Lecture 8 – Solar Photovoltaics (III)

Dr. Yu Zhang

ECE, UCSC

ECE180J

Outline

- Different PV Systems
- PV Integration
- PV Capital and Generation Costs
- PV Environmental Impact and Safety
- PV Lifespan

- B3: Chap 4
- B1: Chap 6

PV Water Pumping Systems

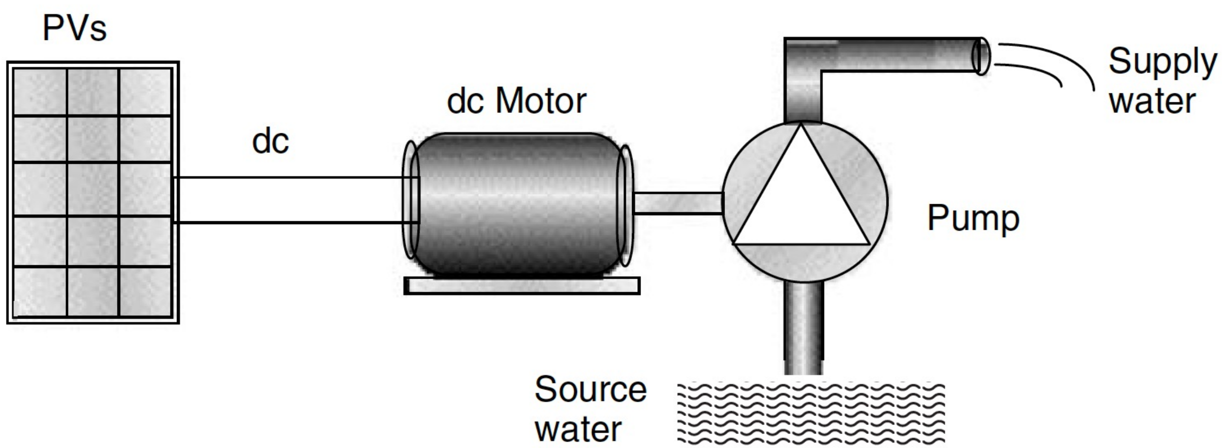


Figure 9.3 Conceptual diagram of a photovoltaic-powered water pumping system.

Systems have PV directly coupled to their loads, without any batteries or major power conditioning equipment.

- When the sun shines, water is pumped (no electric energy storage).
- Potential energy can be stored in a tank of water up the hill for future use.
- These systems are simple, reliably, and least costly.
- But need to be carefully designed to be efficient.

Stand-alone PV Systems

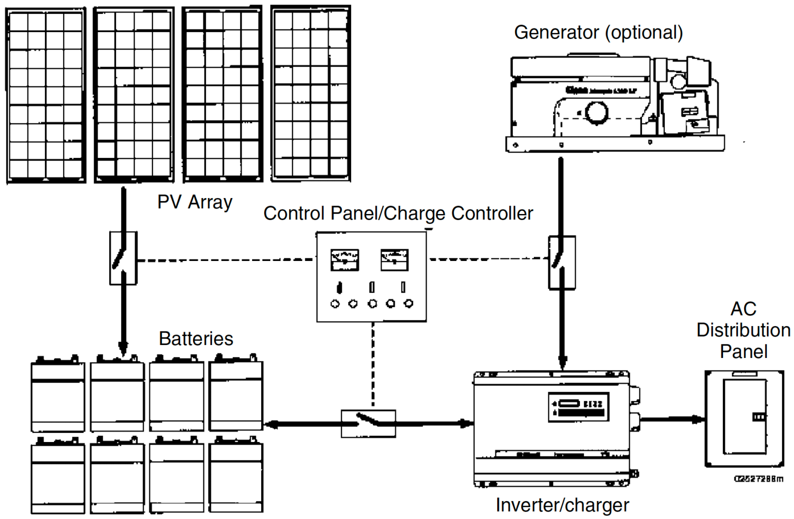


Figure 9.2 Example of a stand-alone PV system with optional generator for back-up.

- An inverter converts battery DC voltages into AC
- If everything run on DC, no inverter needed
- The charging function of the inverter allows the generator to top up the batteries when solar is insufficient.

Pros: Stand-alone PV systems can be very cost effective in <u>remote locations</u>

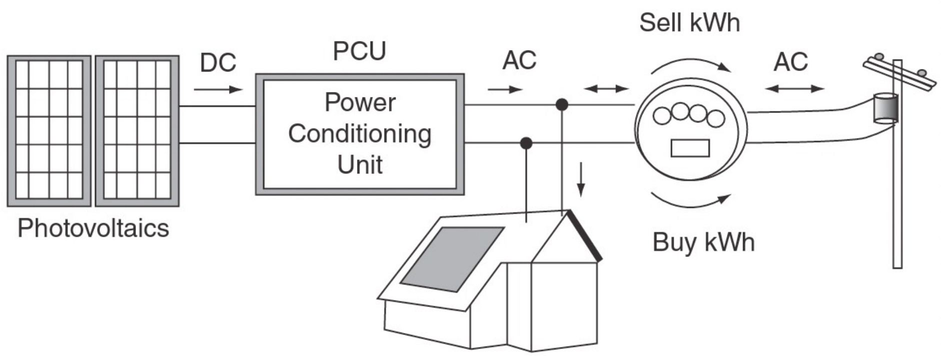
For those locations: the only alternatives may be

- noisy and high-maintenance generators burning expensive fuel
- extending the existing utility grid to the site: costs $$$ dollars per mile

Cons: These systems suffer from several inefficiencies including

1) battery losses
2) PVs usually not operate at their most efficient operating point
3) inefficiency increased by mounting the array at an overly steep tilt angle
4) require much more attention and care than grid-connected systems

Grid-connected PV Systems



PCU = charge controller + inverter + grid charger
The integrated system provides the facility to charge the battery bank and continuously monitors the state of battery voltage,
solar power output and the load.

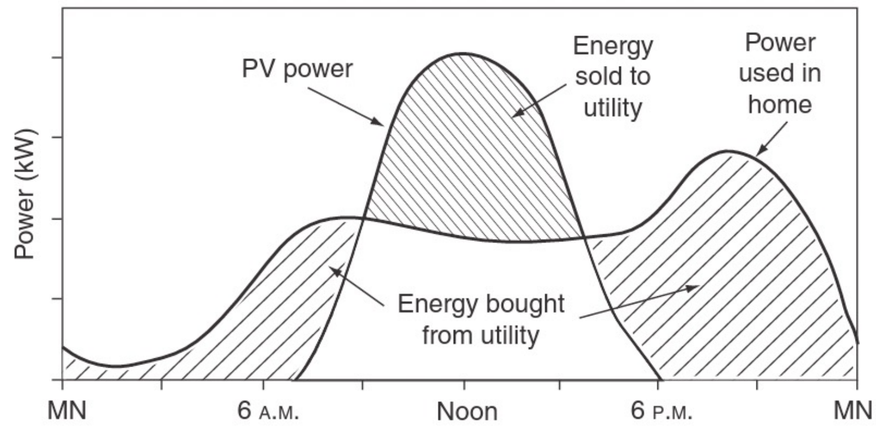
The grid charger is an auxiliary charger in a Solar PCU. It charges the battery from the grid when solar is not available.

- If the PVs supply less than the immediate demand of the building, the PCU draws supplementary power from the utility grid.
- If the PV supply more power than is needed, the excess is sent back to the grid, potentially spinning the electric meter backwards.

Net Metering and Feed-In Tariffs

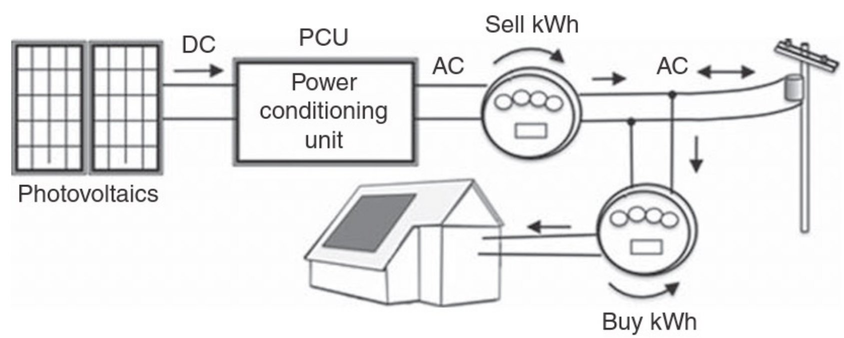
Net Metering: A system in which PV panels are connected to a power grid and surplus power is transferred onto the grid, allowing customers to offset the cost of power drawn from the utility.

