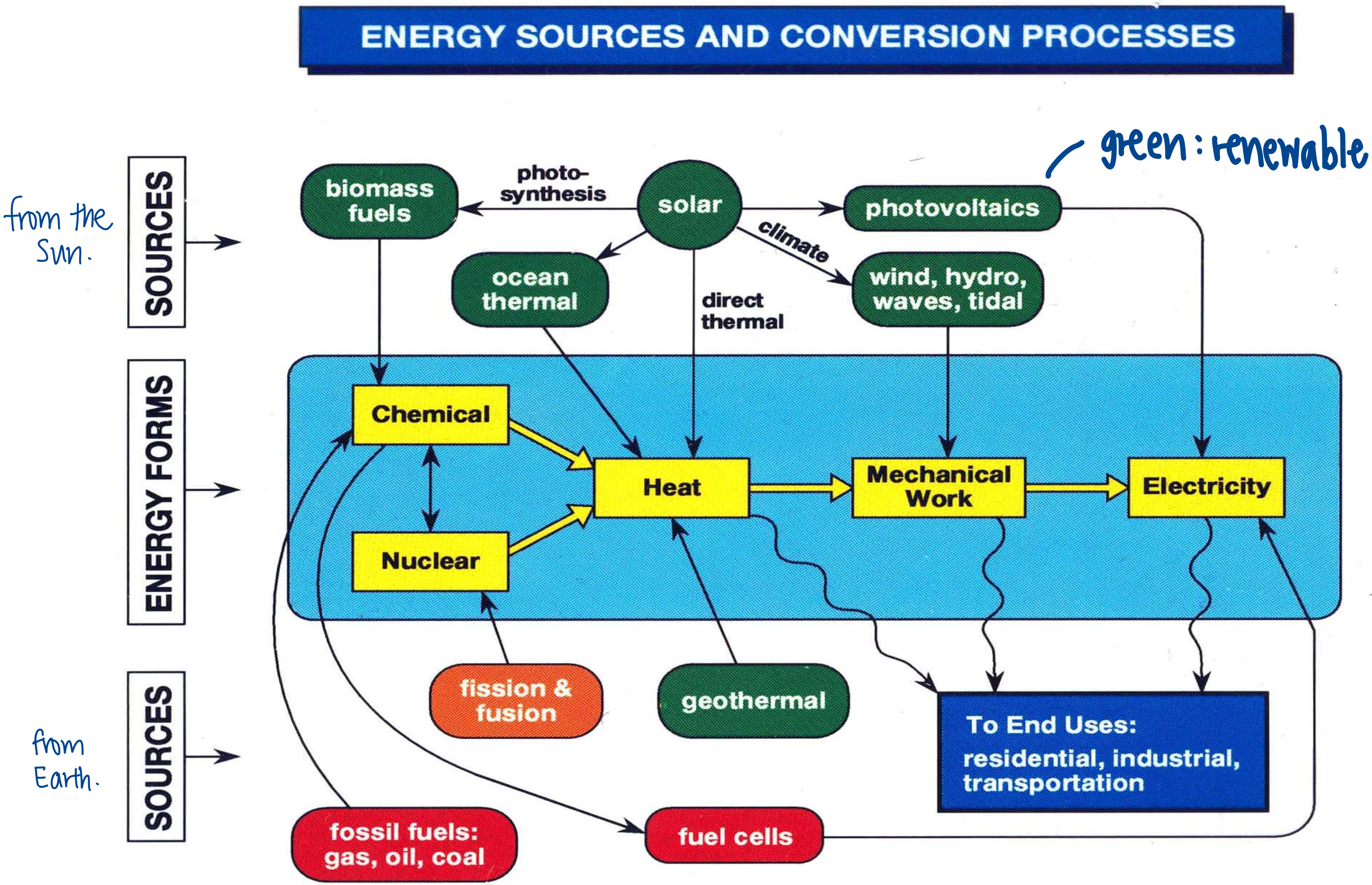
EE4511
Sustainable Energy Systems

Topic 1: Solar Energy Systems

NUS
National University
of Singapore


ENERGY SOURCES AND CONVERSION PROCESSES
green : renewable
from the Sun.
SOURCES
biomass fuels
photo-synthesis
solar
photovoltaics
climate
ocean thermal
direct thermal
wind, hydro, waves, tidal
ENERGY FORMS
Chemical
Heat
Mechanical Work
Electricity
Nuclear
fission & fusion
geothermal
To End Uses: residential, industrial, transportation
from Earth.
SOURCES
fossil fuels: gas, oil, coal
fuel cells

Solar Energy

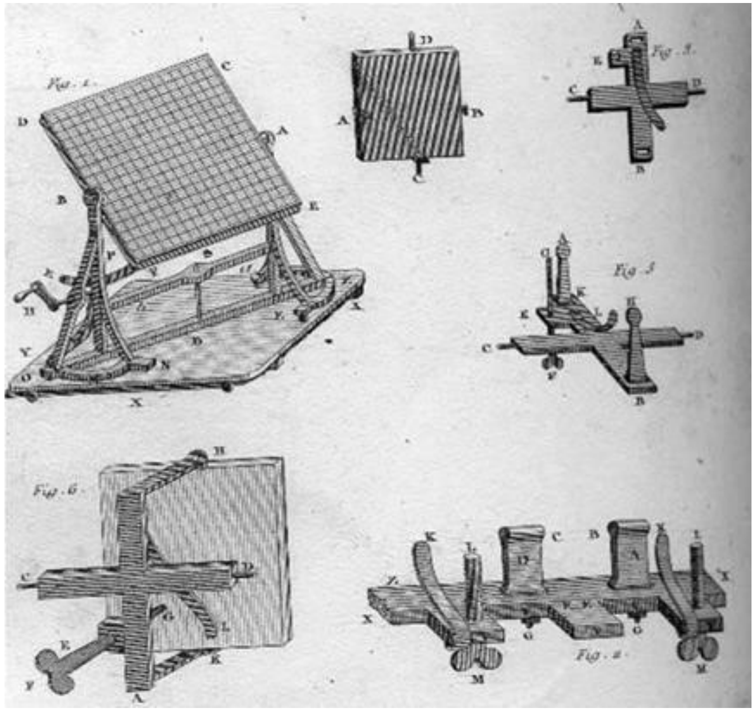
↳ energy from the Sun.

– energy from the Sun.

Solar Energy - History

- 1500 BC Egyptian ruler Amenkotep III supposedly had "*sounding statues*" that emitted a tone when air inside was heated by the sun
- 212 BC Archimedes purportedly used burning mirrors to set fire to ships according to Galen in De Temperamentis

- 1700 AD French scientist, George Buffon, made multiple flat mirrors to concentrate light to a point.
- 1747, he ignited a wood pile 195 ft away (wood ignites at ~250°C with flux of 4.7kW/m^2)
- 1760 Swiss de Sanesure made a solar oven that reached 320°F
- 1860 Bessemer made a solar furnace that melted copper and zinc



- 1860 Augustin Mouchet built "axicons" (simple cone) to focus on a tube; built steam engines with a 40 ft2 reflector
- 1878 William Adams built a 2 kW solar water pump near Bombay, India

photons in sunlight

History of Photovoltaics…

- 1839: Photovoltaic effect was first recognized by French physicist A. E. Becquerel.
- 1883: First solar cell was built by Charles Fritts (1% efficient).
- 1921: **Einstein won the Noble Prize for his explanation of *photovoltaics***.
- The first practical photovoltaic cell was invented at Bell Laboratories in 1954.

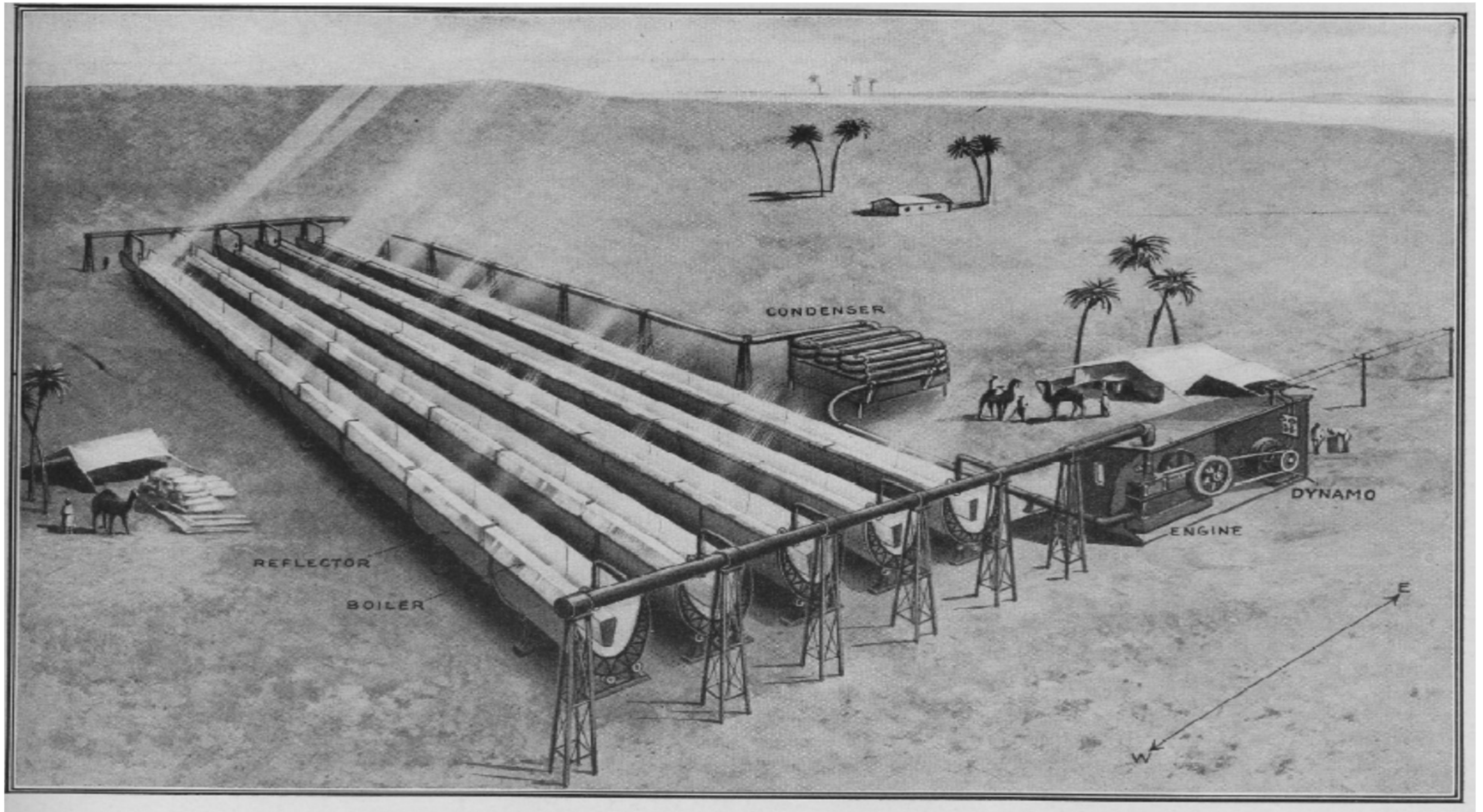
silicon w impurities

The inventors of the Bell Solar Battery, from left, Gerald Pearson, Daryl Chapin, and Calvin Fuller, check devices for the amount of solar electricity derived from sunlight, here simulated by a lamp. http://www.nrel.gov/docs/fy04osti/33947.pdf

Lucent Technologies Inc./Bell Labs

1913 Meadi, Egypt Solar Engine

Shuman used five 60-metre-long **parabolic "troughs",** mirror-lined heat absorbers aligned to track the sun's progress across the sky, to concentrate the rays onto boilers, which then produced sufficient steam to pump 23,000 litres of water a minute.



A Successful 100 H.P. Sun Power Plant Located at Meadi, on the Nile, Egypt.

http://www.solarenergy.com/info_history.html

History – First applications of PV technology

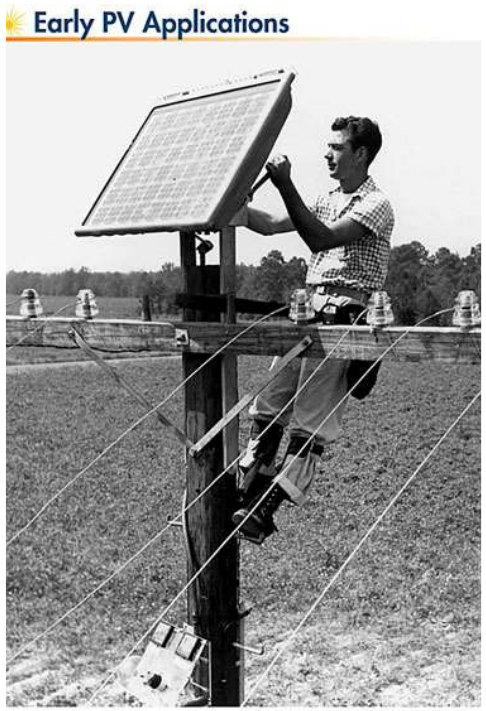
- Nearly every satellite and spacecraft since 1958 has relied on a PV system for power generation.

costs doesn't matter
↳ ↑ efficiency
↳ don't care costs

DOE/NREL, NASA/Smithsonian Institution/ Lockheed Corp.

- Rural communications systems in the 1950s were the first terrestrial applications of PV technology.

costs matters!!!
↳ only when costs ↓, then applied to terrestrial purposes



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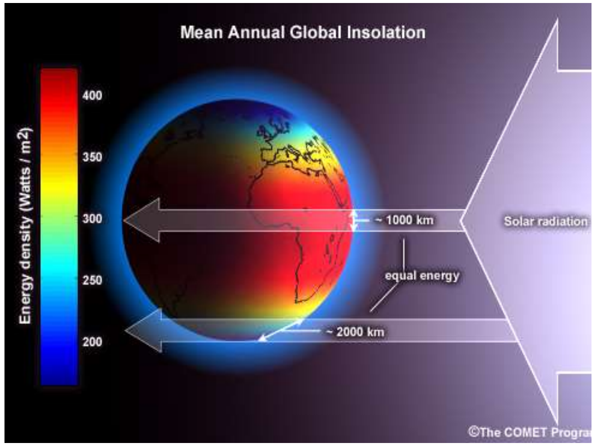
How Much Solar Energy Strikes the Earth?

How Much Solar Energy Strikes Earth?

- The sun emits 6.2×10^7 W/m^2 (62mil W/m^2)
- The earth intercepts part of this energy corresponding to the earth's diameter
- The amount of power crossing earth's orbit is **1388 watts / m^2**

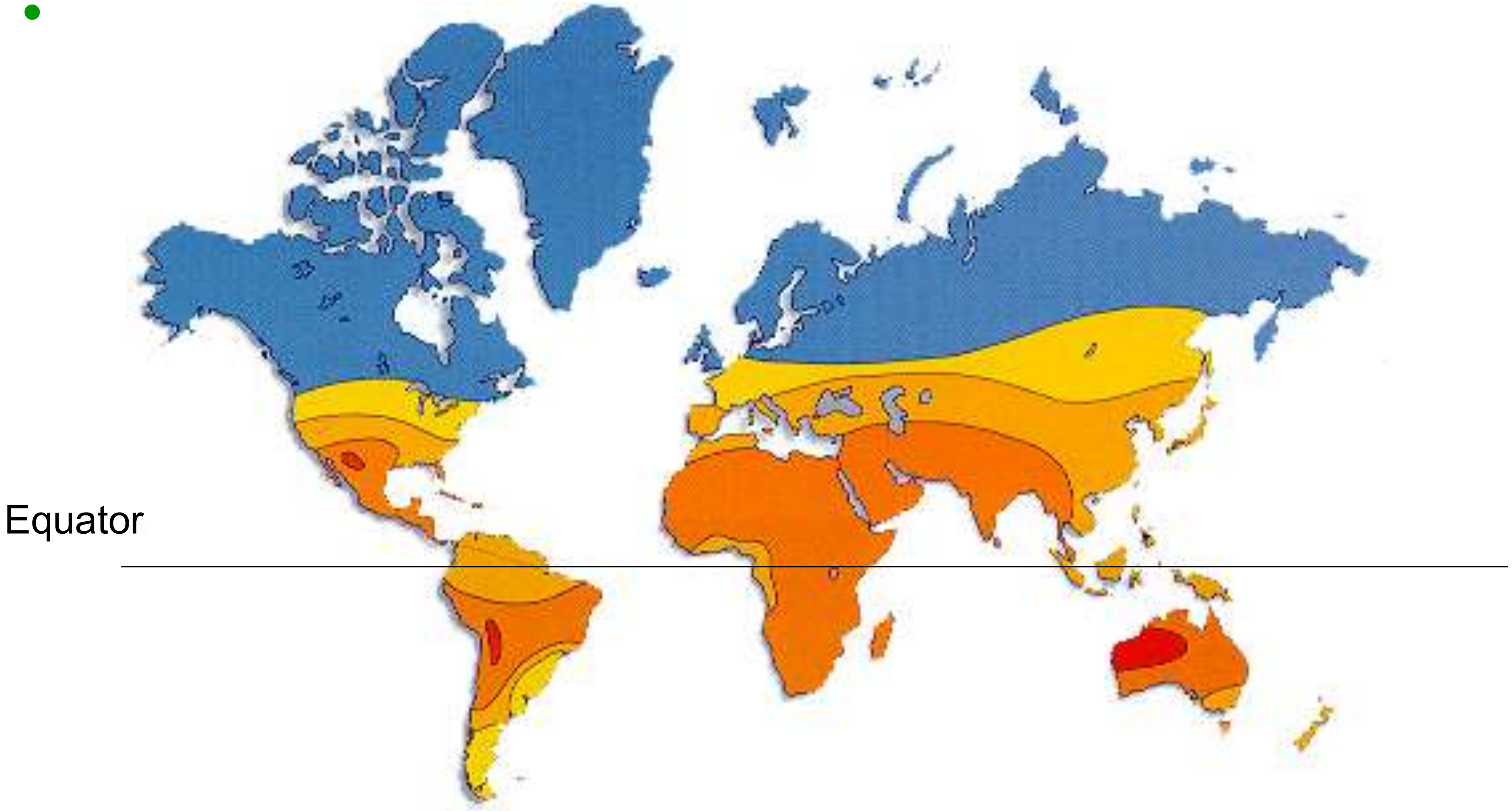


173,000TW

- A total of 173,000 terawatts (trillions of watts) of solar energy strikes the Earth continuously, out of which approximately 36,000 TW strikes the land
- **That's more than 10,000 times the world's total energy use.**

We could use some of this energy without depleting the sun!

