wild Horse Project (a combined solar and wind generation project).

The primary portion of the project has a solar capacity of 450 kW. This required 2,408 panels made in Memphis, TN by Sharp Electronics (Model ND-187U1F). Max output 187 W per panel. Efficiency @ 12.7%. [currently available panels have substantially higher wattages].

PSE representatives noted that:

- 50 to 70% max power with bright overcast.
- 5 to 10% with dark overcast.
- Output 650,000 kWh/year (about 15% of max capacity)
- Interconnected to the 34.5 kV project grid which is also a major wind farm.
- Five-acre footprint or about 10 acres/MW equivalent.
- Most construction for the solar arrays completed within a 4-month period (June through September).
- PSE received a 25-year warranty for the panels.
- PV array design criteria set for winds up to 120 mph (located at the top of a small mountain).
- PSE expected to see a loss in power production of 1 to 1.5% per year due to degradation of the PV modules; however, less has been observed over the years it has been in service.
- The company noted that the Columbia River dam system is used to balance the load for renewables (both wind and solar generation).

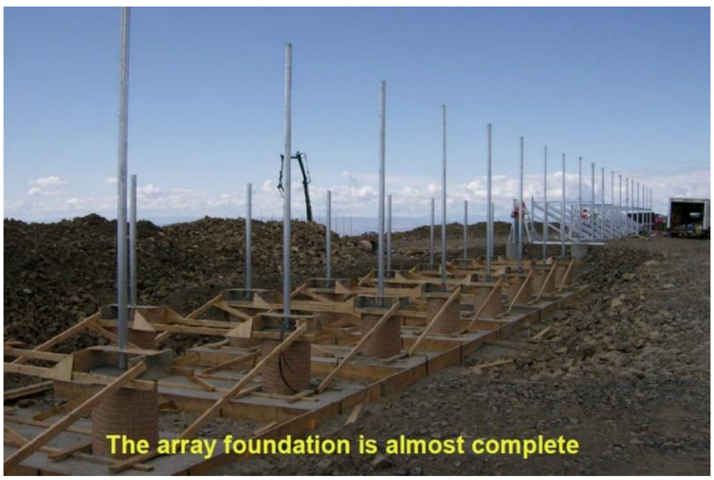


This is a plan view of the 450-kW array. Each small block shown is one PV panel.

Strings of 14 modules in series. Modules rated at Voc = 32.7V or 458VDC for each string. Total Watts = 187W/panel X 2408 panels = 450 kW (rounded). An inverter converts DC power to AC power.

Four construction photos follow:

An aerial view of the 450-kW array under construction.



The construction of the foundation is underway.

Concrete for pier foundations specified at a minimum of 4,000 psi @ 28 days, air entrained, 5 sack mix (470 lb per CY), a maximum 4" slump although water reducers allowed. If reducers are used, the max slump = 6". Max aggregate size either 1.5" or 0.75". As noted earlier, the wind design speed is 120 mph (3 sec gust).

Reinforcing steel ASTM A615 at 60 ksi minimum or A706 + additional requirements.

Support structure ready for panel installation

Setting and connecting panels onto the support structure

PV Capacities and the Northwest

Portions of the Northwest are known for clouds and precipitation. This does impact PV projects for some NW states. The total installed PV capacities by state as of 2024 follow (source: Solar Energy Industrial Association):

- Washington: 682 MW
- Oregon: 1,776 MW
- Idaho: 830 MW
- Montana: 293

Compared to states such as:

- California: 46,874 MW
- Texas: 22,872 MW
- Nevada: 6,382 MW
- Arizona: 7,675 MW
- Utah: 2,753 MW
- Colorado: 4,112 MW

PV Panel Costs and System Sizes

The cost of cells is not commonly quoted; however, there are plenty of other PV estimates which are relevant. For example, most residential PV systems range between 4.5 to 12.0-kWdc in total capacity. The average cost in the US for a 6-kW rooftop system is about $18,000 without the ITC or about $12,000 with the ITC at 30%. Typical installed residential costs per watt range between $2.50 to $5.00/W. Individual panel costs commonly range between $200 to $350 each (between $0.80 to $1.40 per Watt). Across a range of PV projects, panel sizes vary by wattage with the larger panels (about 650 W with a 29 ft^2 surface area and dimensions of about 93" X 45"). Lower wattage panels such as 200 W are closer to 12 ft^2 (dimensions of about 65" X 26").

Useful Websites

- **Solar Explained**, EIA: https://www.eia.gov/energyexplained/solar/
- **Agrivoltaics**: NREL, "Beneath Solar Panels, the Seeds of Opportunity Sprout," , https://www.nrel.gov/news/features/2019/beneath-solar-panels-the-seeds-of-opportunity-sprout.html
- **Solar Resource Maps**, NREL, https://www.nrel.gov/gis/solar-resource-maps.html
- **Global Horizontal Irradiance**, NREL, "Utility-Scale PV": https://atb.nrel.gov/electricity/2021/utility-scale_pv
- **UW MSCE Energy Infrastructure**, https://www.energy-infrastructure.uw.edu/