- The meters can run in either direction that requires no new equipment.
- Utility can offer time-of-use (TOU) rates to encourage peak load shifting.



Feed-in Tariff: The separate rates created by a two-meter system measuring all PV power generated and power consumed in the building.

- Can be designed to guarantee a generous price for all customer's generated electricity at the beginning.
- Can reduce the uncertainty of PV values and make them easier to finance.



See more details in https://en.wikipedia.org/wiki/Feed-in_tariff

Principal Components in Grid-connected PV Systems

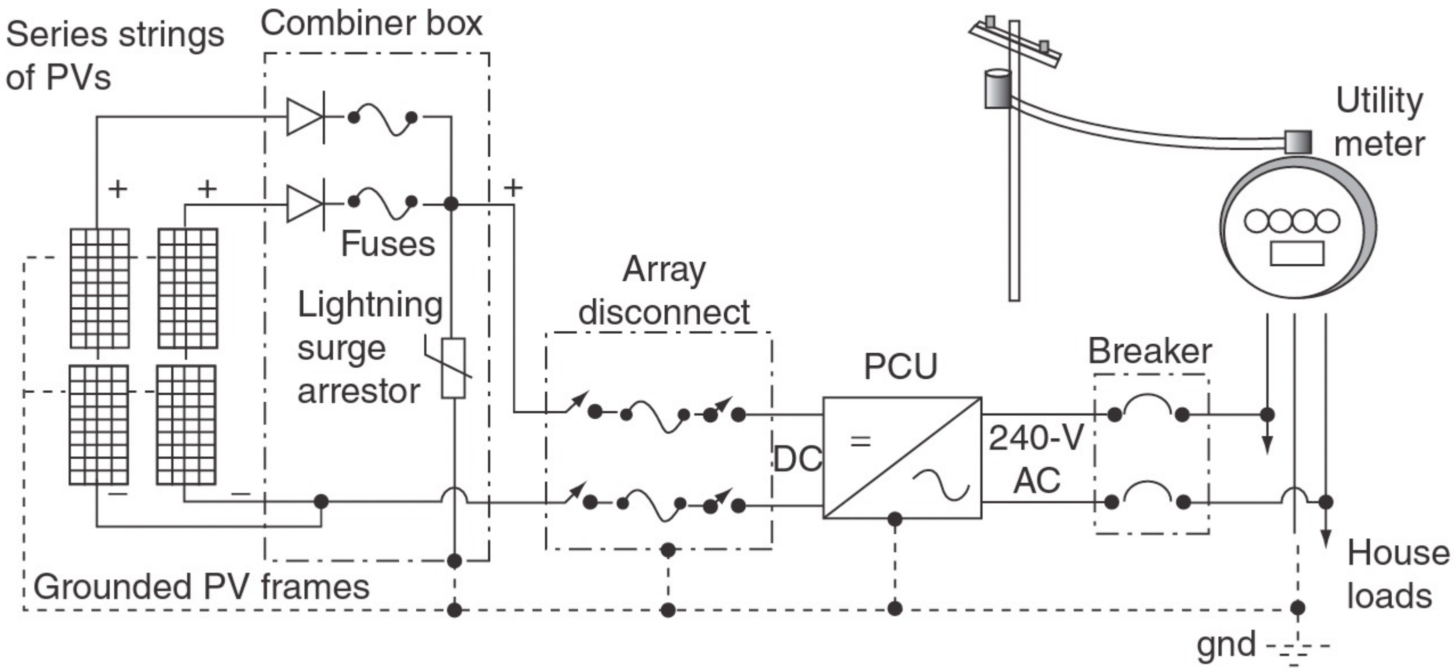


FIGURE 6.2 Principal components in a grid-connected PV system using a single inverter and a single utility meter.

- Each string sent to a combiner box (blocking diodes, fuses, and an arrestor).
- A fused array disconnect switch allows the PV to be isolated from the system
- PCU sends 240 V AC power to the utility service panel.
- 120 V power is delivered to each household circuit by tying each end of the inverter output to opposite sides of the service panel.

Solar Inverters

The electricity produced by solar panels is converted from DC to AC by solar inverters.

- **Off Grid Inverters**

Used in remote systems wherein the solar inverter is fed DC power from a battery panel that is charged by solar panels. Several such inverters have integrated with basic battery chargers which can be used to boost the battery from an AC power source.

- **Grid-tie Inverters**

Associated with the grid: feed power in the electricity grid by corresponding phase and frequency. These inverters are designed to automatically shut down once sensing a loss of supply from the utility.

Solar Inverters (cont'd)

- **Battery Backup Inverters**

Particularly designed to draw energy from a battery. The charge of the battery is preserved by using an on-board charger and an additional energy is transferred to the grid. Able to provide AC power to particular loads during power outages.

- **Micro Inverters**

Modern in the solar industry: small, compact size and portable with a lot of performance. They include all the features of any central inverters.

Solar Inverters (cont'd)

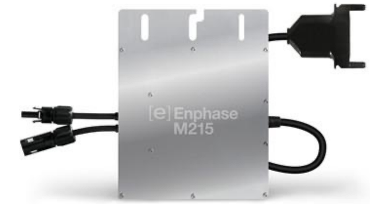
STRING INVERTERS

Most common choice for residential applications; convert DC from multiple solar panels into AC at ground level by your service panel.

Pros:
- Proven Technology
- Predictable
- Cost-effective

Cons:
- Not optimized for shading
- Difficult to expand
- No monitoring
- Safety

MICROINVERTERS



Mounted directly behind each solar panel; eliminate potentially hazardous high voltage DC wiring.

Pros:
- Easy design, installation, & scalability
- MPPT
- Optimized for shading
- Remote monitoring capability

Cons:
- More expensive
- Relatively new technology

Attributes of Grid-connected PV Systems

Pros (cost effectiveness):

• relative simplicity can result in high reliability
• maximum-power-tracking unit assures high PV efficiency
• potential to be integrated into the structure of the building (no additional costs for land)
• ability to deliver power during the middle of the day, when utility rates are highest, increases the economic value of their kWh

Cons: compete with the relatively low price of utility power

[The ugly truth behind grid-tie solar systems. Watch before you buy!]

PV Systems for Remote Power

- PV modules are now widely used in developed countries to provide electrical power in locations where it would be inconvenient or expensive of using conventional grid supplies. They are often used to charge batteries to ensure continuity of power.

- In many developing countries, in rural areas, especially in countries with high solar radiation levels – and PV usage is growing very rapidly.

  - PV-powered water pumping
  - PV refrigerators to help keep vaccines stored safely in health centers
  - PV systems for homes and community centers, providing energy for lights, radios, audio and video systems
  - PV-powered telecommunications systems
  - PV-powered lighting for streets

PV Systems for Houses

- The grid can absorb PV power that is surplus to current needs, making it available for use by other customers and reducing the amount that has to be generated by conventional means; and at night or on cloudy days, when the output of the PV system is insufficient, the grid can provide backup energy from conventional sources.

In these grid-connected PV systems, an inverter transforms the direct current (DC) power from the PV arrays into alternating current (AC) power at a voltage and frequency that can be accepted by the grid, while ‘debit’ and ‘credit’ meters measure the amount of power bought from or sold to the utility.

PV Systems for Non-domestic Buildings

- The grid can absorb PV power that is surplus to current needs, making it available for use by other customers and reducing the amount that has to be generated by conventional means; and at night or on cloudy days, when the output of the PV system is insufficient, the grid can provide backup energy.

- In most countries operating a 'Feed-in Tariff' scheme, users are paid a premium rate per kWh for all PV power generated. When available, PV power replaces power that would otherwise have to be purchased from the grid at the normal 'retail' price; and during periods of low demand, any surplus PV power can be sold to the grid.

Large PV Power Plants

- Large, PV power systems, many on a multi-megawatt scale, have been built to supply power for local or regional electricity grids in a number of countries, including Germany, Switzerland, Italy and the USA.