How Much Sun is there in the World?



Every hour the sun beams onto Earth more than enough energy to satisfy global energy needs for **an entire year**

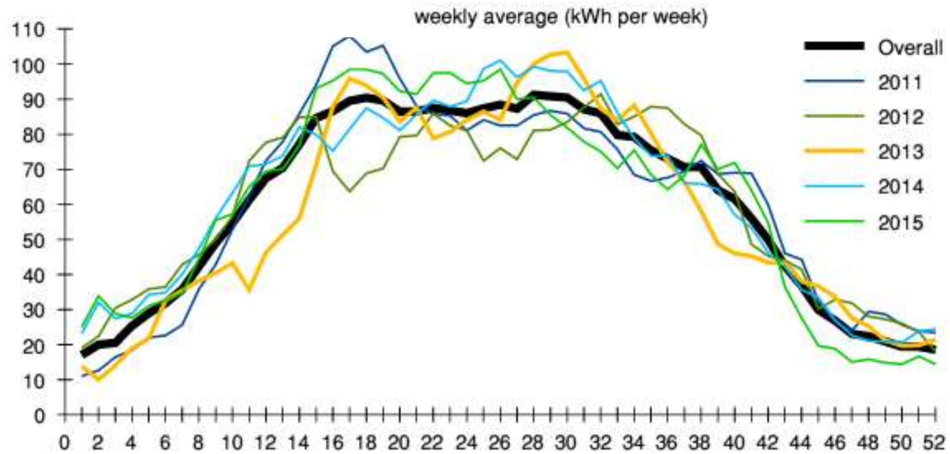
http://www.oksolar.com/images/world_performance.gif

Solar Energy Overview

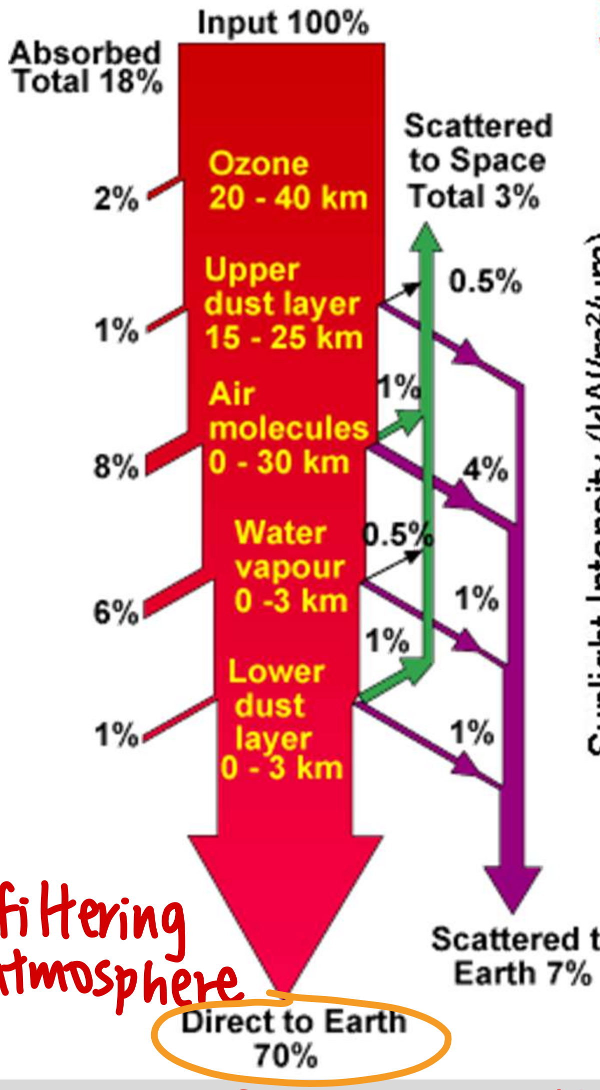
While the energy from the Sun is free, it costs money to collect it

- Solar energy is best suited for sunny places to be able to save enough to pay off the equipment investment
- Climate records show the availability of this solar energy

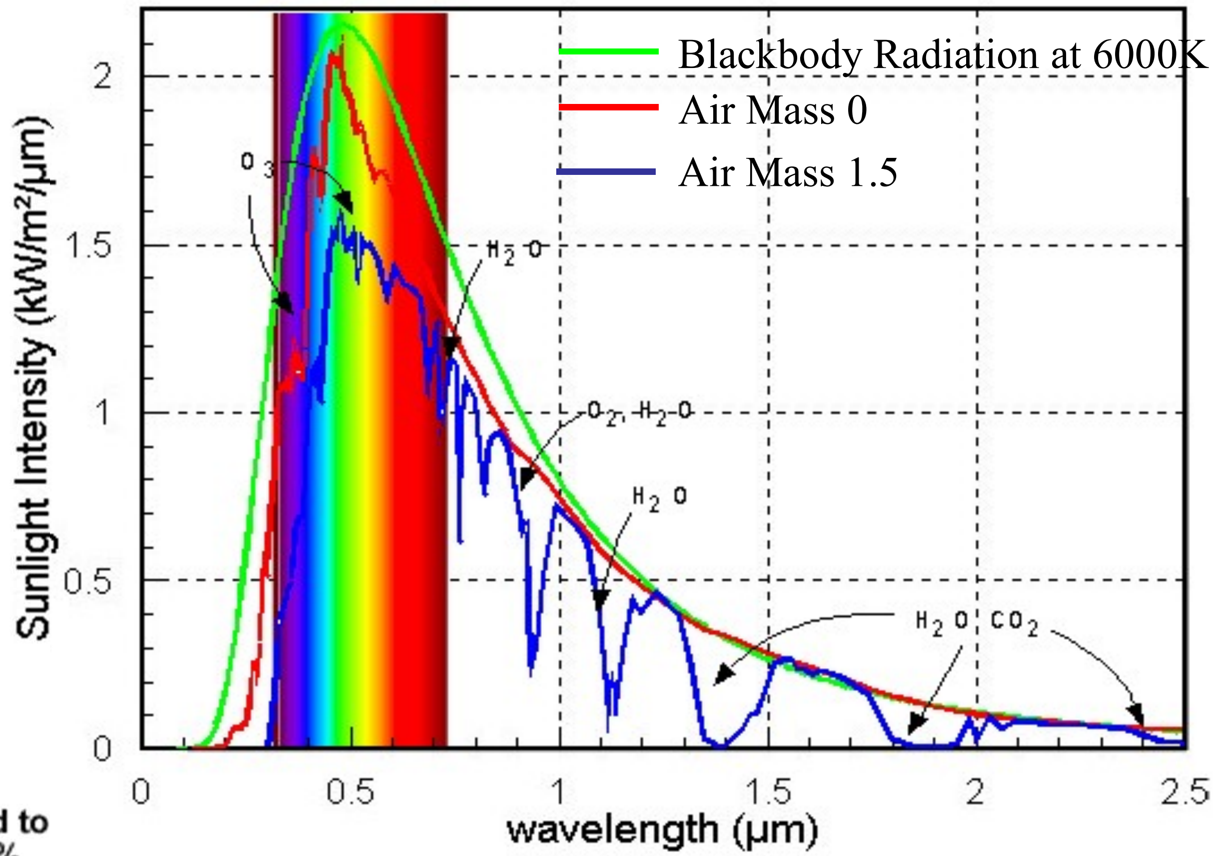
- The **variability** must not be ignored when designing a system
- Like all climates, the statistical variability requires that a "long" sample be used, perhaps five years to fifty years



Solar Spectrum



after filtering through atmosphere

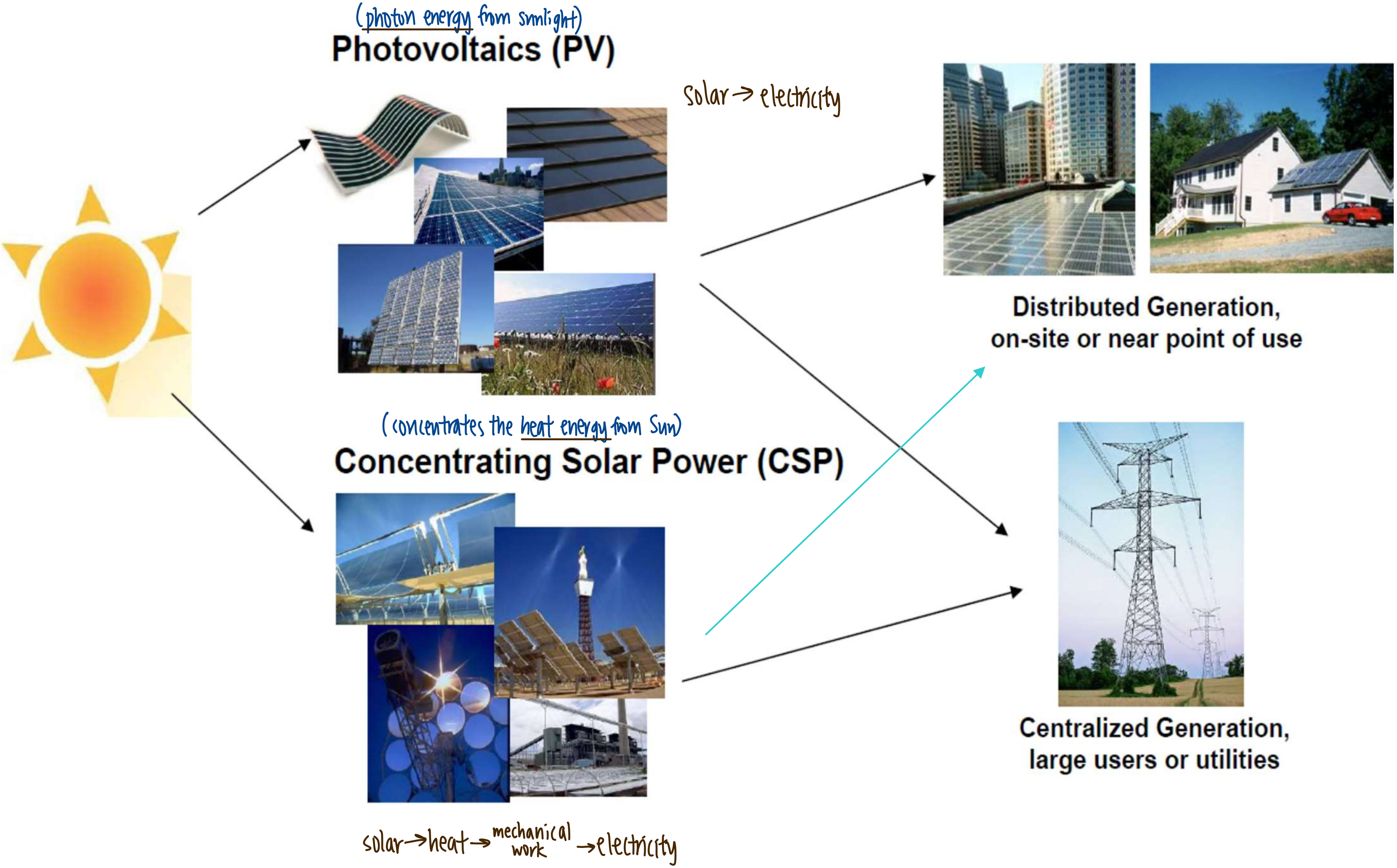


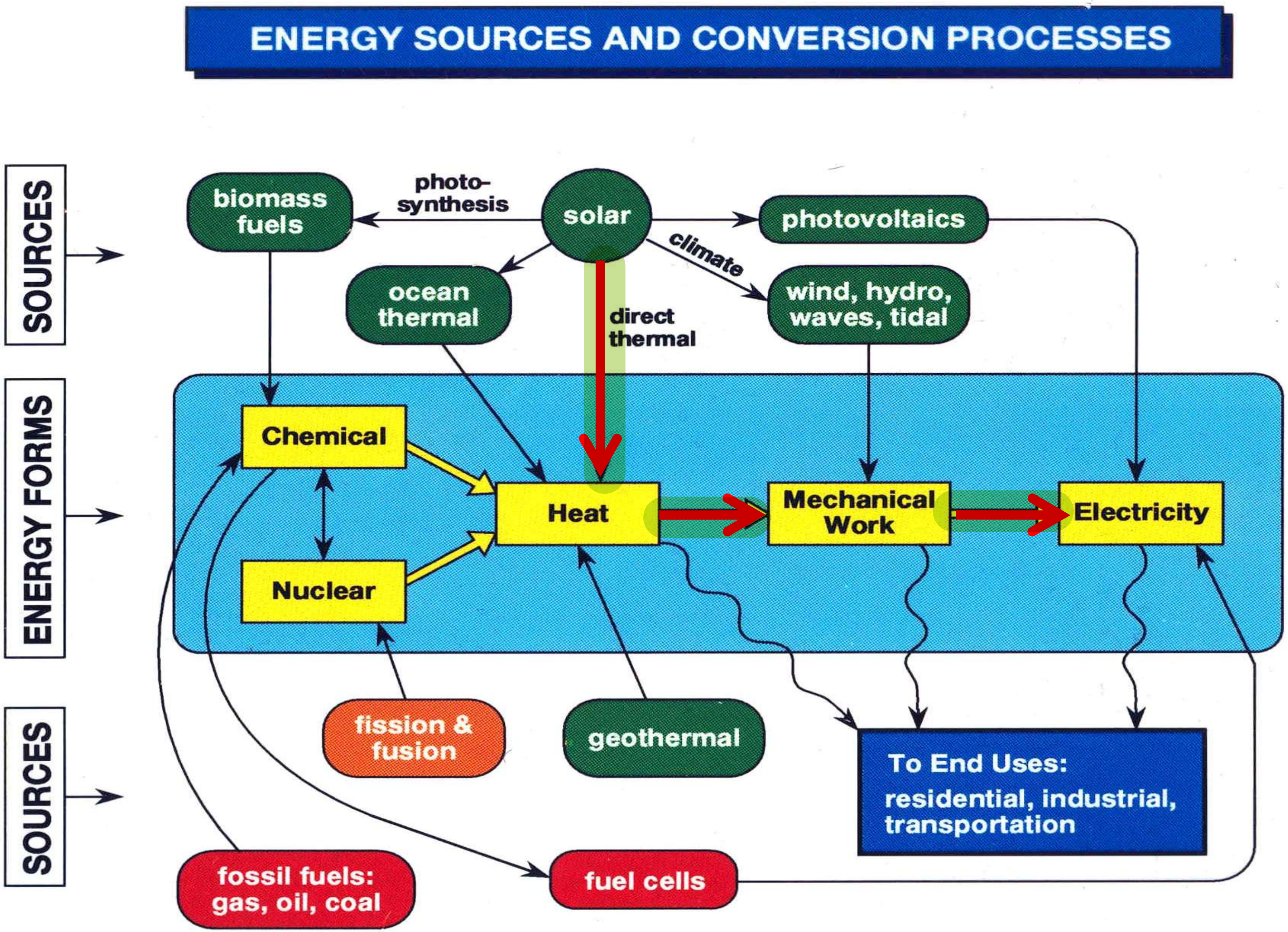
~70% of the amount entering Earth's atmosphere

- Energy from our sun (1388 W/m^2) is filtered through the atmosphere and is received at the surface at ~1000 watts per square meter or less; **average is 345 W/m^2**
- Air, clouds, and haze reduce the received surface energy

Left: Hu, C. and White, R.M., "Solar Cells: From Basic to Advanced Systems", McGraw-Hill, New York, 1983; Right: http://pvcdrom.pveducation.org/

Generating Electricity from the Sun

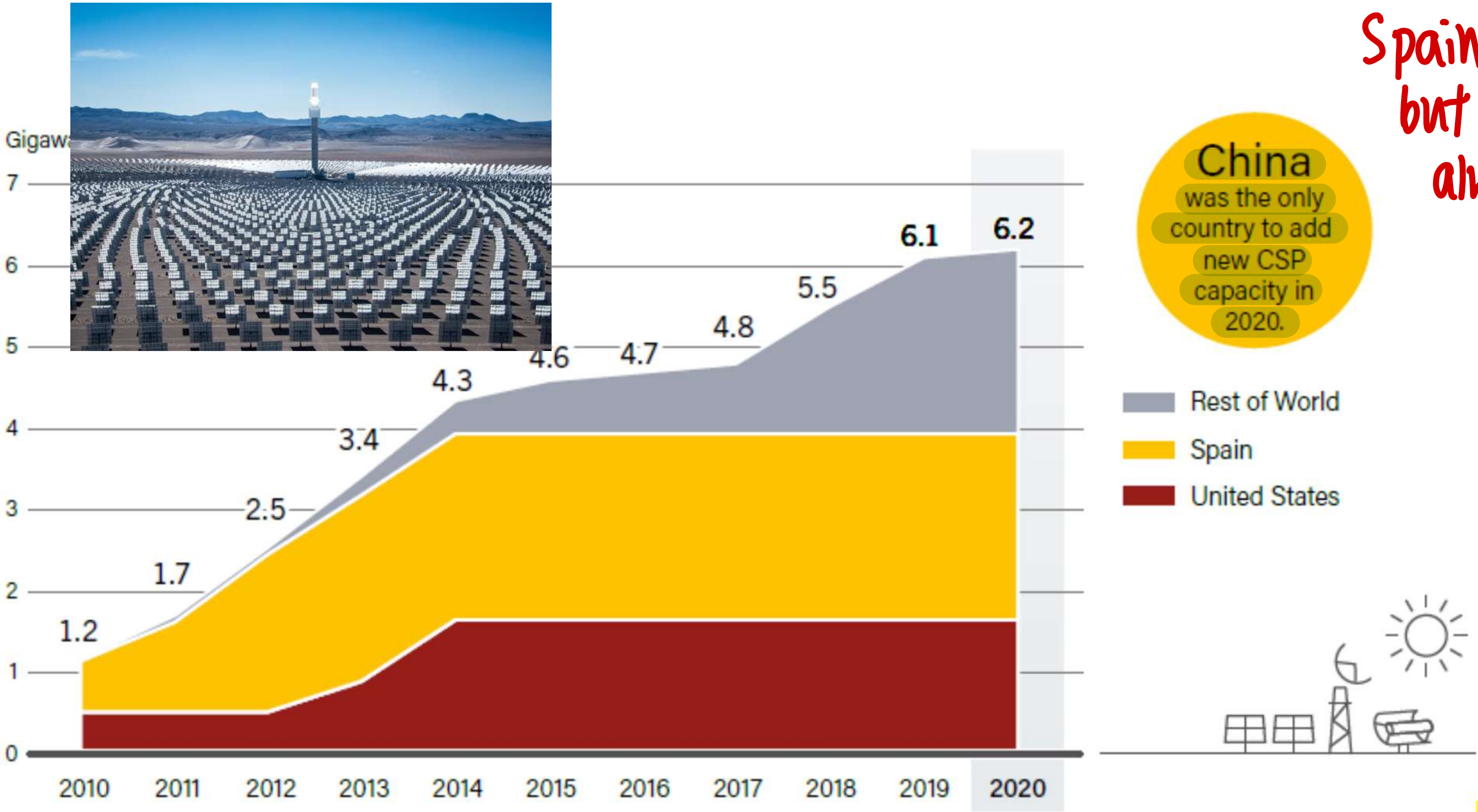




Solar Thermal Power Generation

Concentrated Solar Thermal (CSP) : Cumulative installed power

Spain still leader, but stagnant already...



- About 100 MW of Concentrating Solar Thermal Power (CSP) came online in 2020, increasing the global capacity to 6.2 GW
- **Spain is the world leader**

Source: Ren21's Renewables – 2021 Global Status Report

Concentrating Solar Power (CSP)

- **Solar thermal systems convert sunlight to heat**
- Categorized by reflector/collector types
  - None; uses **lens**; regular or Fresnel
  - **Flat mirror** (possibly many of them)
  - **Parabolic**/cylindrical: single axis forms "trough"
  - Paraboloidal: axis of revolution forms **"dish"**
  - Spherical: approximates paraboloid, but focus can move to track sun

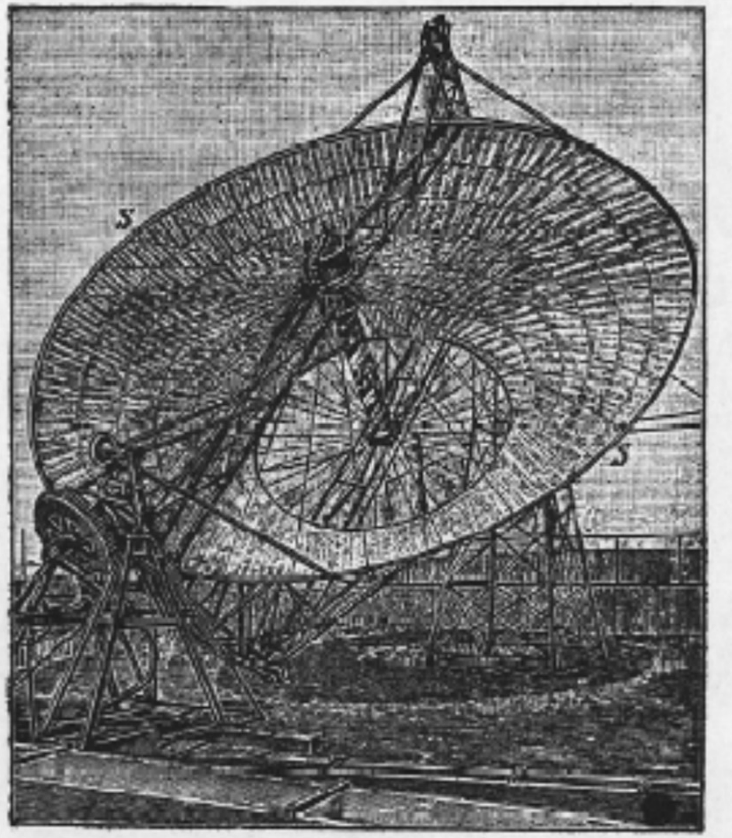
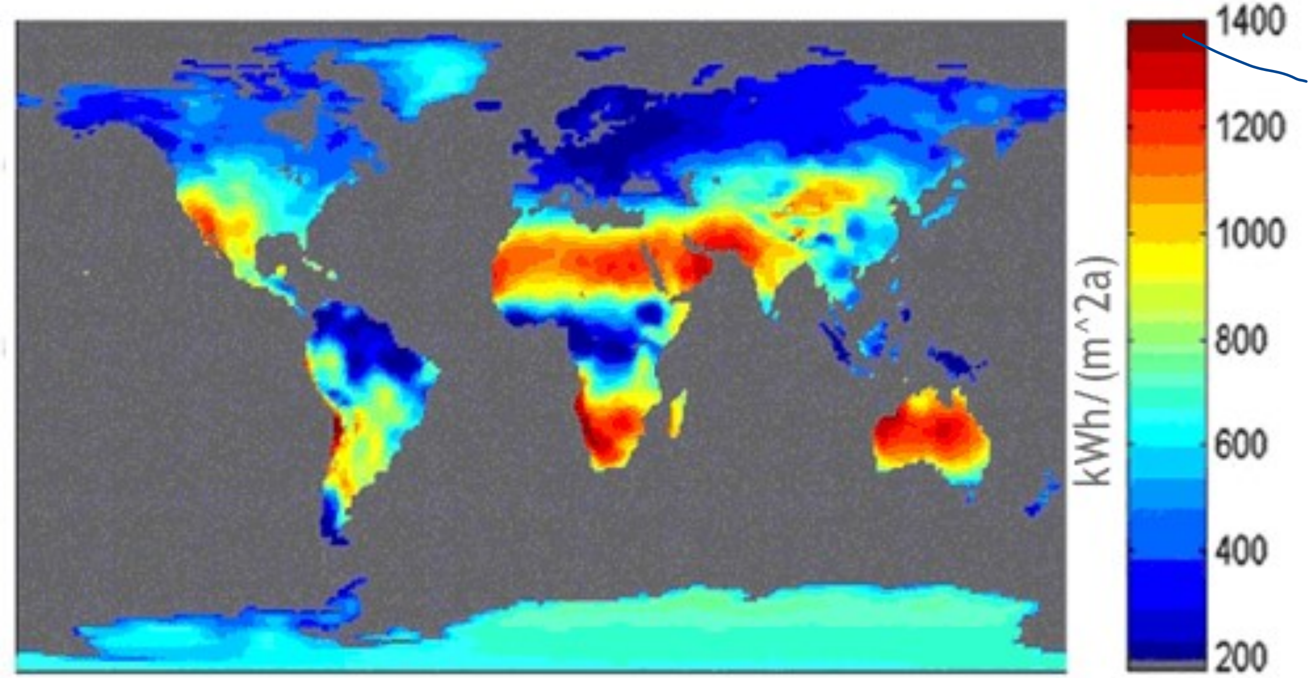


Fig. 1. Common Form of Sun Motor Adopted by Experimenters, Utilizing a Large Number of Mirrors and a Central Boiler.

Solar Energy: Thermal

Quality of heat; the value in temperature

- Low-temperature extraction of heat from ground; ~20 to 30° C
- Water heating for home and business; ~35° C to 50° C
- High-temperature process-heating water for industry; ~100° C to 200° C
- **Solar thermal power plants; ~400° C or higher**



Suitable for solar thermal power plants.

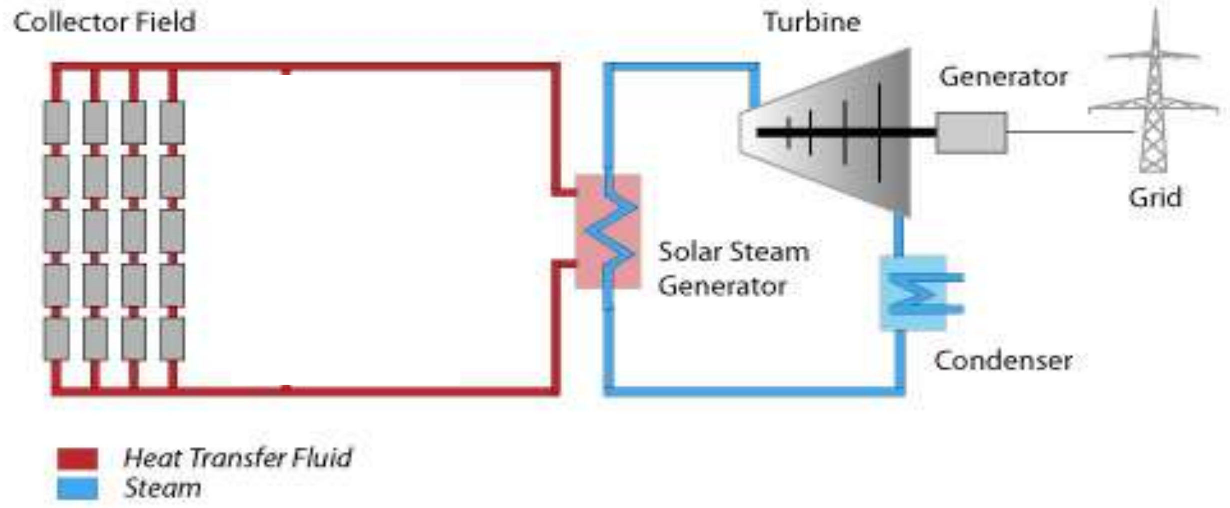
Solar → thermal → mechanical → electrical energy

Introduction & Principles

Solar thermal power plant comprises **power plants** which first convert solar radiation into heat. The resulting thermal energy is subsequently transformed into mechanical energy by a thermal engine, and then converted into electricity.

For thermodynamic reasons high temperatures are required to achieve the **utmost efficiency**. Such high temperatures are reached by increasing the energy flux density of the solar radiation incident on a collector.

*Concentrated radiation or concentrating collectors



Types of Solar Thermal Power Plants

According to the type of solar radiation concentration, solar thermal power plants are subdivided into:

Concentrating (point and line focussing systems)

- type of receiver of the solar radiation
- the heat transfer media and the heat storage system
- additional firing based on fossil fuel energy

Non-concentrating systems

- solar updraft tower power plants
- solar pond power plants

most recent, not as well-established

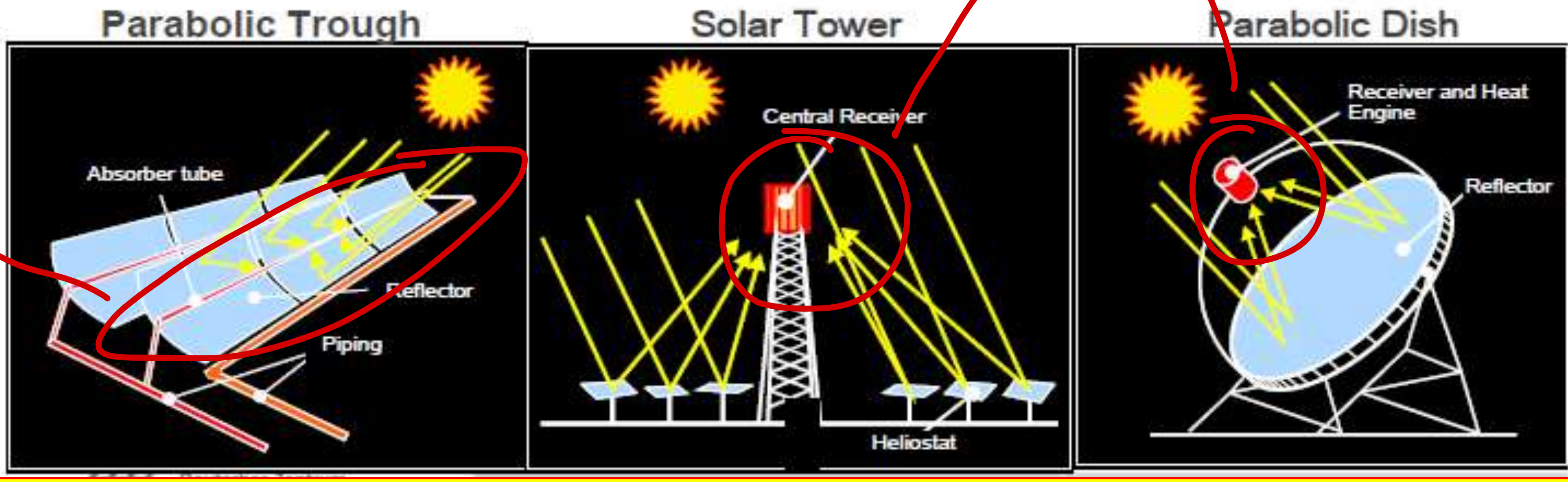
Concentrating systems

oldest

- **Parabolic trough and Fresnel trough power plants**
  - as line focussing power plants.
- **Solar tower power plants**
  - (i.e. central receiver systems) as point focussing power plants,
- **Dish/Stirling systems**
  - as point focussing power plants

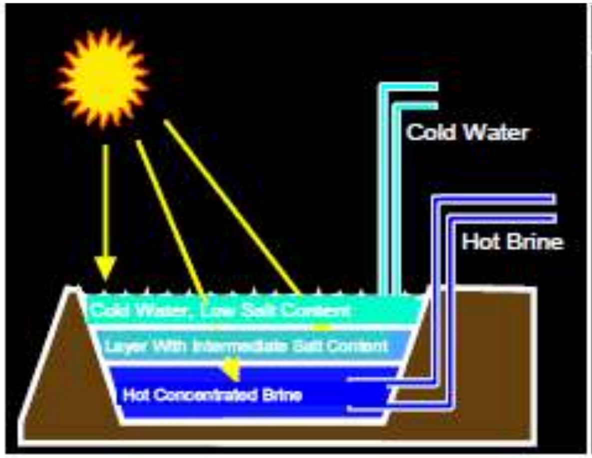
at a point

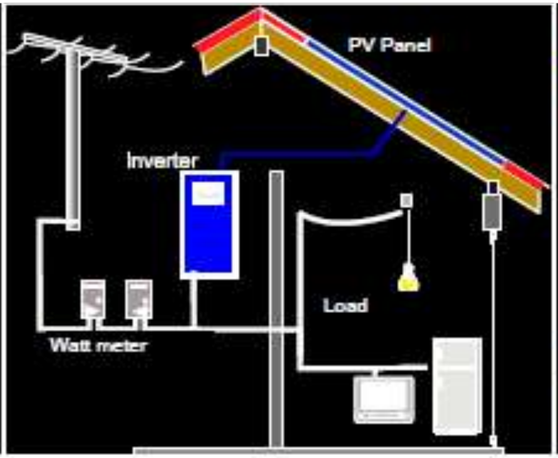
along a line

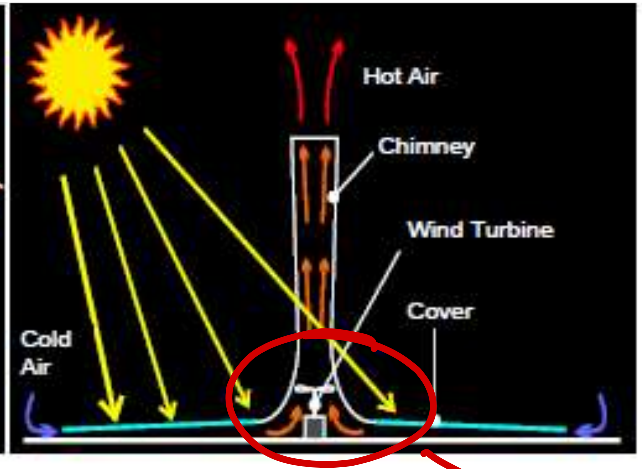


All operate somewhat alike:
- **Use lenses and reflectors to concentrate solar power.**
- **Heat drives thermal power plant**

Non-concentrating systems







spins the turbine

Solar Pond | Solar Photovoltaic Systems | **Solar updraft Tower**

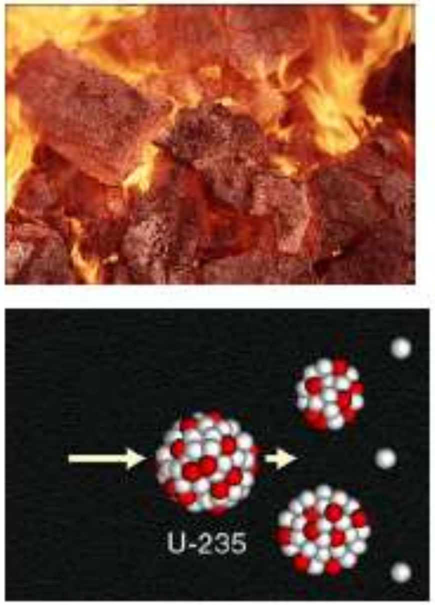
A solar pond - is simply a pool of saltwater which collects and stores solar thermal energy.

good insulator of heat

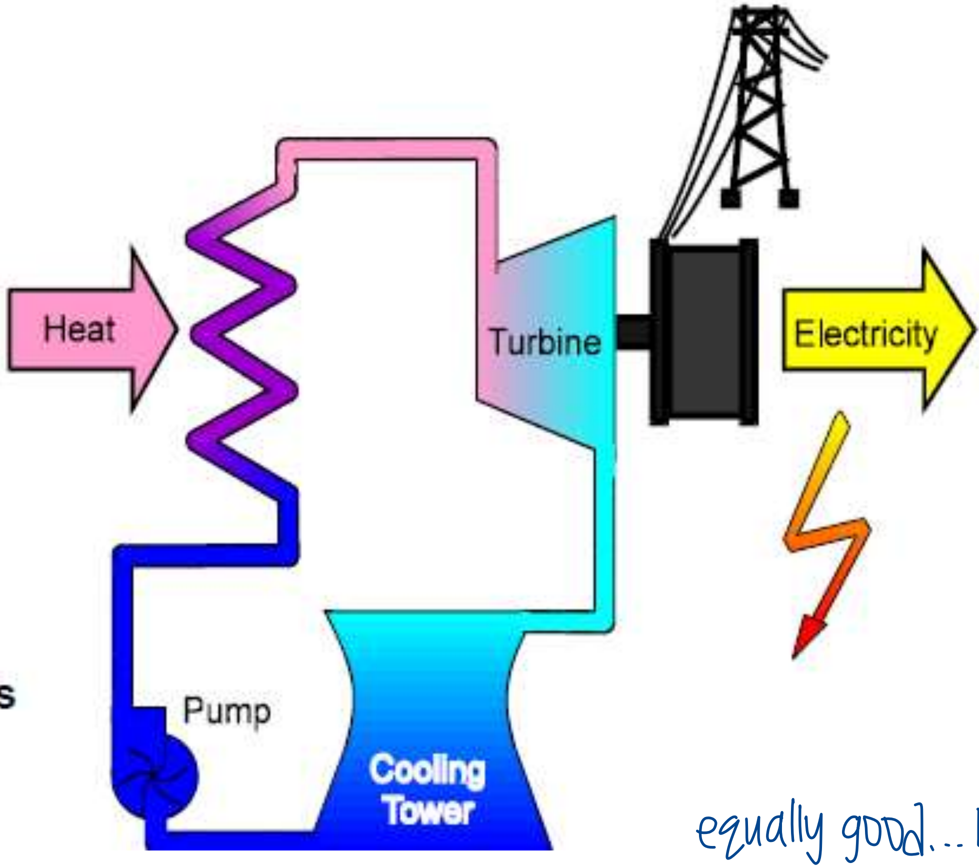
Updraft tower - Sunshine heats the air beneath a very wide greenhouse-like roofed collector. The resulting convection causes a hot air updraft in the tower by the chimney effect.