- Large PV power plants are attractive in those areas of the world that have substantially greater annual total solar radiation than northern Europe, such as North Africa or southern CA. Such areas also have clearer skies, which means that the majority of the radiation is direct, making tracking and concentrating systems effective and further increasing the annual energy output.

World's Largest PV Power Stations

Large PV Power Plants

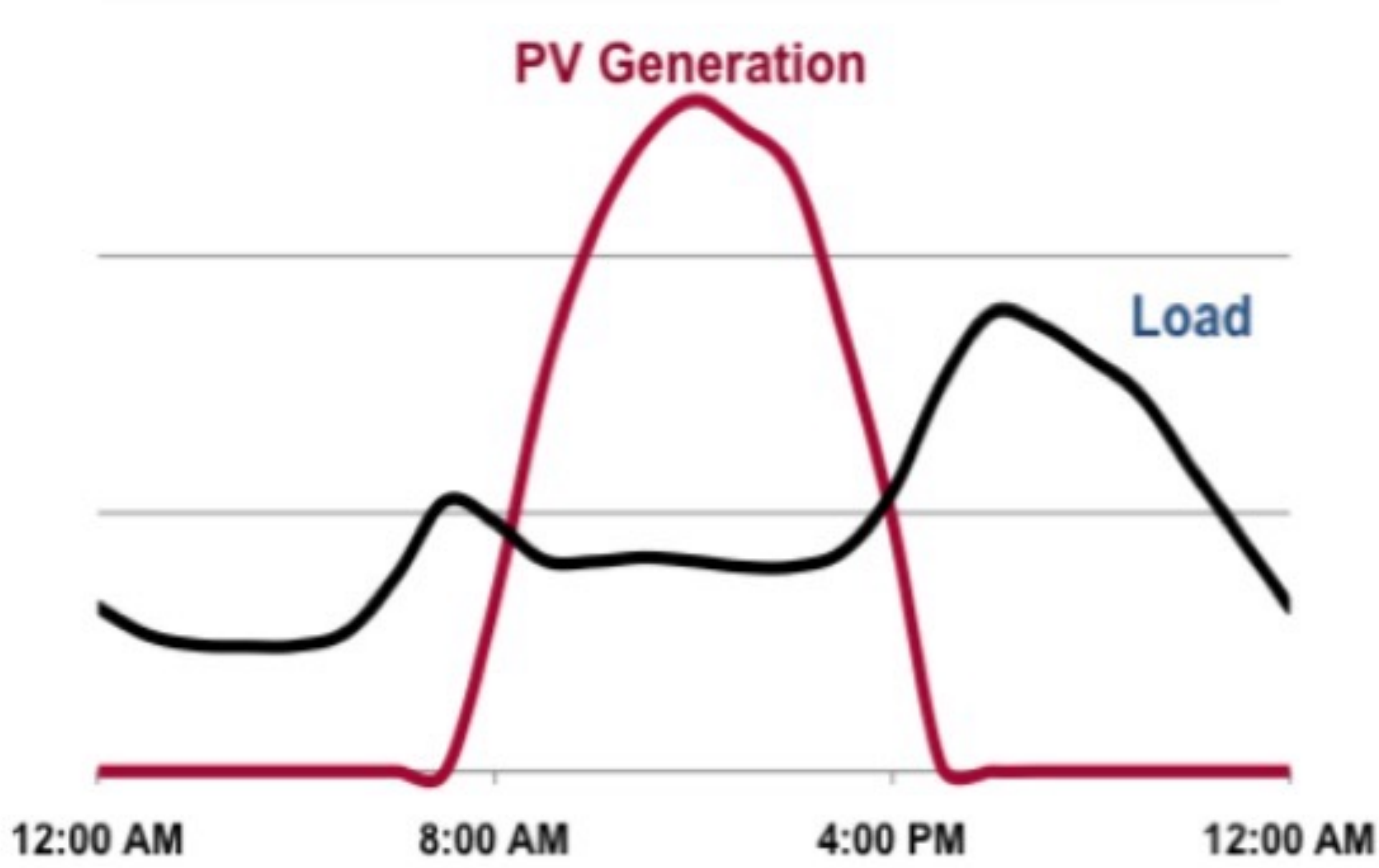
Q: Pros & Cons of large, stand-alone PV plants compared with building-integrated PV systems?

A:

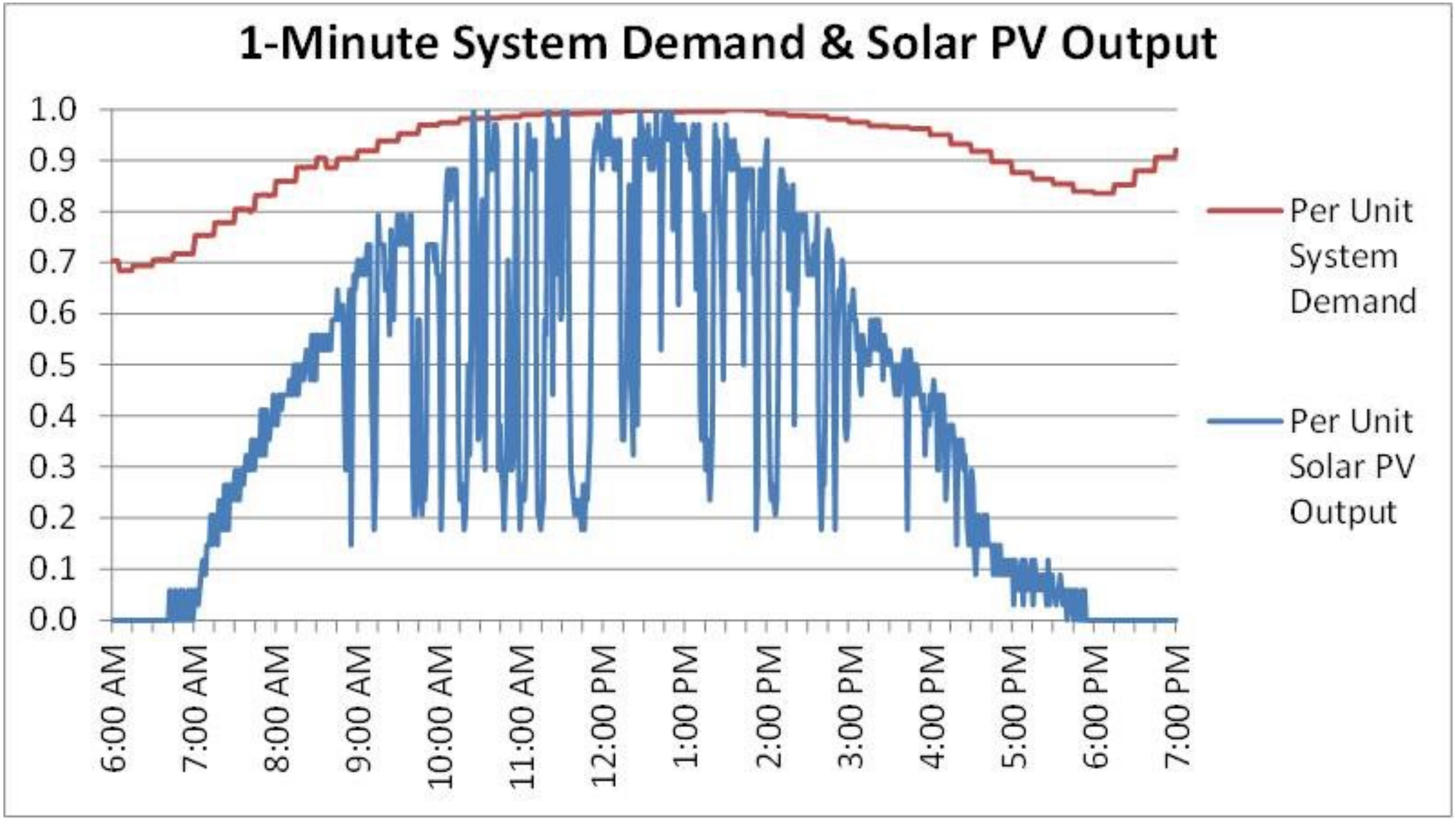
Cons	Pros
The electricity they produce has to be distributed by the grid, which involves transmission losses; the price paid for the power by a local utility may only be the 'wholesale' price at which it can buy power from other sources.	Take advantage of economies of scale in purchasing and installing large numbers of PV modules and associated equipment
Require substantial areas of land, which has to be purchased or leased, adding to costs	Be located on sites that are optimal in terms of solar radiation