Solar Energy: Thermal

Why Concentrating Solar Technologies ?



Conventional power plants



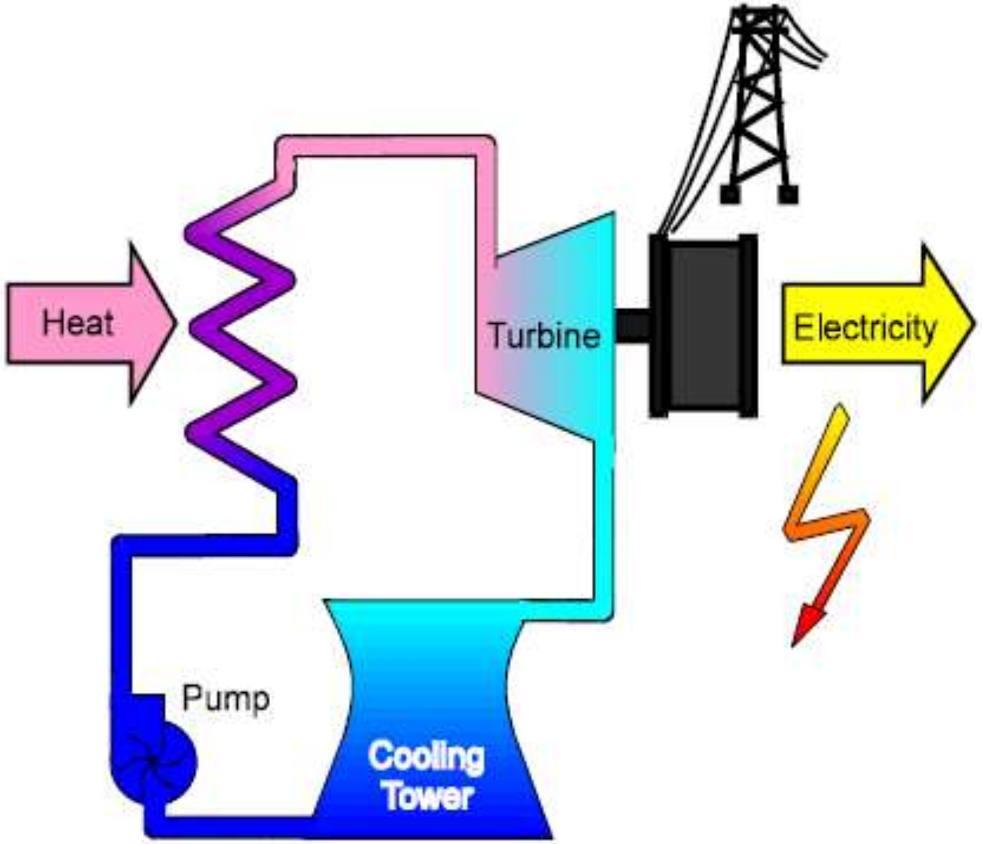
equally good... but renewable!

Concentrating collectors can reach temperature levels similar to those of existing fossil-fuel fired thermal power stations (e.g. power plants fired with coal or natural gas)

Solar Energy: Thermal

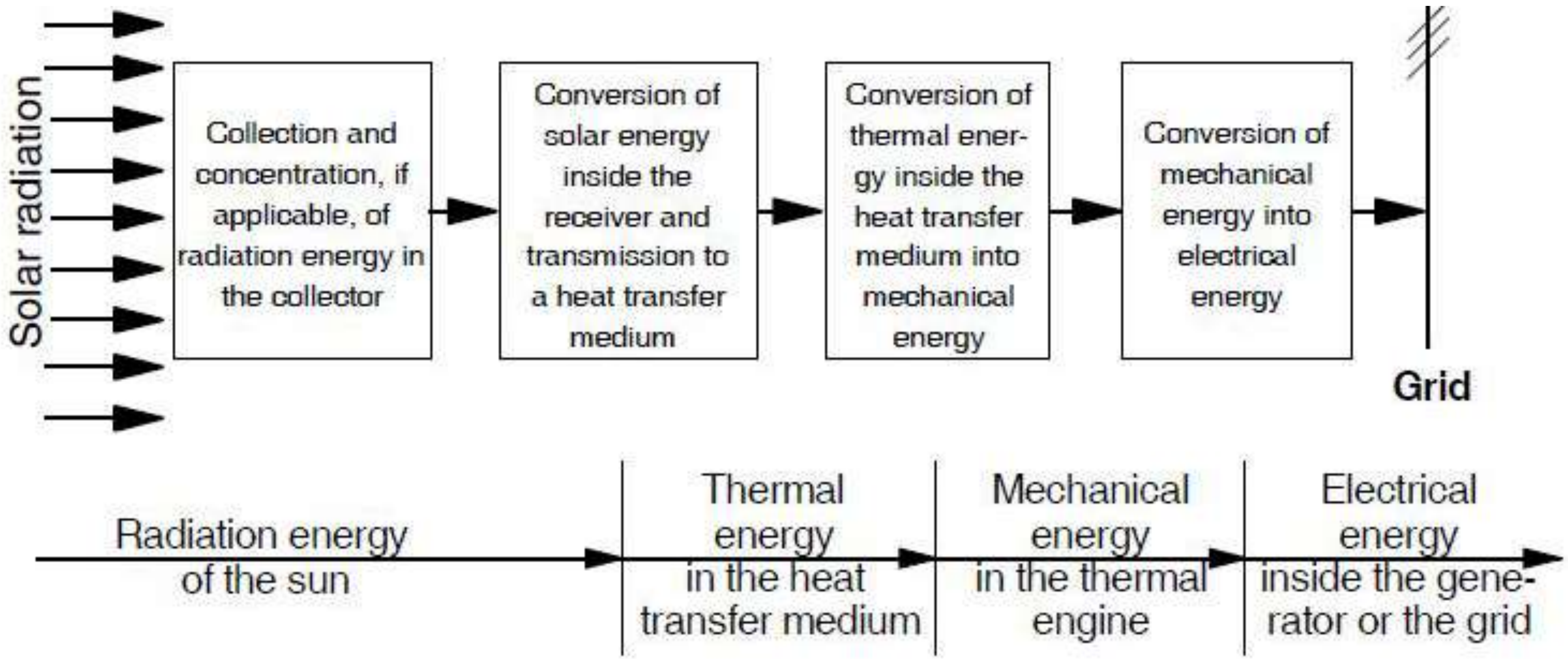
Why Concentrating Solar Technologies ?

Solar thermal power plants



It is a system where solar radiation is concentrated and then converted into thermal energy at medium/high temperature (300ºC – 800ºC).
This thermal energy is then used in a thermodynamic cycle to produce electricity.

Process Of Solar Thermal Power Generation



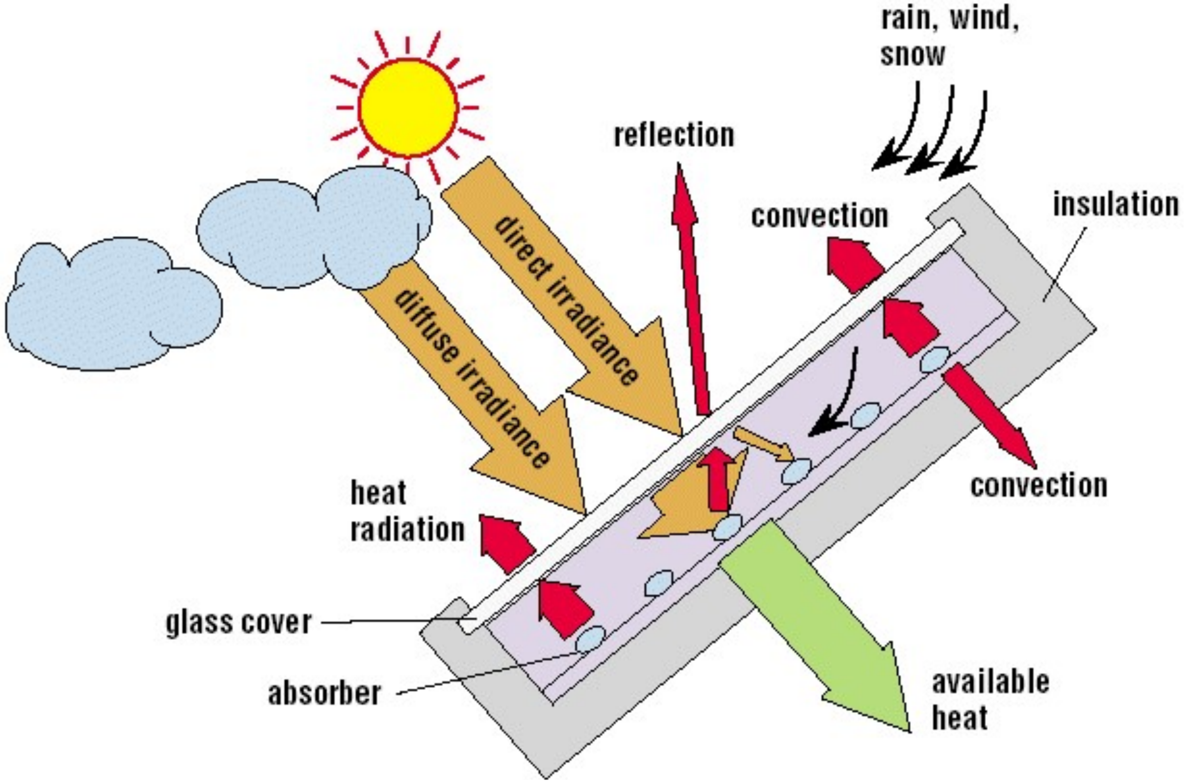
- Concentrating solar radiation by means of a collector system;
- Increasing radiation flux density (i.e. Concentrating of the solar radiation onto a receiver);
- Absorption of the **solar radiation** (i.e. Conversion of the radiation energy into thermal energy (i.e. Heat) inside the receiver);
- Transfer of **thermal energy** to an energy conversion unit;
- Conversion of thermal energy into **mechanical energy** using a thermal engine (e.g. Steam turbine);
- Conversion of mechanical energy into **electrical energy** using a generator.

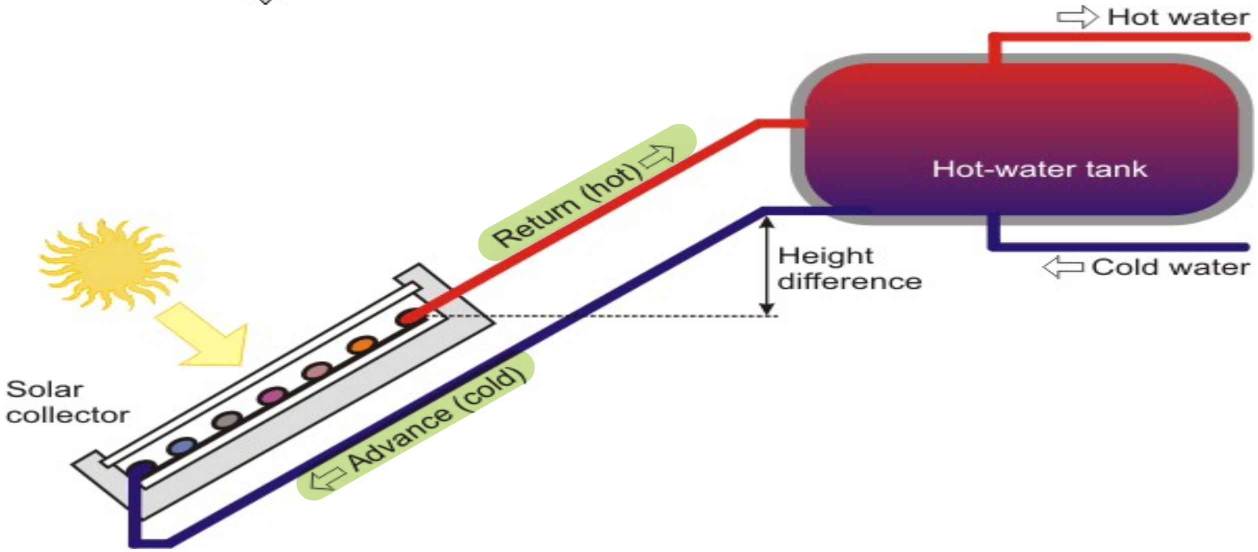
Solar Energy: Thermal

- The intense solar radiation needed to produce electricity from thermal energy **requires solar concentrating** systems.
- The energy thus collected is used to heat working fluids or materials that are then used to produce electricity
- CSP industry is pursuing multiple approaches to intermediate load power markets

These systems are complex to build, so they are only feasible for utility-scale power plants. $$$$

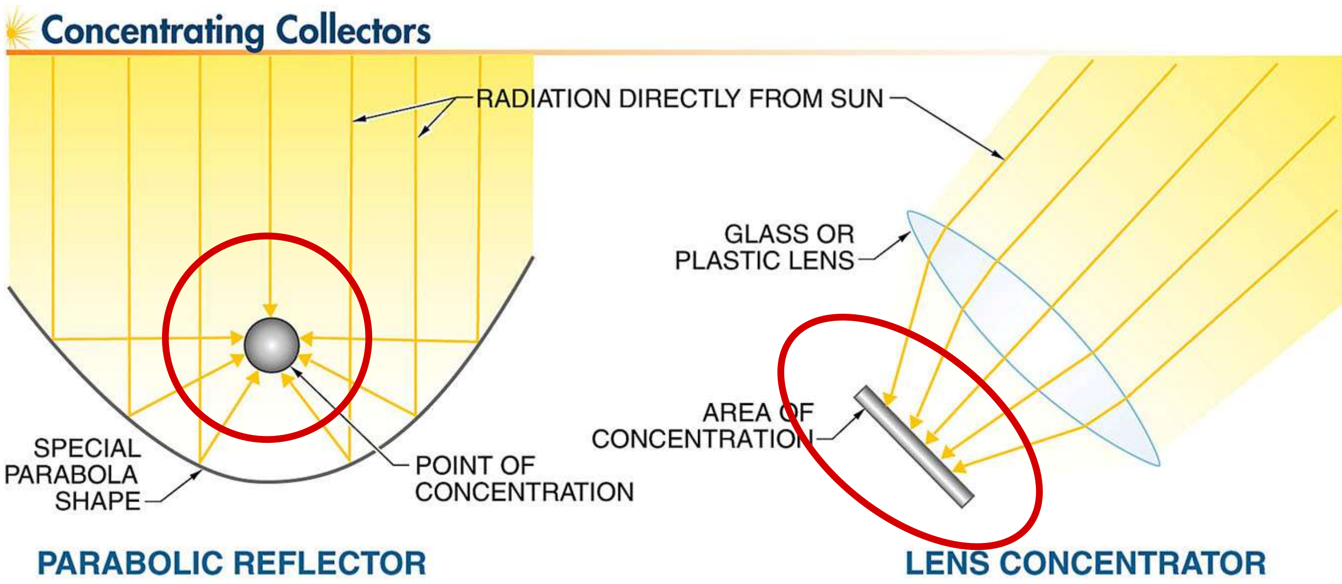
Processes at a flat-plate collector





Solar Energy: CSP

•Concentrating collectors focus a large area of direct solar radiation onto a relatively small area.