PV Integration

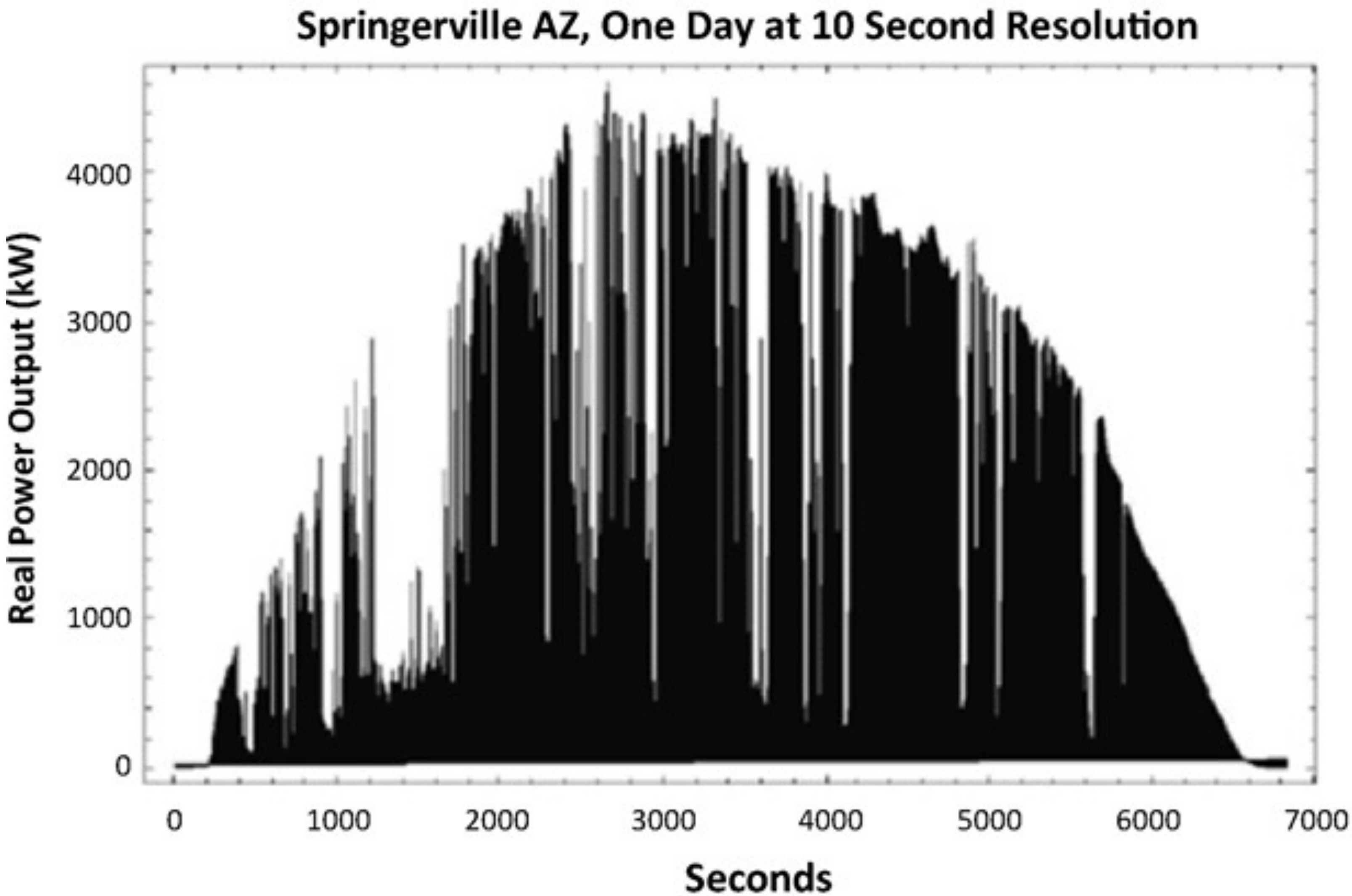
Challenges: **Intermittence, volatility, uncertainty**



PV Integration (cont'd)

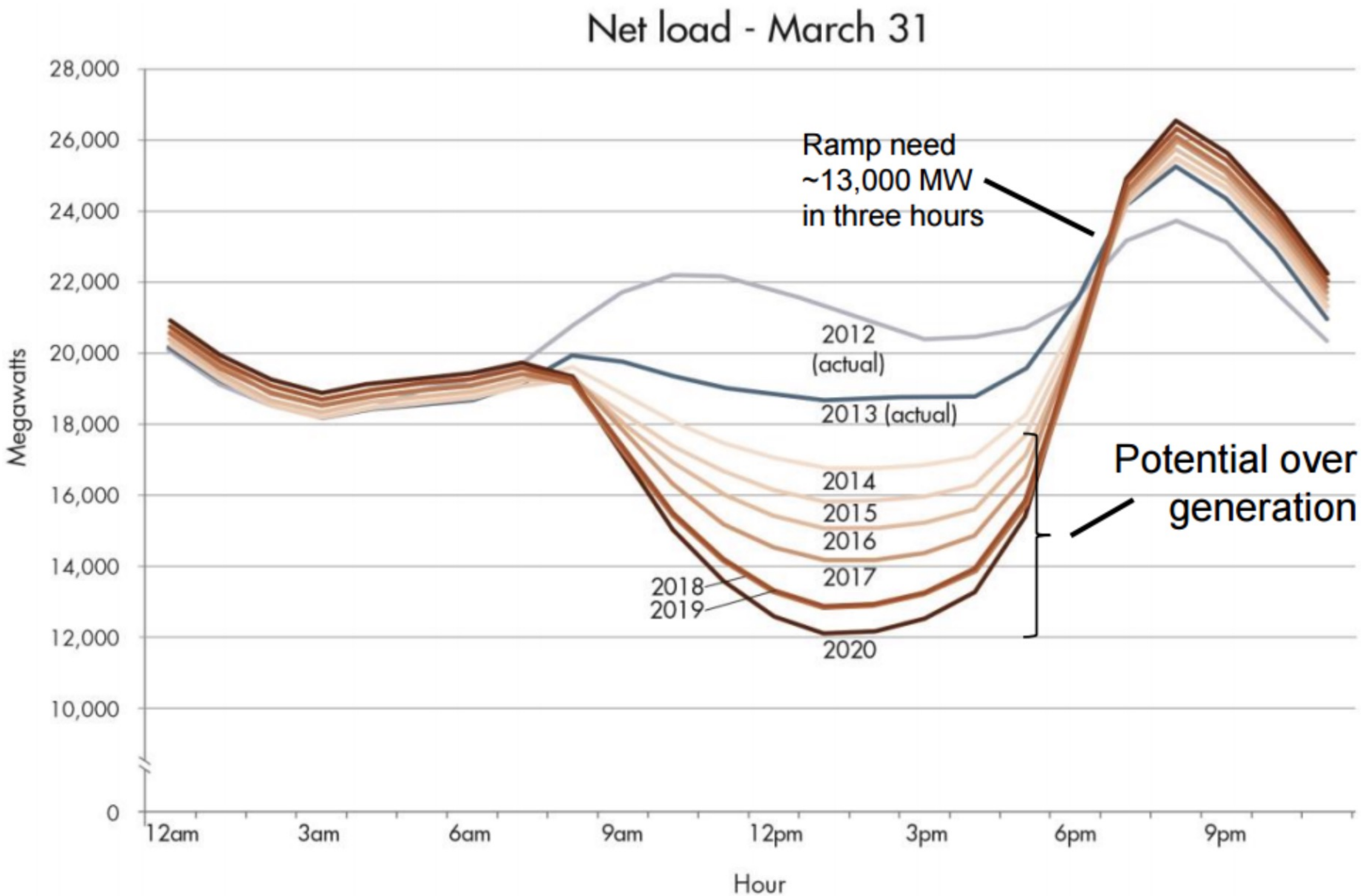


PV Integration (cont'd)

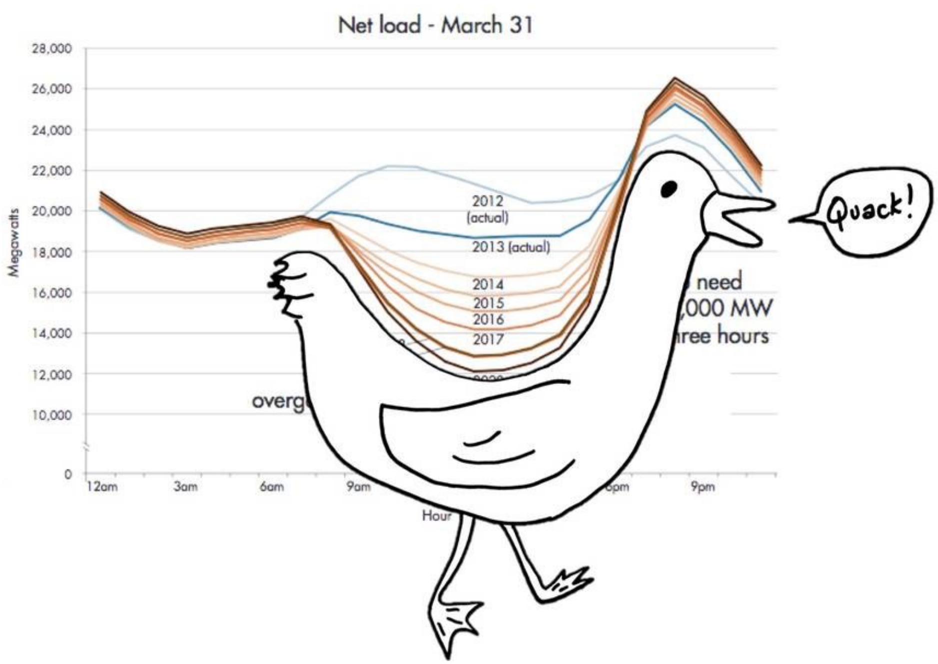


Net Load

Challenges: **Big net load variation**



Duck Curve

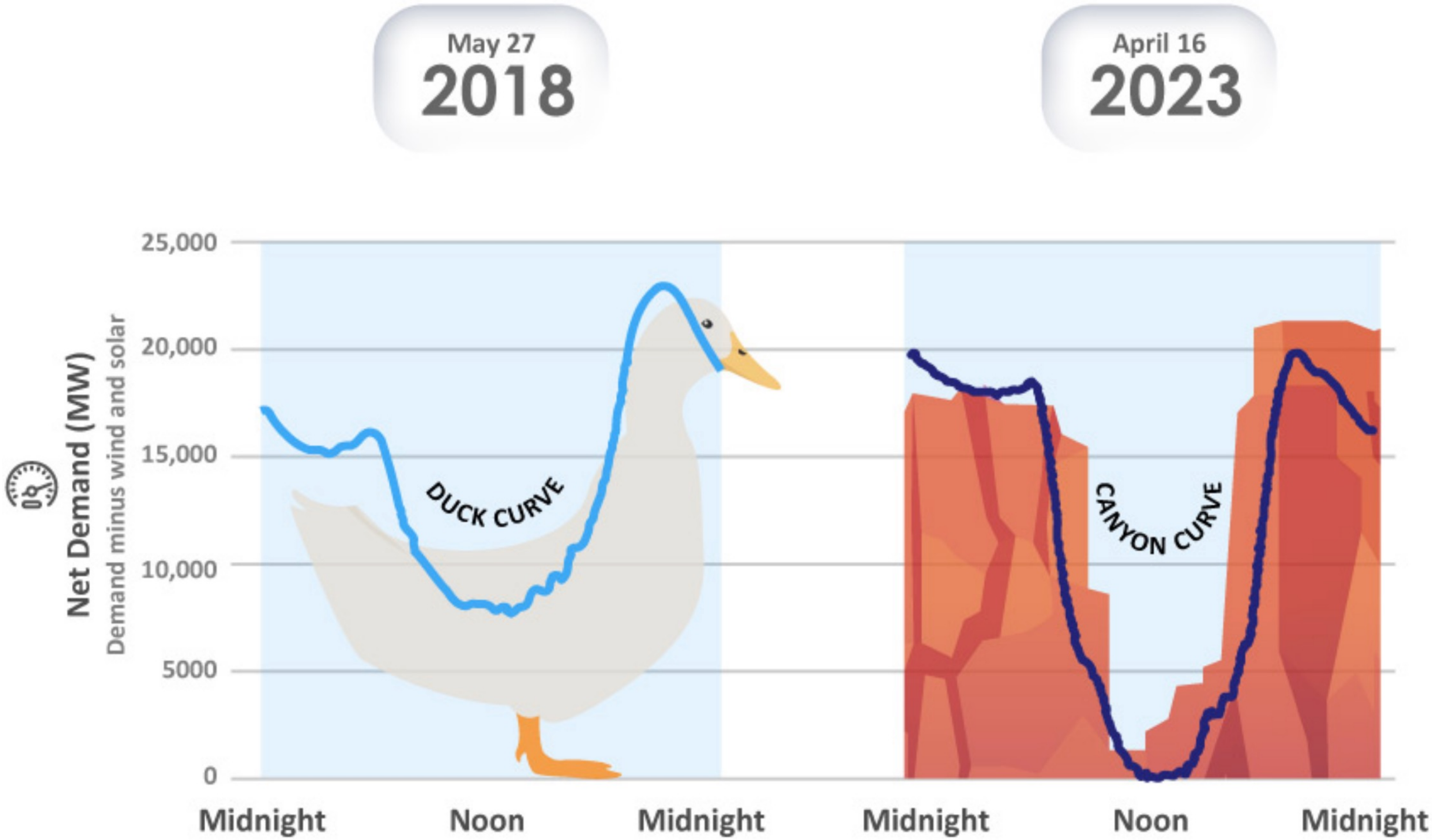


The duck curve (first introduced by CAISO) emphasizes the challenges associated with a growing solar resource that resulted in net demand being reduced during the day (the duck's belly) and sharply increasing at sunset (the duck's neck), with both the belly getting deeper and the neck getting steeper and longer every year.

The industry has been working to improve how the grid operates with the duck curve, since the belly can cause both over-generation issues and renewable curtailment, and the neck can make it more difficult for the resource fleet to be flexible enough to ramp up. The need for flexibility is paramount to address these challenges.

Source: Arshad Mansoor (president & CEO of EPRI)

From Duck Curve to Canyon Curve



PV Integration Solutions

Q: In what ways would national energy systems need to be modified to cope with long, medium and short-term fluctuations in PV outputs?

A:

• If the capacity of variable output power sources such as PV is fairly small in relation to the overall capacity of the grid (renewable penetration ratio: 10-20%) → no major problem.

• The grid is designed to cope with large fluctuations in demand and supply like PV can be considered equivalent to 'negative loads'. Fluctuations may be smoothed out if PV plants were situated in many different locations.

• If penetration ratio is large, then we need to include a greater proportion of 'fast response' power plants, such as hydro or gas turbines, and increased amounts of short-term storage and/or 'peaking' power plants (generally run only when there is a high demand).

PV Capital Costs

The ***capital* cost** of a PV energy system is proportional to its rated power output, usually quoted in $ per peak kW ($/kWp). This includes:

1) cost of the PV modules

2) *balance of system (BOS)* costs: the costs of the interconnection of modules to form arrays, the array support structure, land and foundations

3) costs of cabling, charge regulators, switching, metering and inverters

4) cost of either storage batteries or connection to the grid

Economic Pros & Cons

Q: What are the economic pros and cons of PV systems?