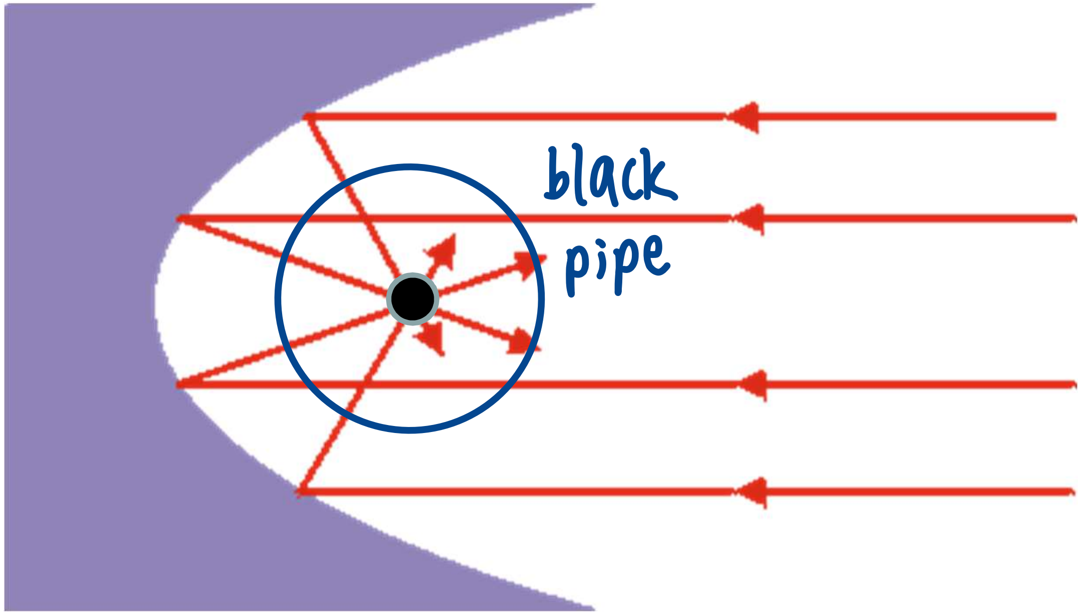
Concentrating collectors have increased efficiency and reduced size because of the ability to channel more solar radiation onto the desired surface

CSP Techniques:

1. Parabolic Trough

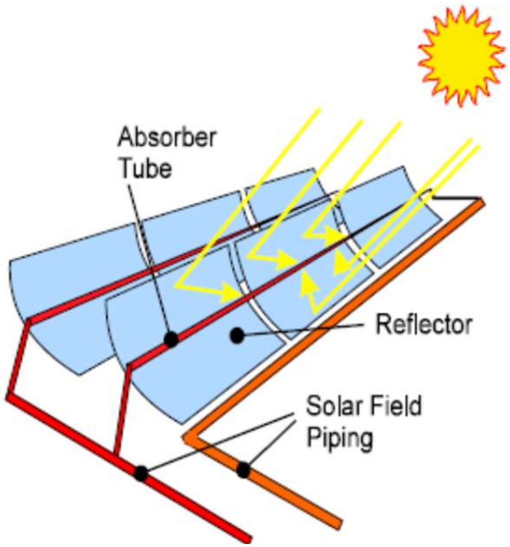
Parabolic Troughs

- **Focuses parallel rays to a line**
- A black pipe is placed with its center at the focus
- Cylindrical reflector approximates the parabolic shape



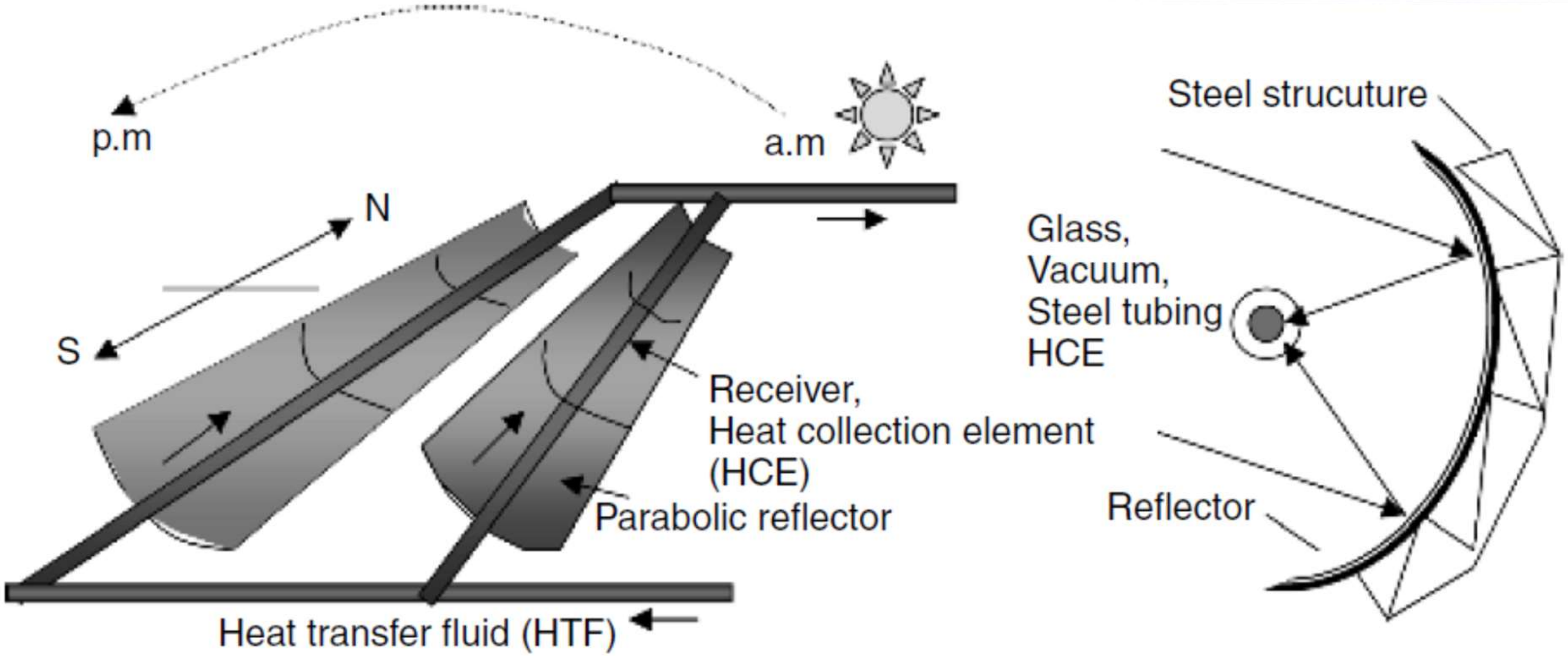
↳ needs mechanism to rotate the troughs such that the surface faces the Sun at all times ⇒ maximises efficiency!

Trough

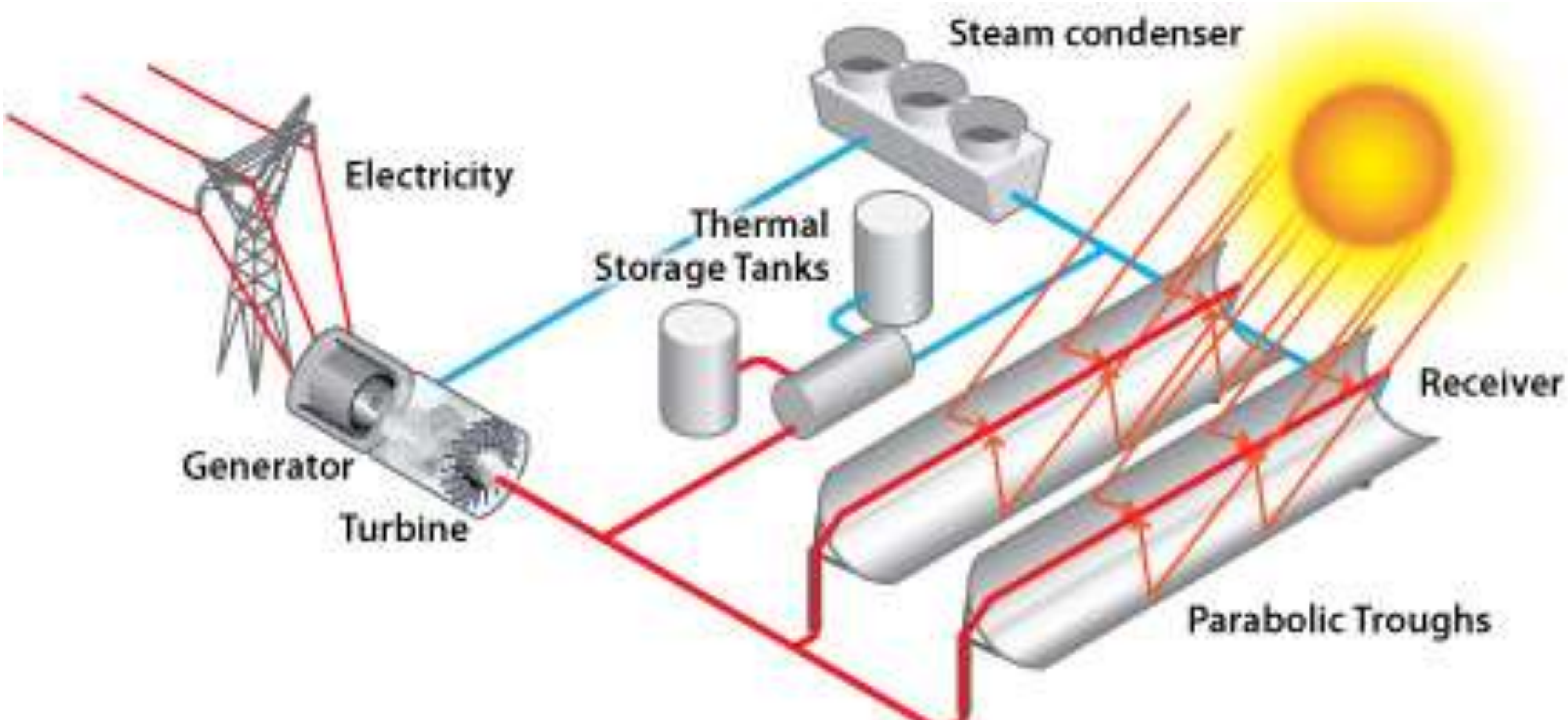


Parabolic Troughs: SEGS (Solar Electricity Generation System)

- SEGS consists of nine large arrays of rows of parabolic-shaped mirrors
- Installed in Mojave desert in California

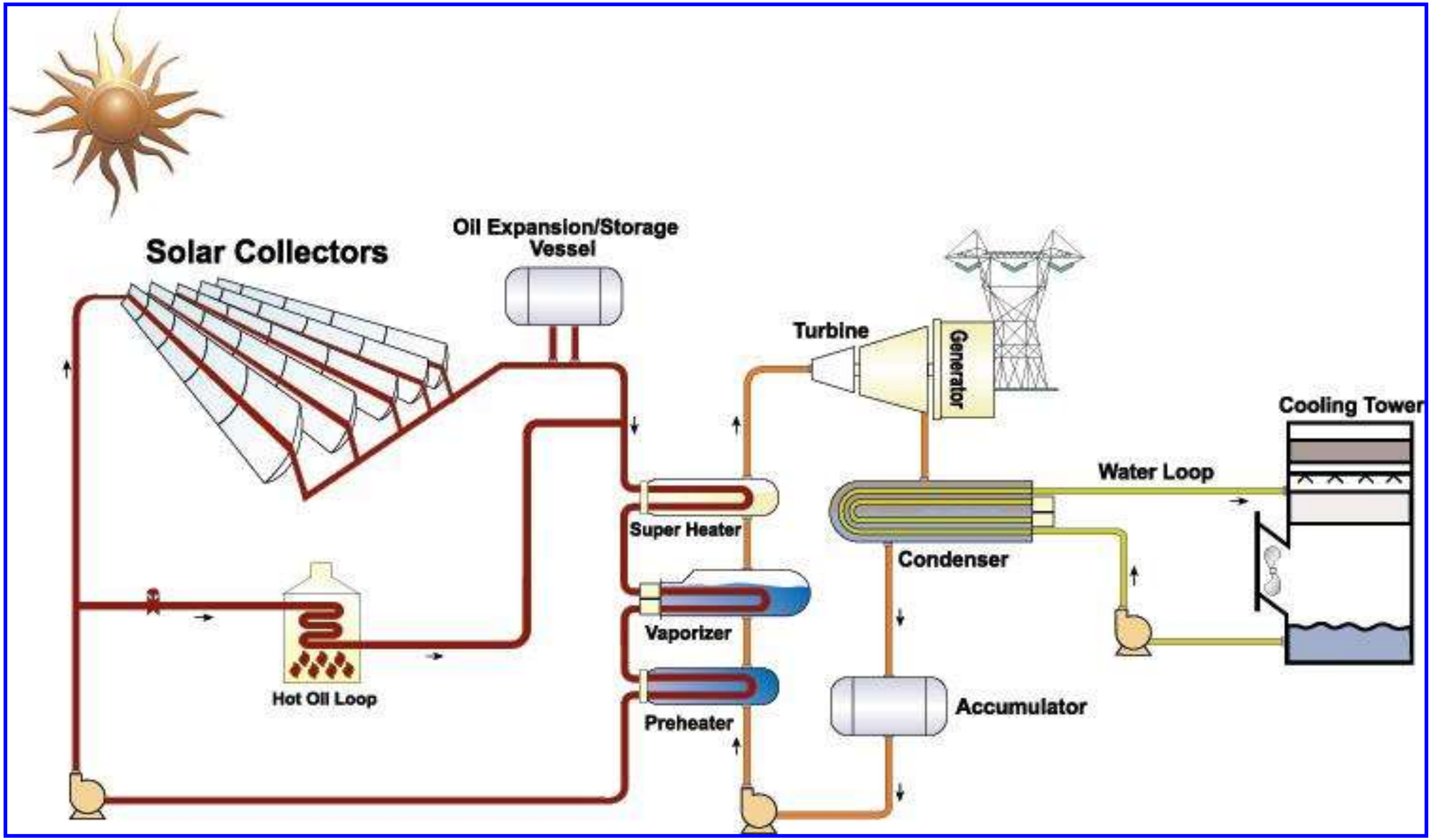


Parabolic Troughs: SEGS



- Made of long rows of concentrating mirrors
- Tracks the sun from East to West with surface that focuses sun's energy
- Heat transfer fluid runs through pipe that is at the focus of the troughs
- Heat is transferred to working fluid (usually water) and used to drive turbine

Complete Parabolic Trough System



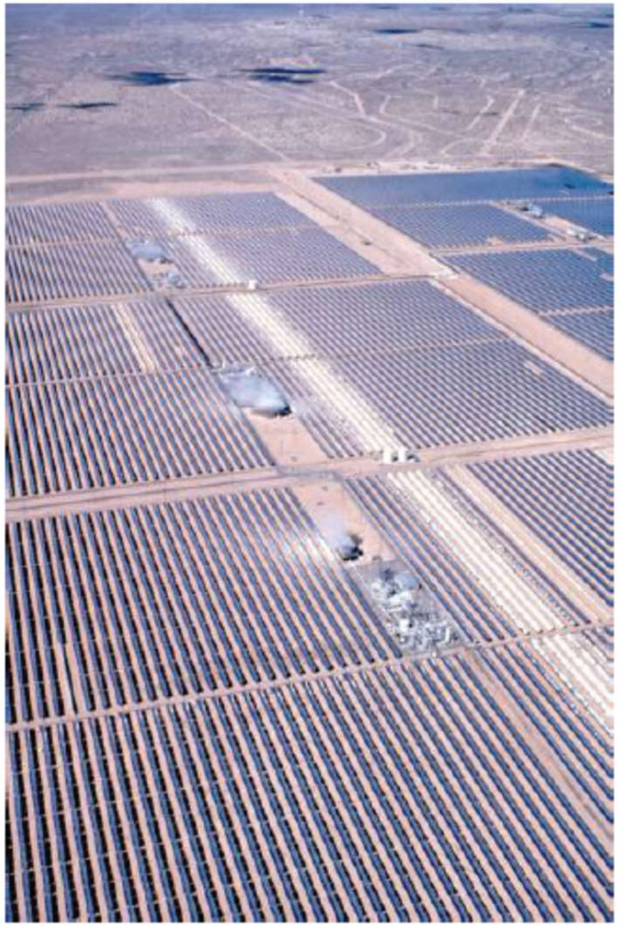
Source: Solel

Solar Parabolic Trough Systems

prevents shadowing

- Arrays need to be **spaced apart** to keep one row from shadowing the next row
- **High water demand** - Cooling water is needed for condensers
- Annual solar-to electricity efficiency is around **10-15%**
- **Least expensive** source of solar electricity
- Sizes from 100kW – 400 MW

Solar Parabolic Trough System
Mojave Desert, USA



- **Solar Energy Generating Systems (SEGS)** in California has the **combined capacity of 354 MW from three separate locations** (total 9 plants)
- Technology – Parabolic trough, no storage
- **Capacity factor – 21%**
- In operation since 2011
- Provides power to 400,000 homes

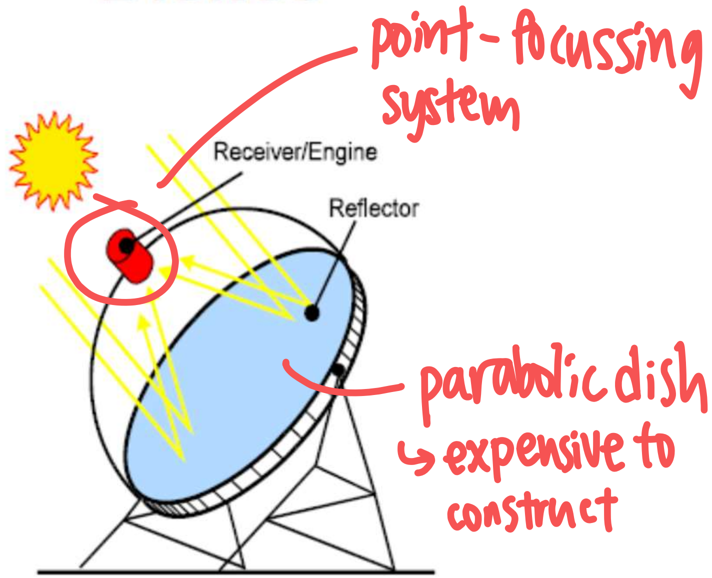
CSP Techniques:

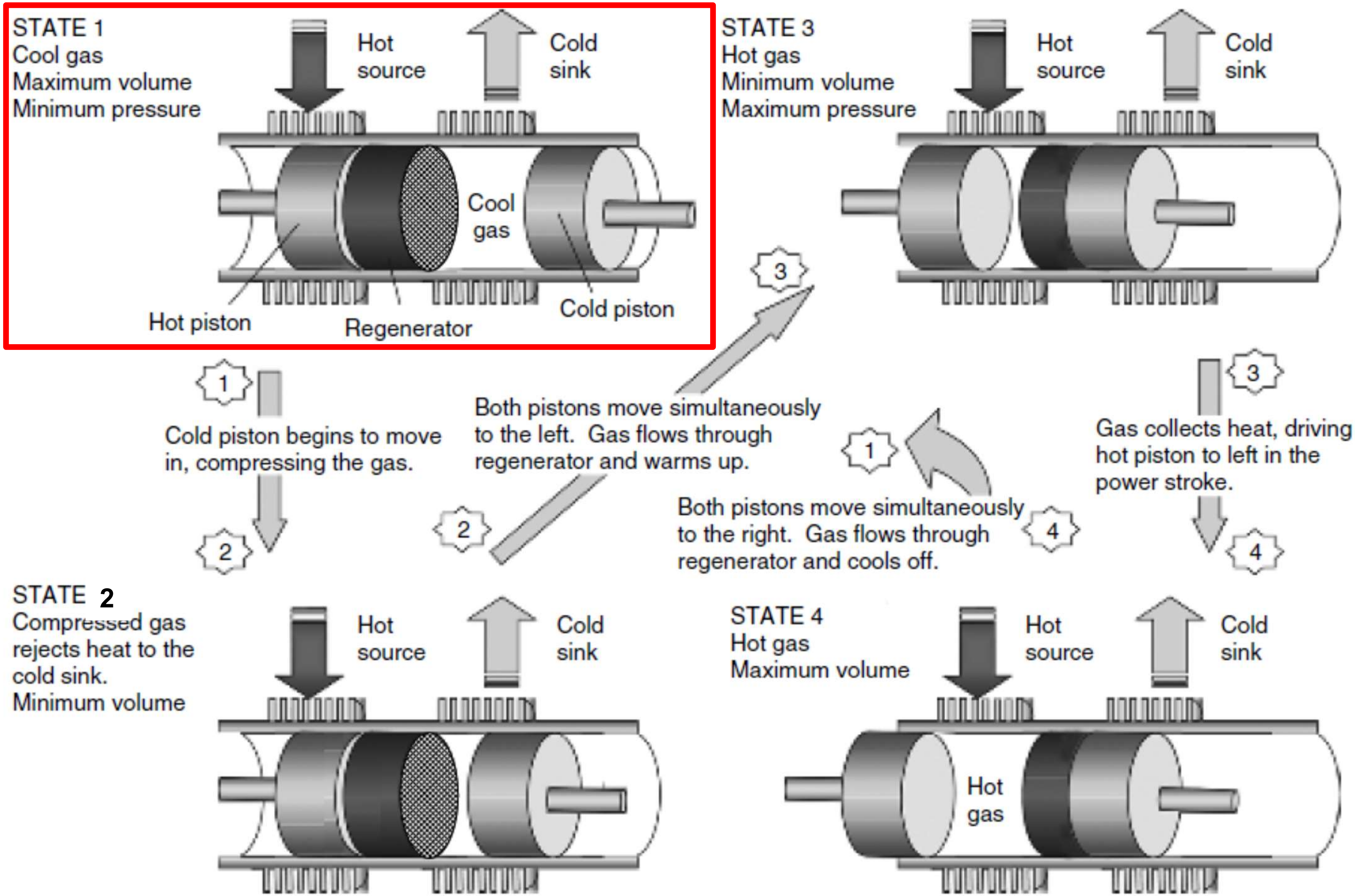
2. Stirling Dish Systems

Solar Dish/Stirling Systems

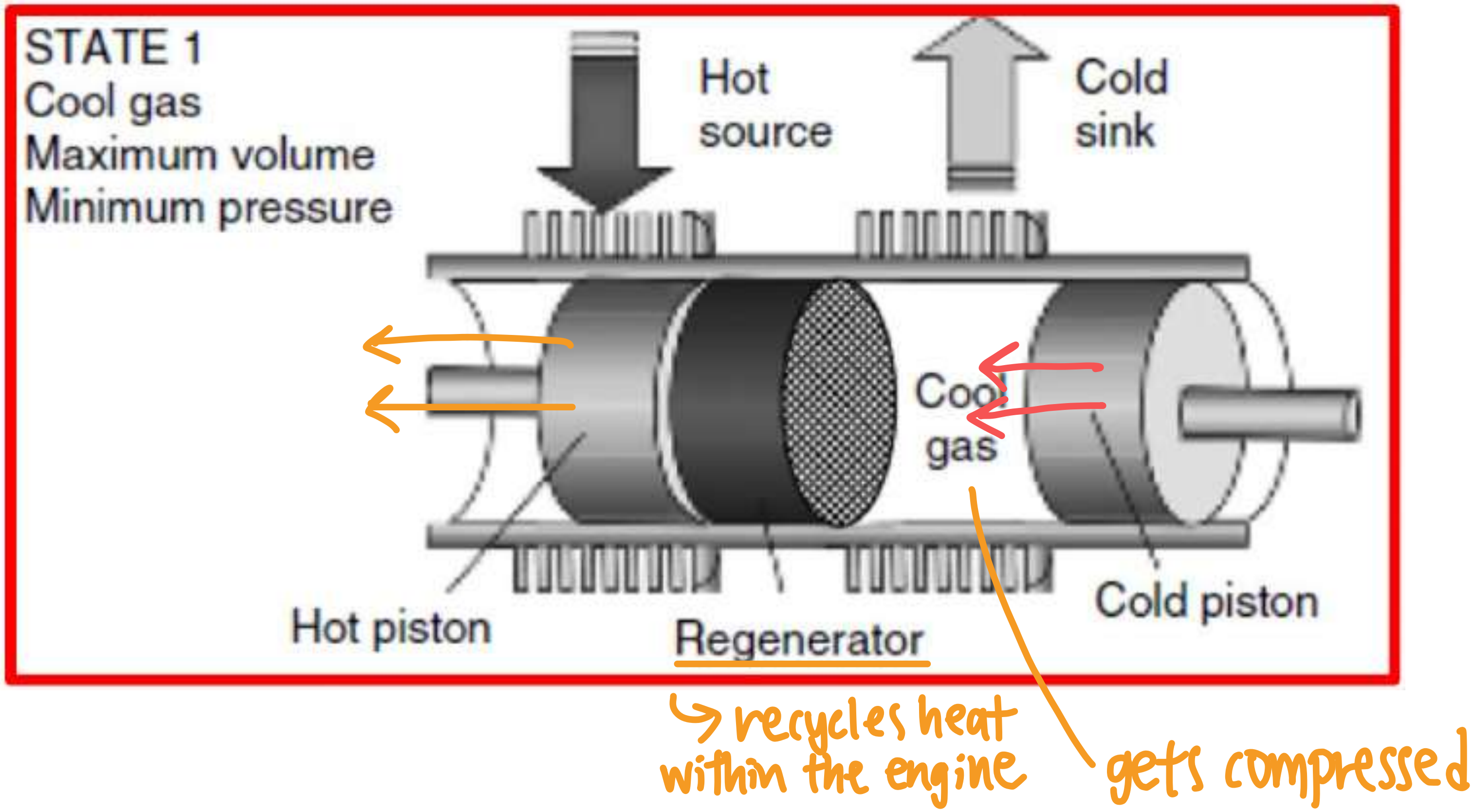
- Uses multiple mirrors that make a parabolic dish
- The dish tracks the sun and focuses it onto a thermal receiver
- The receiver converts this thermal energy to heat and delivers it to a Stirling engine
- Cycle heat engine mounted on receiver generates electricity, **or**
- sunlight heats fluid that is transmitted to a central engine

Dishes



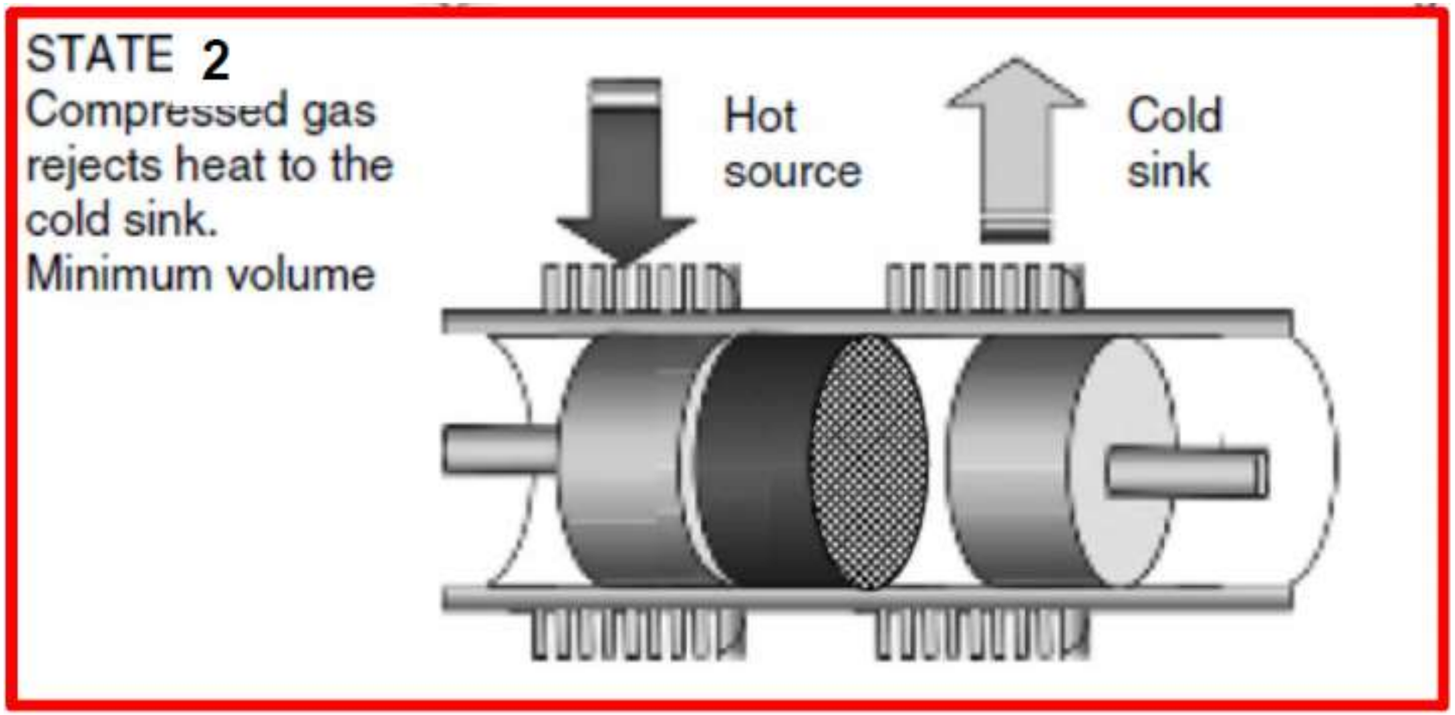


Stirling engine GM Master's book: Section 4.2



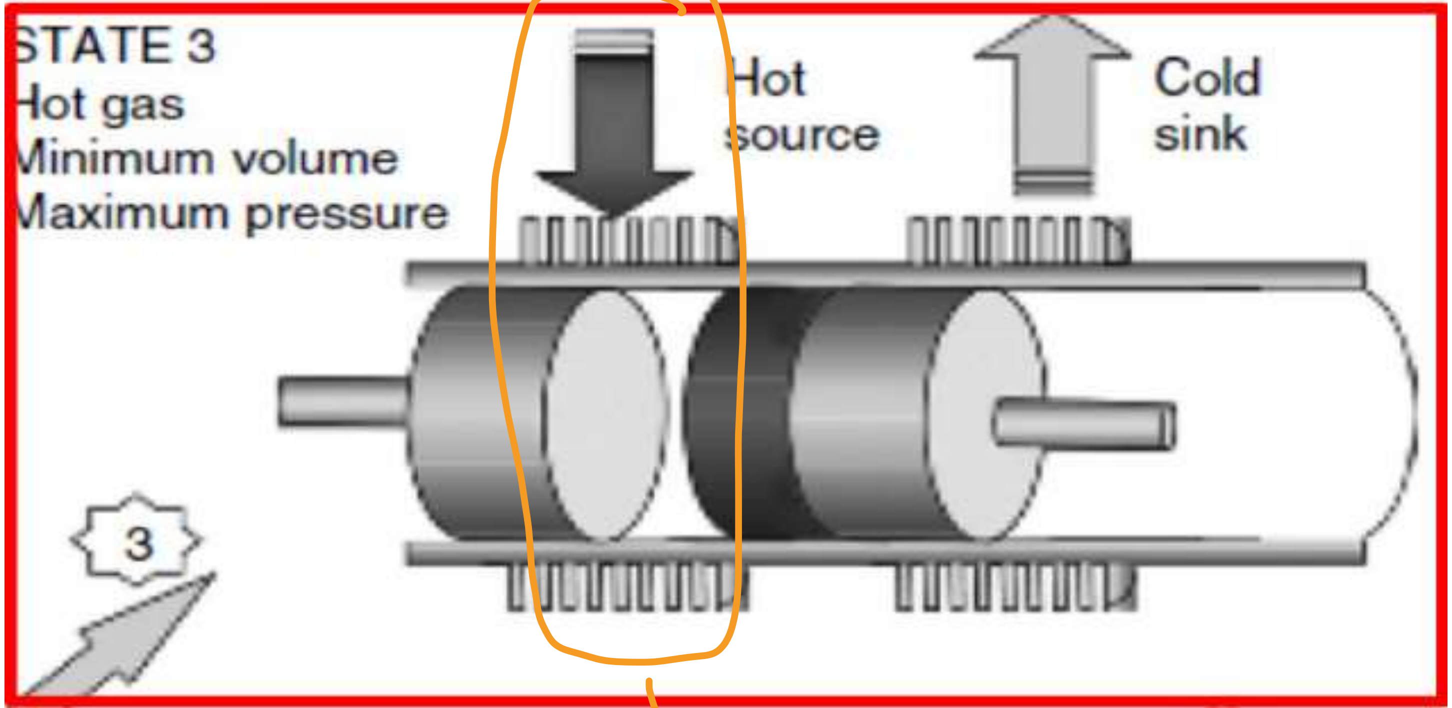
Cool piston begins to move in, compressing the gas

GM Master's book: Section 4.2



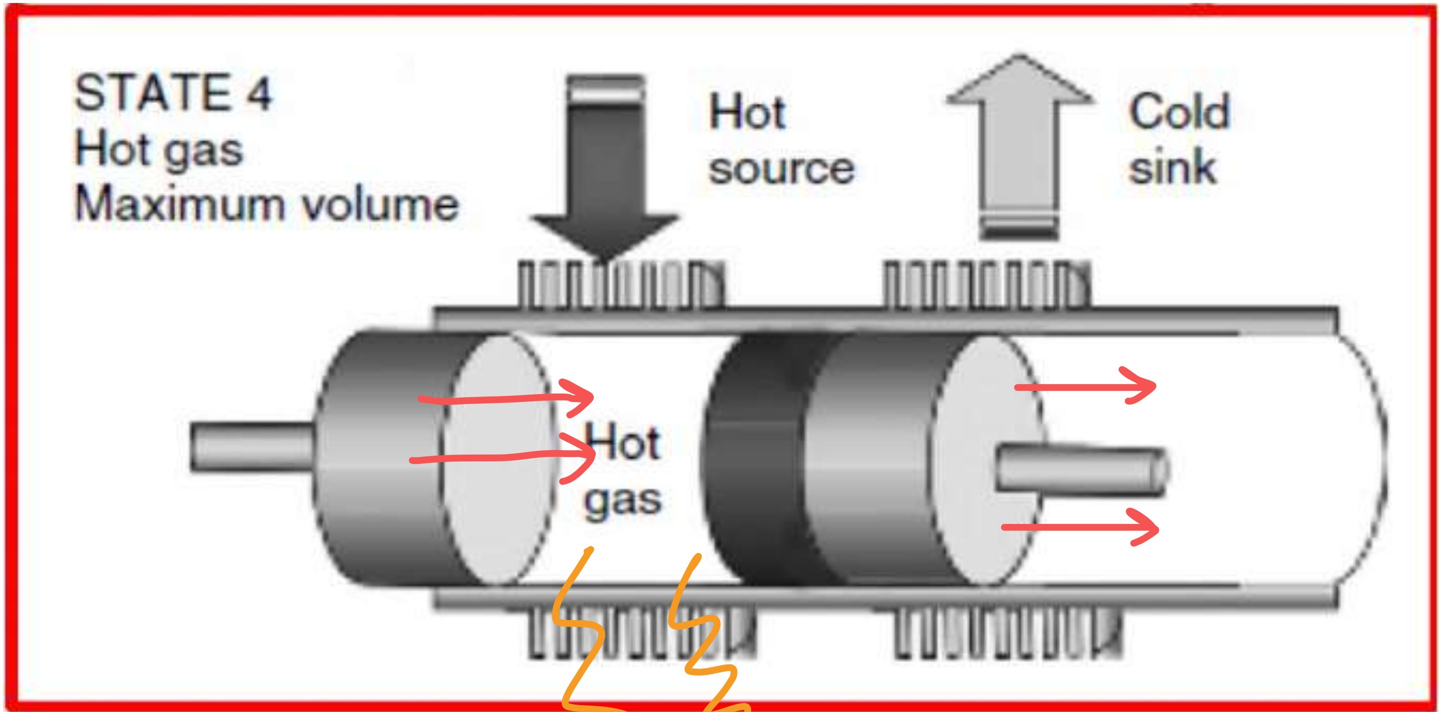
Both pistons move simultaneously to the left