Cons	Pros
initial capital costs of PV systems are currently relatively high	operation and maintenance costs are extremely low in comparison with other energy systems (but PV systems including batteries have additional maintenance requirements)
	no fuel requirements
	no moving parts (except in the case of tracking PV) therefore less maintenance

PV Cost Example: UK

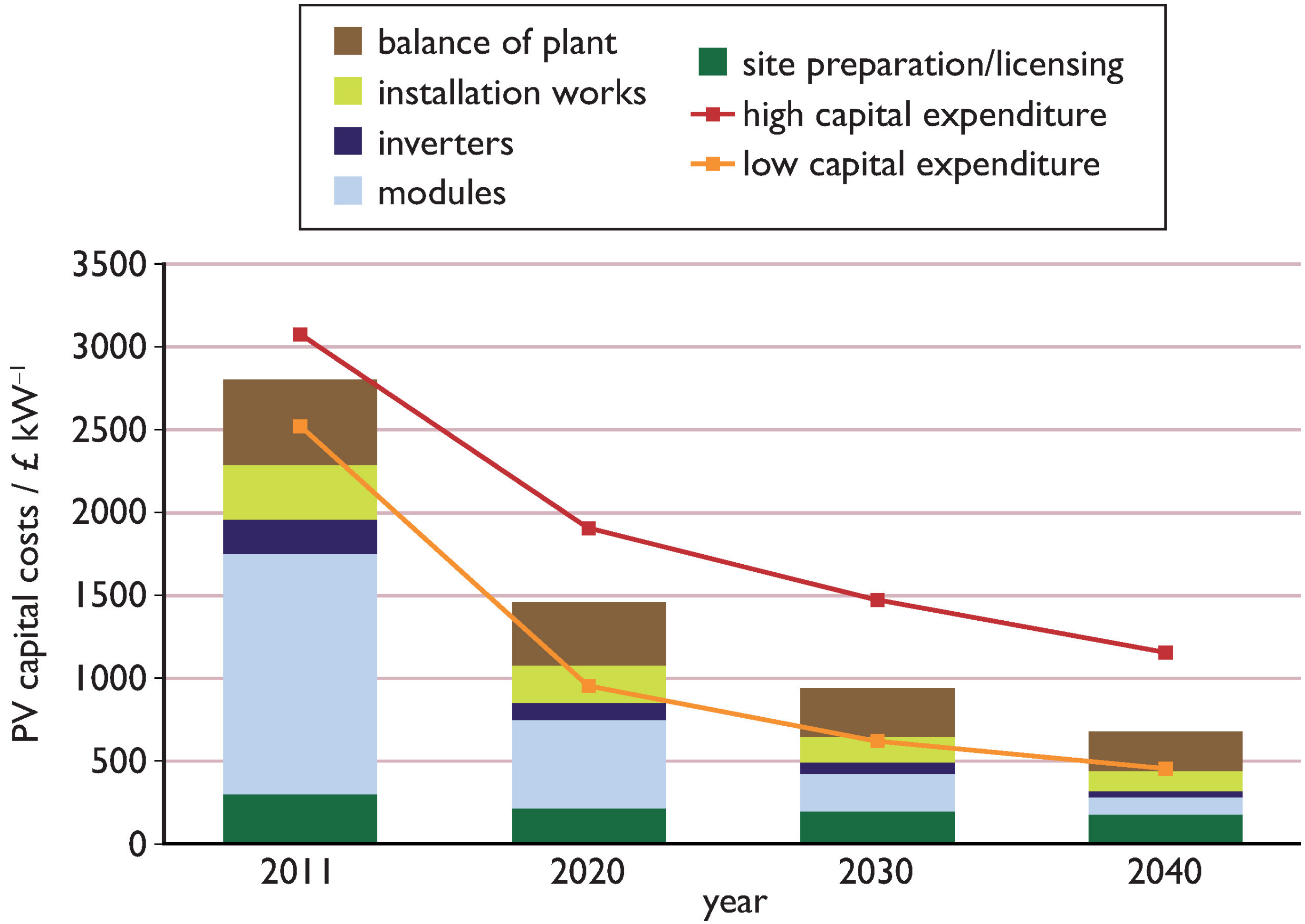
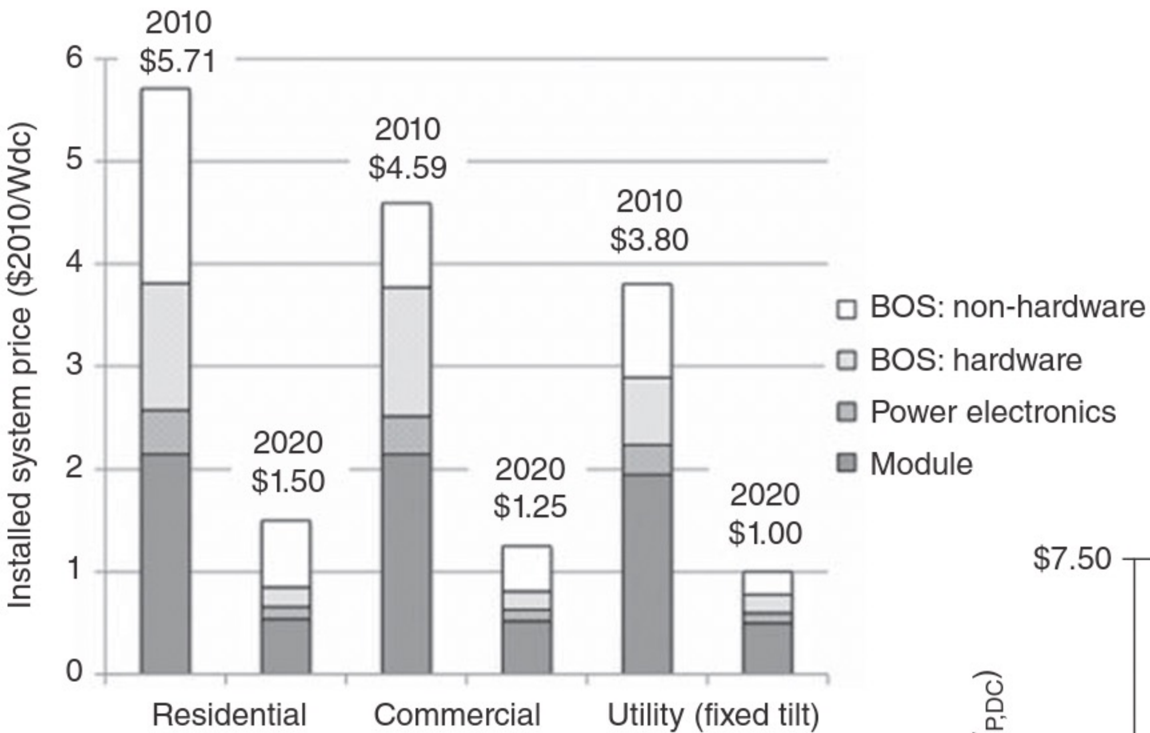
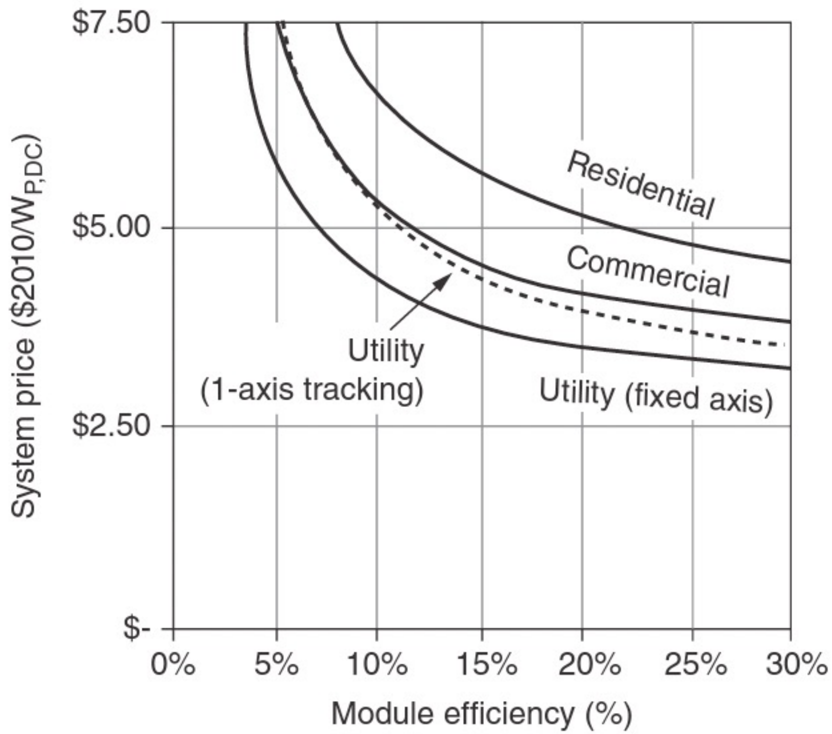


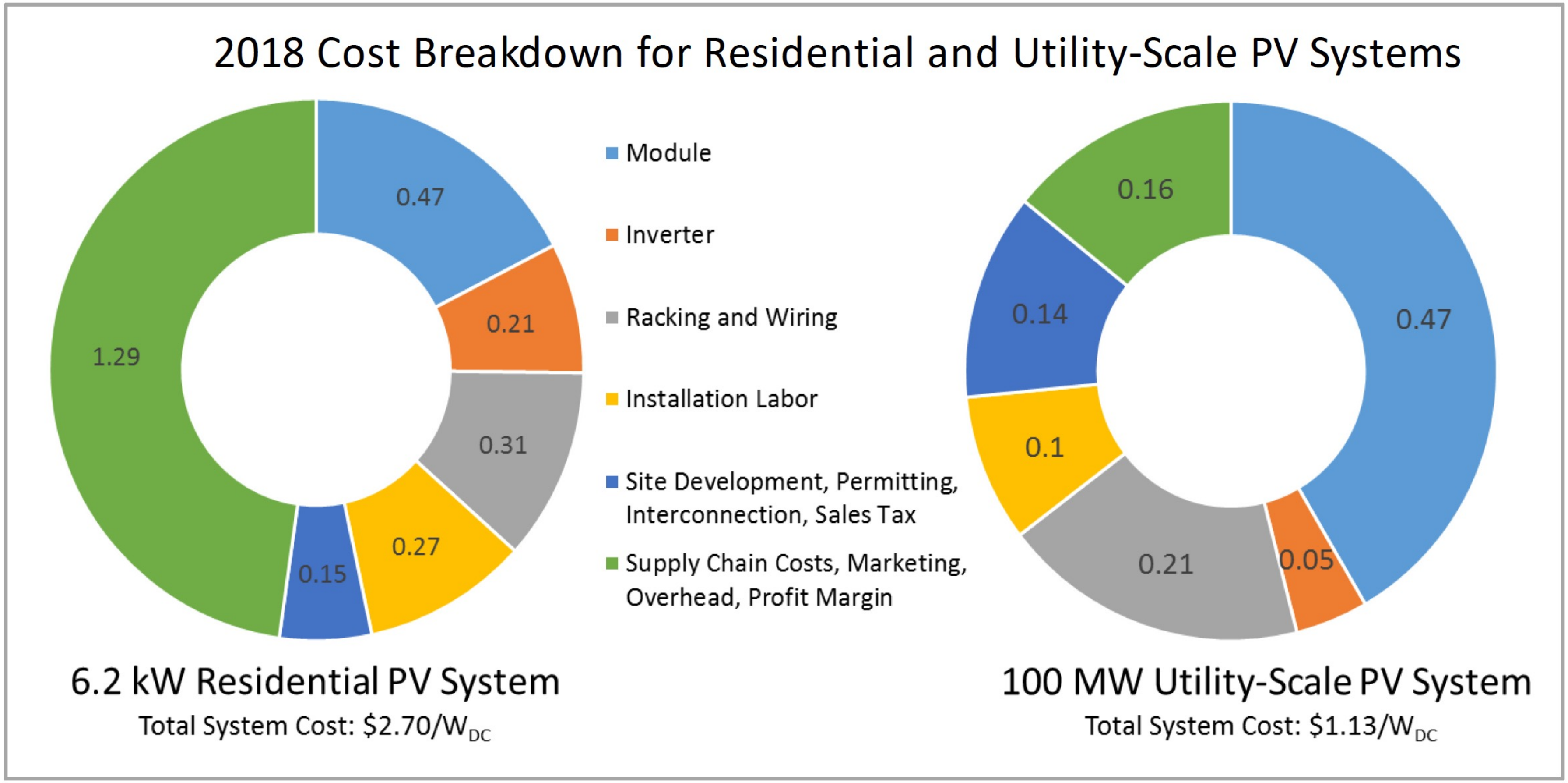
Fig: Capital costs of solar PV systems in the UK in 2010, and projected capital costs in 2020, 2030 and 2040 (source: Committee on Climate Change, 2011).

PV Cost Example: USA





Cost of PV Systems



PV Generation Costs

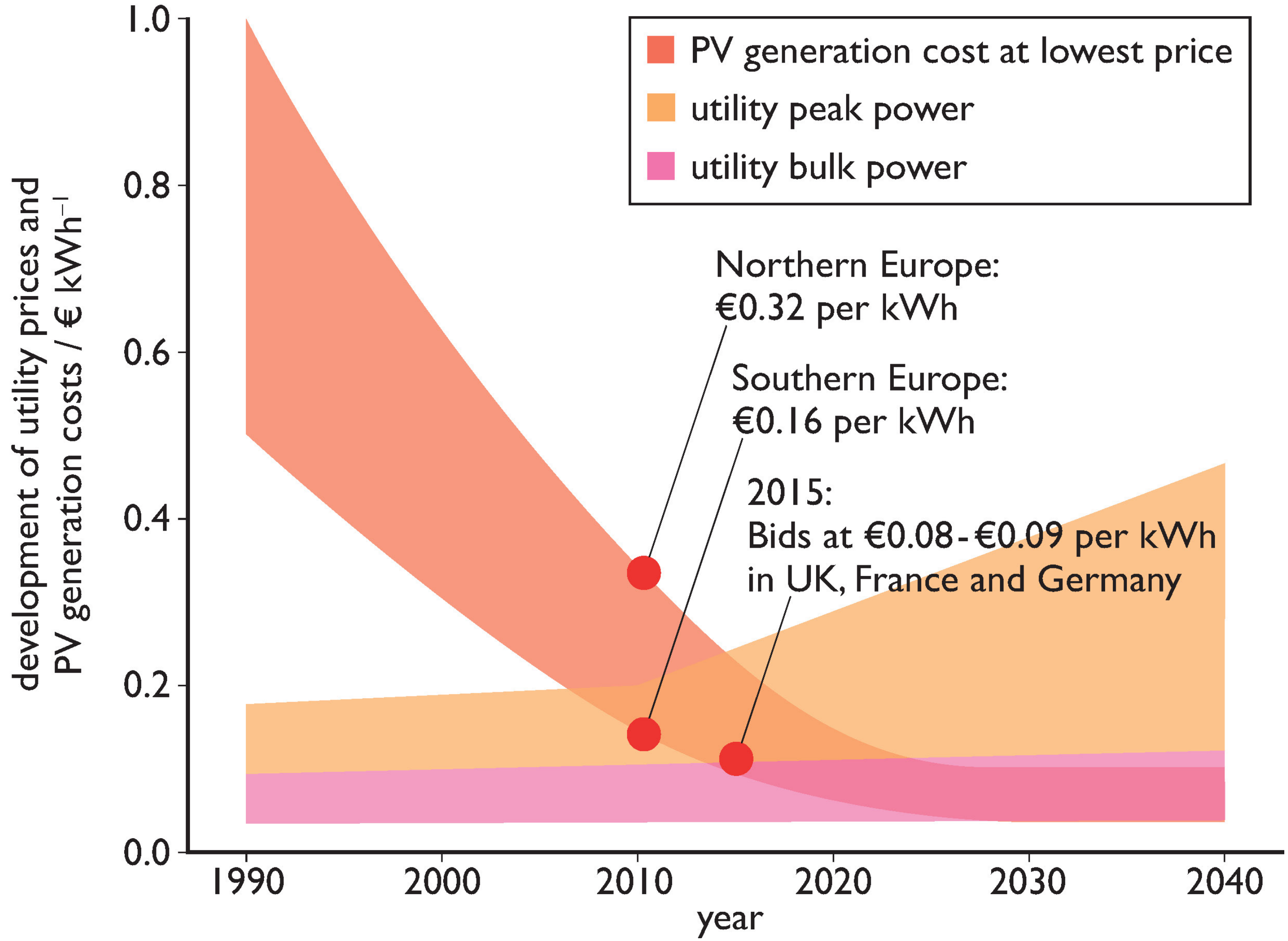


Fig: Progress towards ‘grid parity’: convergence of utility electricity prices and PV costs between 1990 and 2010, and projections to 2040. (source: EPIA/Greenpeace, 2011). (Note: h/a is hours of Sun per annum)

Amortizing Costs

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

Recall the capital recovery factor (CRF):

$$\mathrm{CRF\ (monthly)} = \frac{(i/12)[1+(i/12)]^{12n}}{[1+(i/12)]^{12n} - 1}$$

Example 6.5 Cost of PV Electricity for the Silicon Valley House. The 3.36 $\mathrm{kW_{DC}}$ PV system designed in Example 6.4 delivers 4942 kWh/yr. Suppose the system cost is the 2010 residential average of $5.71/$\mathrm{W_{DC}}$ (without incentives). If the system is paid for with a 4.5%, 30-year loan, what would be its cost of electricity? If the SunShot goal of $1.50/W is achieved, what would the cost be?