Gas flows through regenerator and warms up



now the gas is directly under hot source ⇒ gets heated up

Gas collects heat, driving hot piston to the left



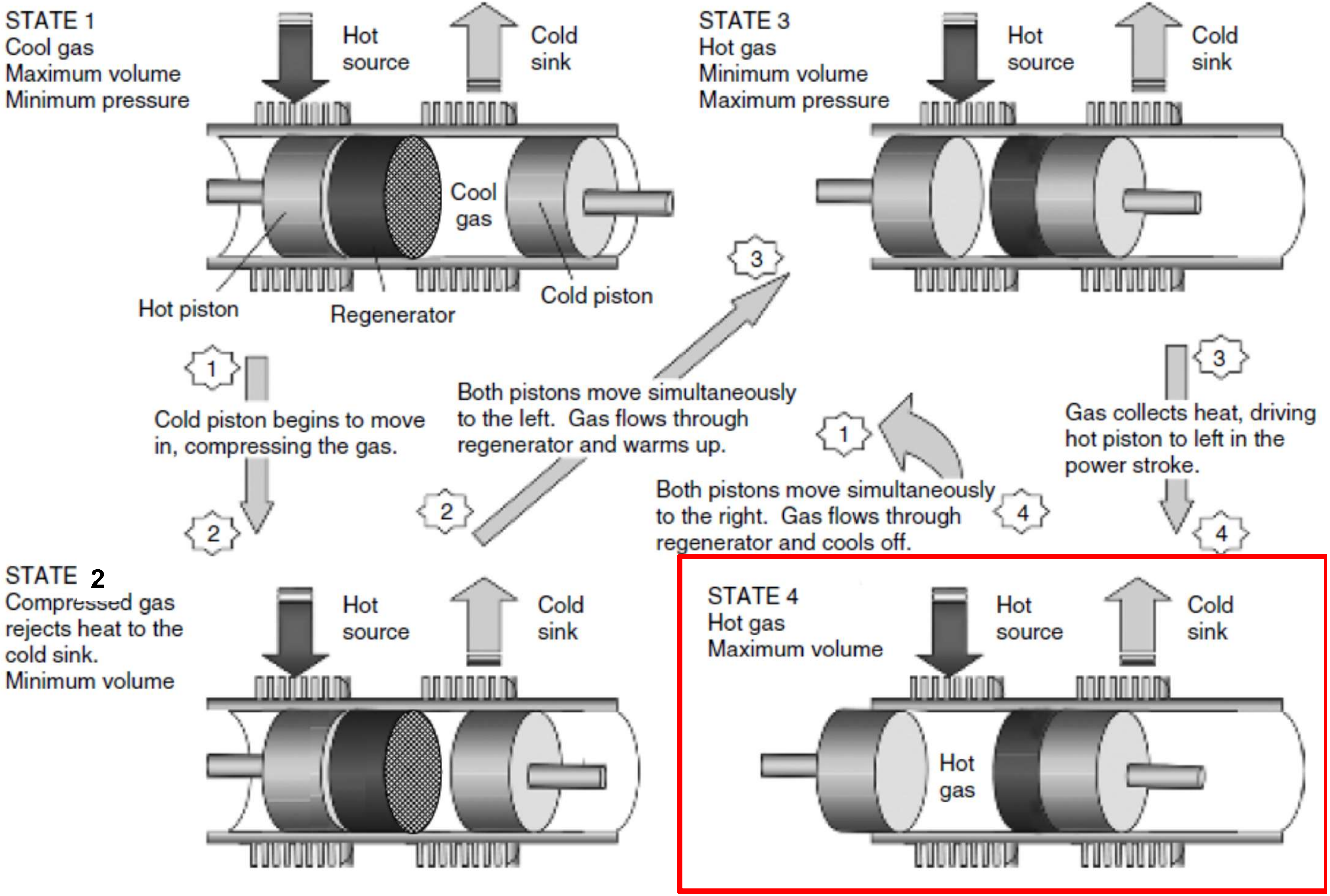
gas cools off

Both pistons move simultaneously to the right.

Gas flows through regenerator and cools off

↳ radiation energy from Sun to mechanical energy

↳ linear movement



Stirling engine

Stirling Engine

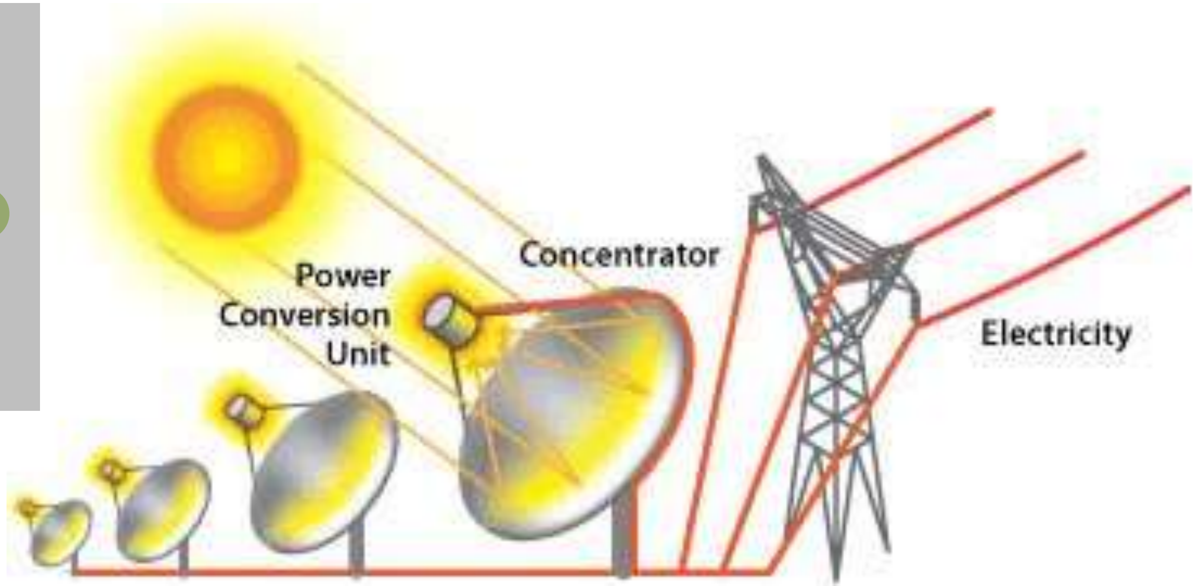
- It is a piston-driven reciprocating engine that relies on external combustion.

↳ no combustion

↳ quiet ⇒ no sound lost

↳ no by-products

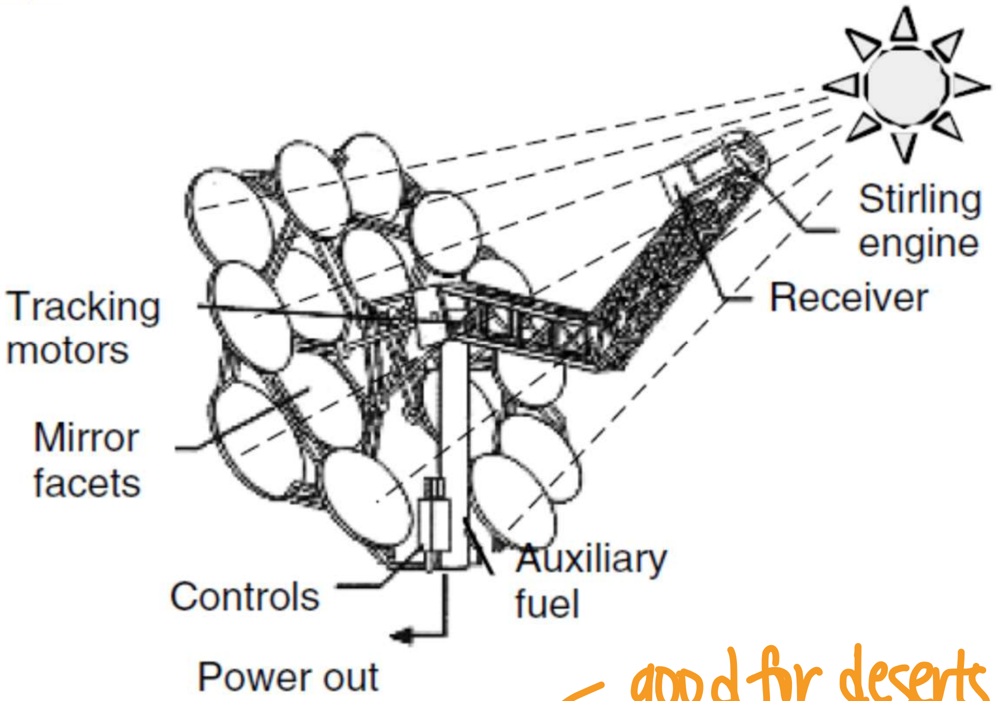
↳ very efficient!



- As such, it can run on any virtually any fuel or other source of high temperatures such as concentrated sunlight shining onto a black absorber plate.

- Very simple and elegant system

The complete Solar Dish System



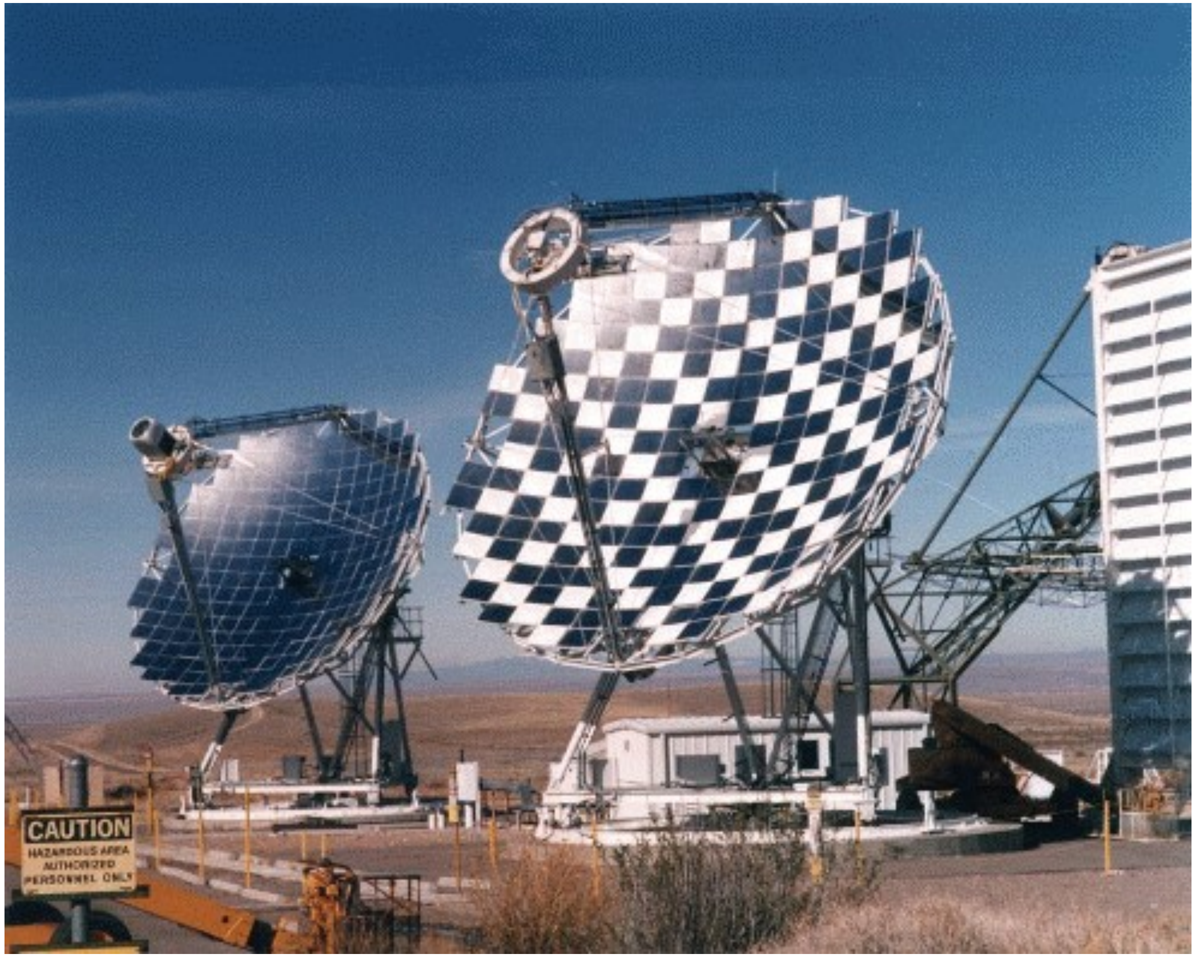
high efficiency!

good for deserts.

- Average efficiency > 20%; peak reaching 30%
- Closed system – very little make-up water is required
- Sizes range from 1kW – 25kW
- Land area required: approx 4 acres/MW
- Can be stand-alone plants for remote areas/desert locations
- Short lead time – 1 year

BUT: high costs!!!

75 kW Solar Thermal Test Facility



- These Sandia trackers have a paraboloidal dish surface similar to a radar antenna

http://www.sandia.gov/Renewable_Energy/solarthermal/NSTTF/dishes.htm

CSP Techniques:

3. Solar Tower

Solar Tower

Uses a system of computer controlled mirrors (***heliostats***) to concentrate sunlight

Heliostats bounce sunlight onto a receiver mounted on top of a tower

Each heliostat is separately driven to focus its beam on the receiver

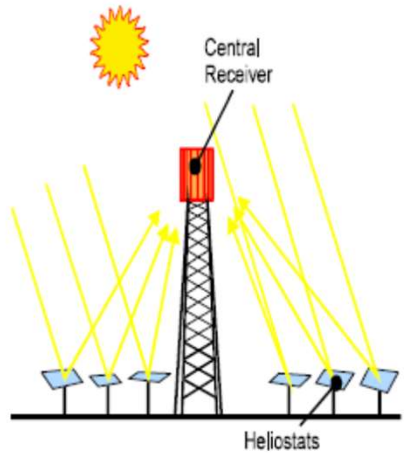
In the receiver, radiation energy is converted into heat and transferred to a heat transfer medium (e.g. air, liquid, salt, water)

Water/Fluid is pumped into receiver to produce steam that drives a turbine/generator

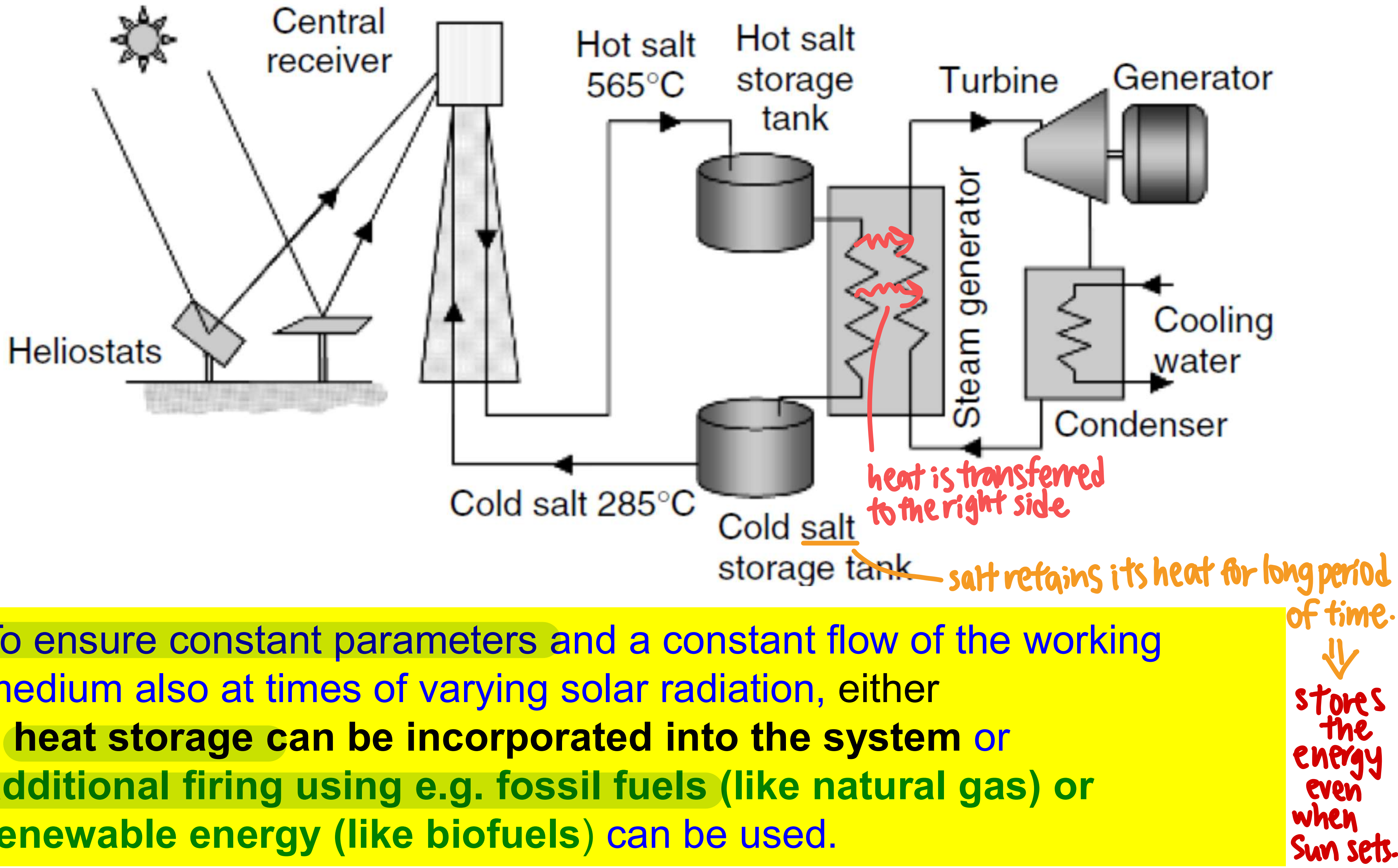
https://www.youtube.com/watch?v=QTNU1JMhzxA

point-focussing system

Tower



Solar Tower – Molten-salt central receiver system



To ensure constant parameters and a constant flow of the working medium also at times of varying solar radiation, either a **heat storage can be incorporated into the system** or **additional firing using e.g. fossil fuels (like natural gas) or renewable energy (like biofuels)** can be used.

Heliostats

makes sure that the system can track Sun even when it shifts positions.