Solution. The system will cost $5.71/W × 3360 W = $19,186.

The capital recovery factor (CRF) for this loan would be

$$\mathrm{CRF}(i,n) = \frac{i(1+i)^n}{(1+i)^n - 1} = \frac{0.045(1.045)^{30}}{(1.045)^{30} - 1} = 0.06139/\mathrm{yr}$$

So the annual payments would be

$$A = P \cdot \mathrm{CRF}(i,n) = \$19{,}186 \times 0.06139 = \$1177.80/\mathrm{yr}$$

The cost per kWh is therefore

$$\text{Cost of electricity} = \frac{\$1066.42/\mathrm{yr}}{4942\ \mathrm{kWh/yr}} = \$0.238/\mathrm{kWh}$$

At the SunShot goal of $1.50/W, the cost would be

$$\text{Cost of electricity} = \frac{\$1.50/\mathrm{W} \times 3360\ \mathrm{W} \times 0.06139/\mathrm{yr}}{4942\ \mathrm{kWh/yr}} = \$0.062/\mathrm{kWh}$$

That is considerably below the $0.116/kWh average 2012 U.S. residential price.

PV Environmental Impact

The lowest of all electricity generating systems

- In normal operation PV energy systems emit no gaseous or liquid pollutants and no radioactive substances.
- Crystalline silicon PV cells contain only minuscule quantities of dopants such as boron and phosphorus.
- PV modules have no moving parts, so they are also safe in the mechanical sense, and they emit no noise.
- The electrical hazards of a well-engineered PV system are no greater than those of other comparable electrical installations.

PV arrays do, of course, have some visual impact.

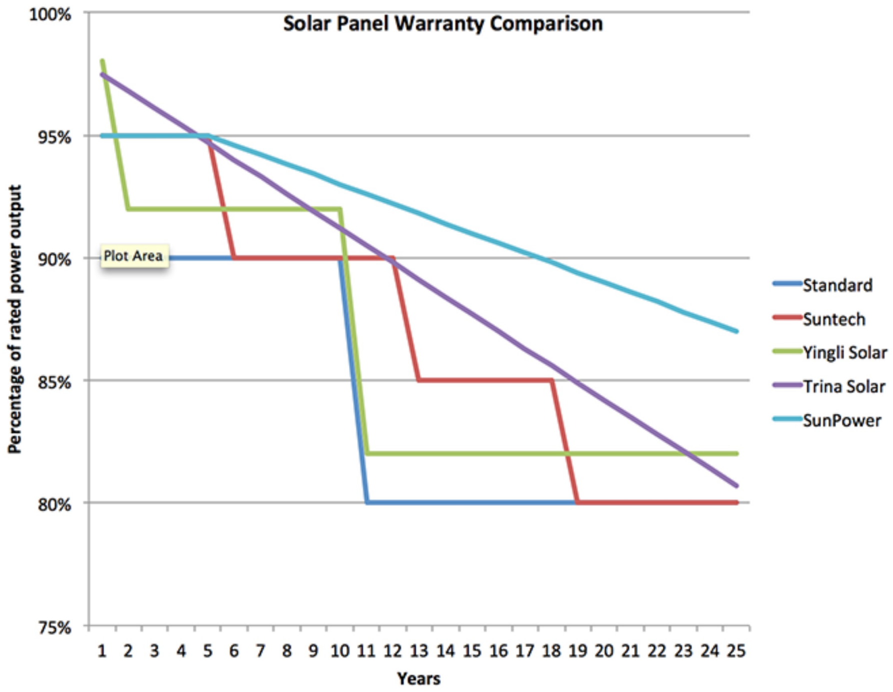
- Solar Roof by SolarCity
- Thoughts by ColdFusion

Safety of PV Production

- The majority of PV cells are made from silicon, which is not intrinsically harmful.
- When small amounts of toxic chemicals are used, such as the cadmium used in manufacturing some PV modules, manufacturers need to follow standard practices to ensure containment of any harmful chemicals in the event of an accident or plant malfunction.
- PV arrays will come to the end of their useful life and have to be disposed of/recycled.
- Most European manufacturers are beginning to recycle PV modules at the end of their working lives under the auspices of the voluntary 'PV Cycle' initiative.

Energy payback time: the time taken for a PV array to produce as much energy as used in its production
about 1.8 years for mono/poly-crystalline PV,
1.1 to 0.8 years for cadmium telluride PV, in southern Euro conditions.

Solar Panel Lifespan



Most manufacturer warranties are 25 years. A variety of outside factors shortening array's lifespan and lead to early degradation

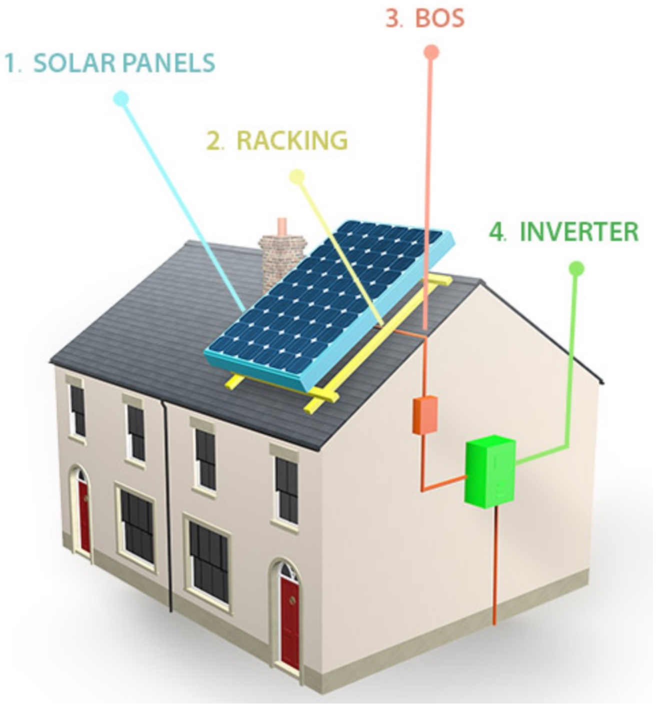
Installation complications:

- Panels their biggest threat during the installation process (e.g. careless installers can step on the panel).
- Repeated stress can cause [micro-fractures]() in PV cells, ultimately leading to an accelerated degradation.

Outside factors:
Soiling: panel's power loss due to the elements like snow, dirt, dust and other particles that accumulate on them. An average of 1% loss of solar radiation results from dust (with the highest loss at 4.7%).
Those that have flat roofs, while they are great for solar installations, typically result in higher dust, snow and dirt buildup.
Wildlife (birds, rodents): trigger damage from trees and other structures.

https://solect.com/maximizing-the-lifespan-of-solar-panels/

Solar Panel Lifespan (cont'd)



1. Quality parts: glass, aluminum frame, solar cells, encapsulant, and tedlar.
2. Know-how in assemblage and installation
– store and transport modules to prevent microcracks
– check visible defect before installation
– ensure handling provokes no damage
– ensure proper electrical connections
– ensure maximum self cleaning and mechanical resistance by slope and clamping
– avoid shadowing on protective diodes
– perform cabling with safety in mind

3. External forces: climate conditions
4. Maintenance: taking care of investment should be a top priority. Combine the panels with a monitoring system.

https://www.hahasmart.com/blog/1367/understanding-the-solar-panel-lifespan

The End and the Beginning …

The truth about solar