- Heliostats are reflecting surfaces provided with a two-axis tracking system which ensures that the incident sunlight is reflected towards a certain target point throughout the day.
- Typically they use a curved surface or an appropriate orientation of partial areas, so that radiation flux density is increased
- Heliostats include mirrors, a sun-tracking system provided with drive motors, and foundations and control electronics.

Faceted glass/metal heliostat

metal membrane heliostat

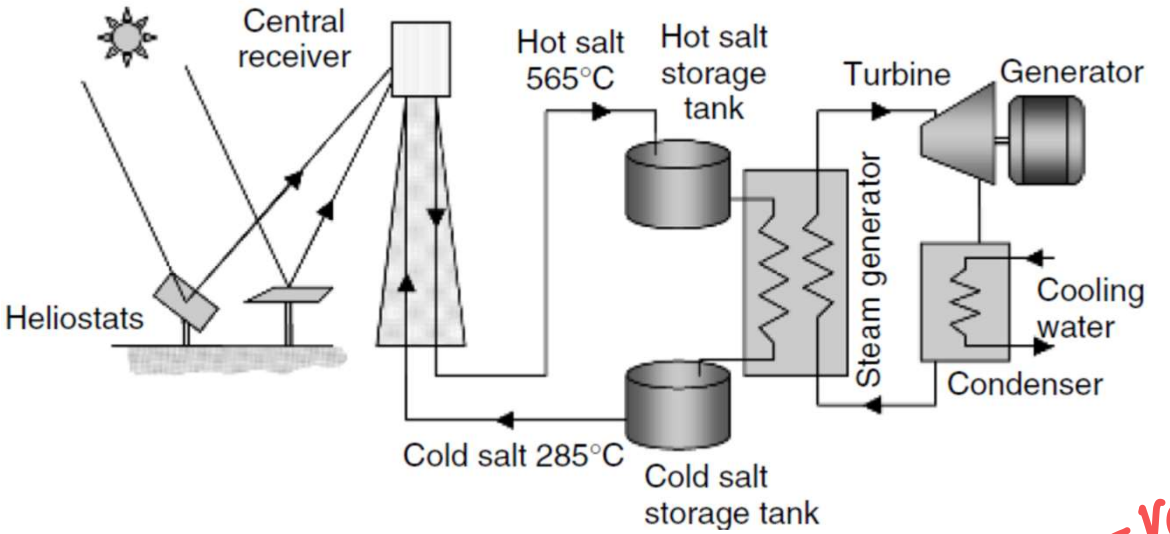
The heliostat field accounts for about half the cost of the solar components of such power plants.

What happens at night?

- Power is stored during the daytime in molten salt at approximately 1050°F
- Salt sometimes used to heat graphite which would be used as a heat storage medium— night-time operations are possible!

extra costs!

- Storage of heat from solar power plants can allow solar power plants to operate around the clock

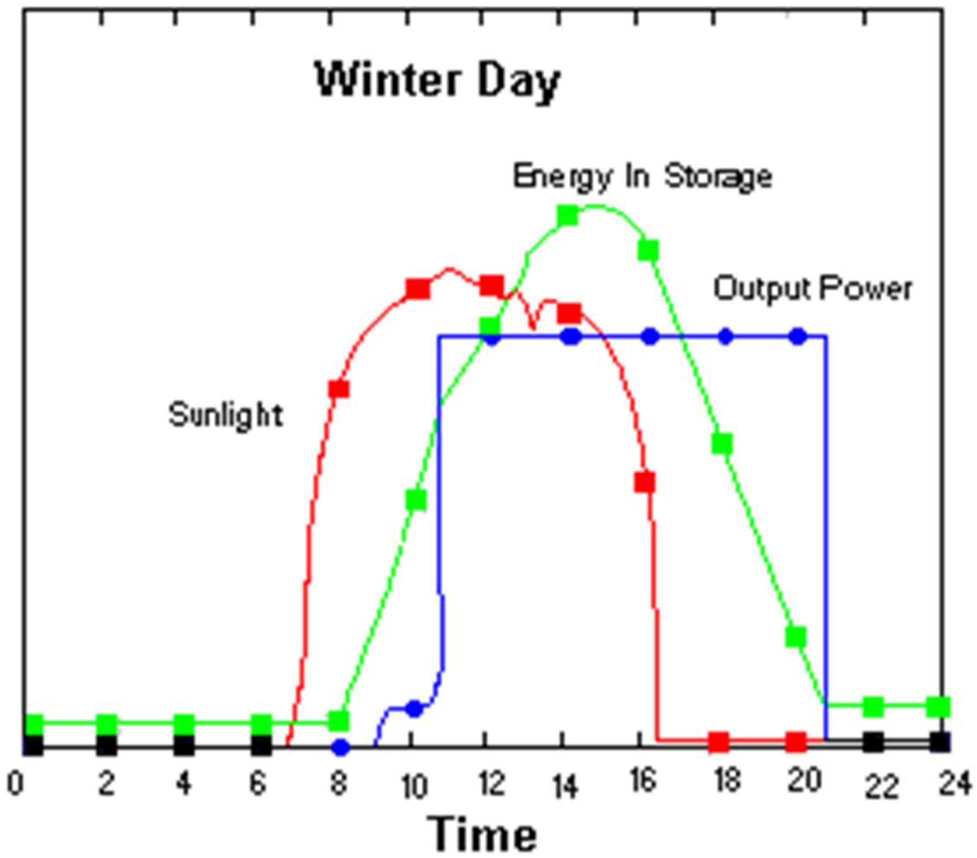


very powerful...

These plants are unique because they can generate power when it is needed…day or night…rain or shine

Solar Towers

- A large tank stores energy to use during cloud passage or at dusk
- **The output power is extracted at a constant rate**



http://www.sandia.gov/Renewable_Energy/solarthermal/NSTTF/feature.htm

Solar Towers: Barstow CA

- Flat mirrors are aimed to melt salt at the receiver target

Solar One – The project produced 10 MW of electricity using 1,818 mirrors, each 40 m² with a total area of 72,650 m²
Solar Two - a second ring of 108 larger 95 m² heliostats were added, totaling 1926 heliostats

Solar Tres - in Spain for commercial electrical production of 15 MW.

- Three times larger than Solar Two
- 2,493 heliostats, each with a reflective surface of 96 m².
- The total reflective area will be 240,000 m²
- A larger molten salt storage tank is used to give the plant the ability to store 600 MWh
- Plant can run 24x7 during the summer

http://www.sandia.gov/Renewable_Energy/solarthermal/nsttf.html

CSP Techniques:

4. Linear Fresnel System

newest one!

Linear Fresnel Systems

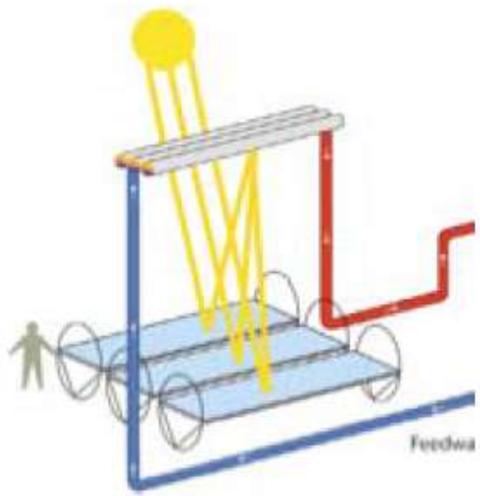
Linear Fresnel Reflectors use long, thin segments of mirrors to focus sunlight onto a fixed absorber located at a common focal point of the reflectors.

Capable of concentrating the sun's energy to approximately 30 times its normal intensity

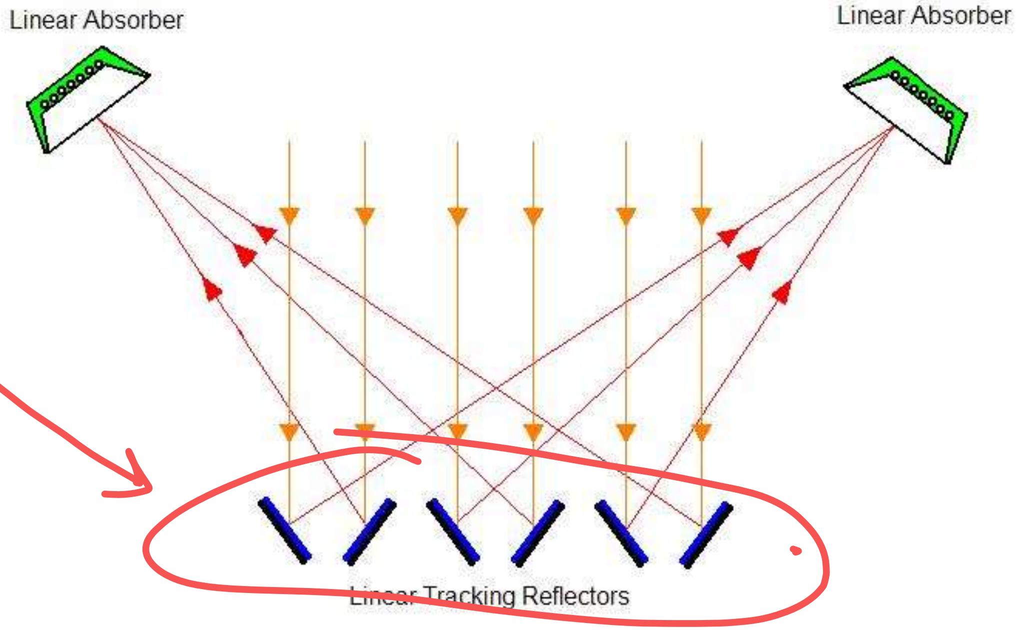
Concentrated energy is transferred through the absorber into some thermal fluid (typically oil) to power a steam generator

thin long mirrors
↳ cheaper!
↳ smaller area
↳ NOT as efficient

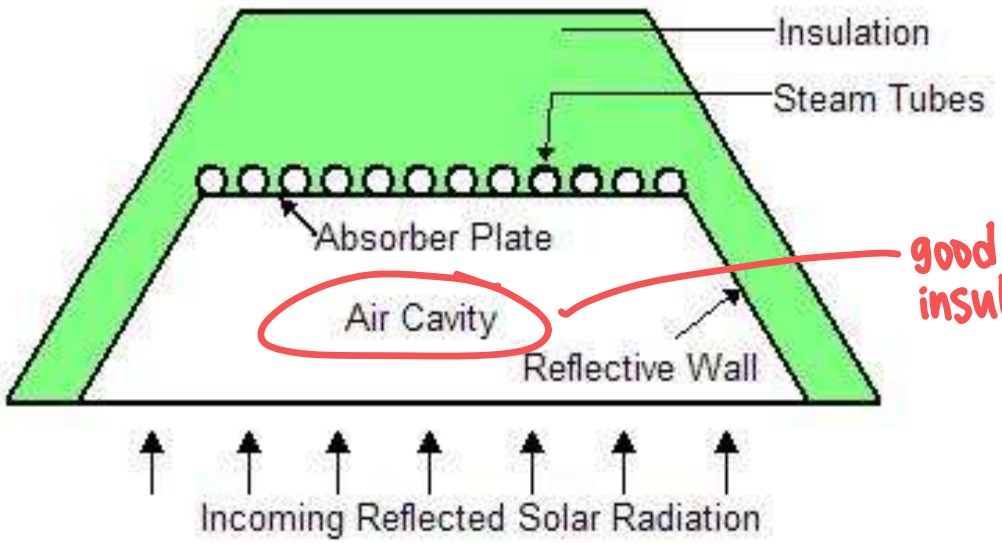
Linear Fresnel



- The system uses alternating inclination of mirrors to focus solar energy on multiple absorbers, **improving system efficiency and reducing overall cost.**



- Incident solar rays are concentrated on insulated steam tubes to heat working thermal fluid.



good heat insulator

- **Efficiency around 15%**

Linear Fresnel Reflector Plant in Jaisalmer, India

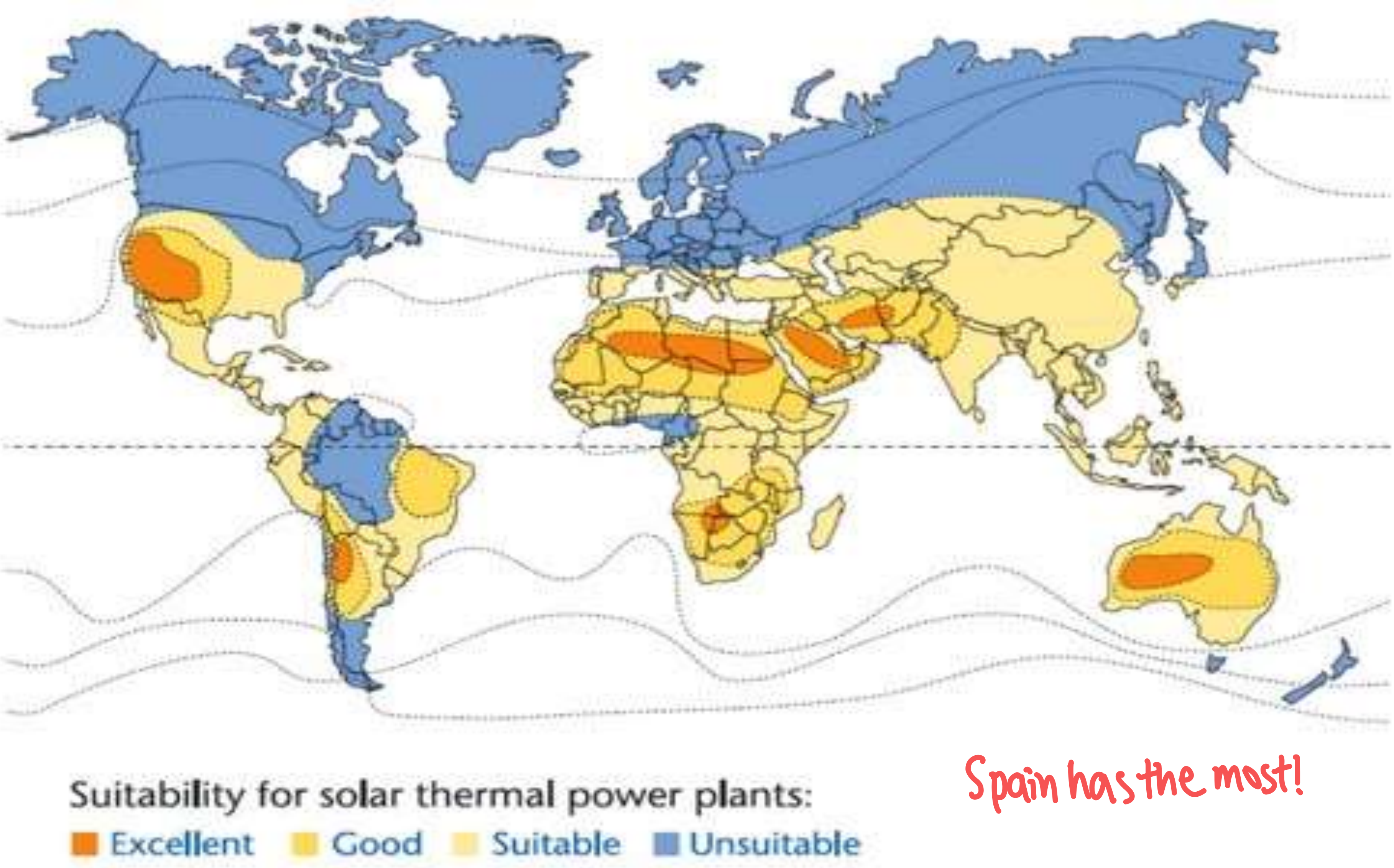
- Technology: Linear Fresnel reflector, no storage
- Capacity: 125 MW
- In operation since 2014

Compared to other technologies, the investment costs per square meter of collector field using LFR technology tend to be lower because of the **simpler solar field construction**.

lower costs

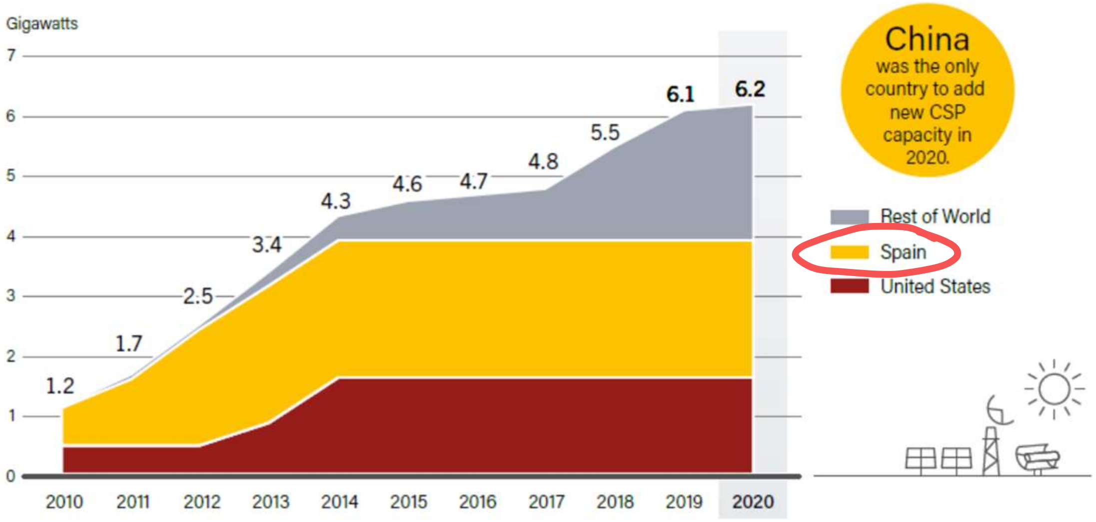
Photo Credit: ©Ferrostaal-Hauke Dressler / PSA

Areas suitable for Concentrated Solar Power (CSP) electricity generation



Spain has the most!

CSP Global Cumulative Installed Power



- CSP Costs fell 50% from 2010 to 2020.
- Modern CSP plants with thermal energy storage are co-located with Solar PV to lower costs and increase capacity factors

The world's largest

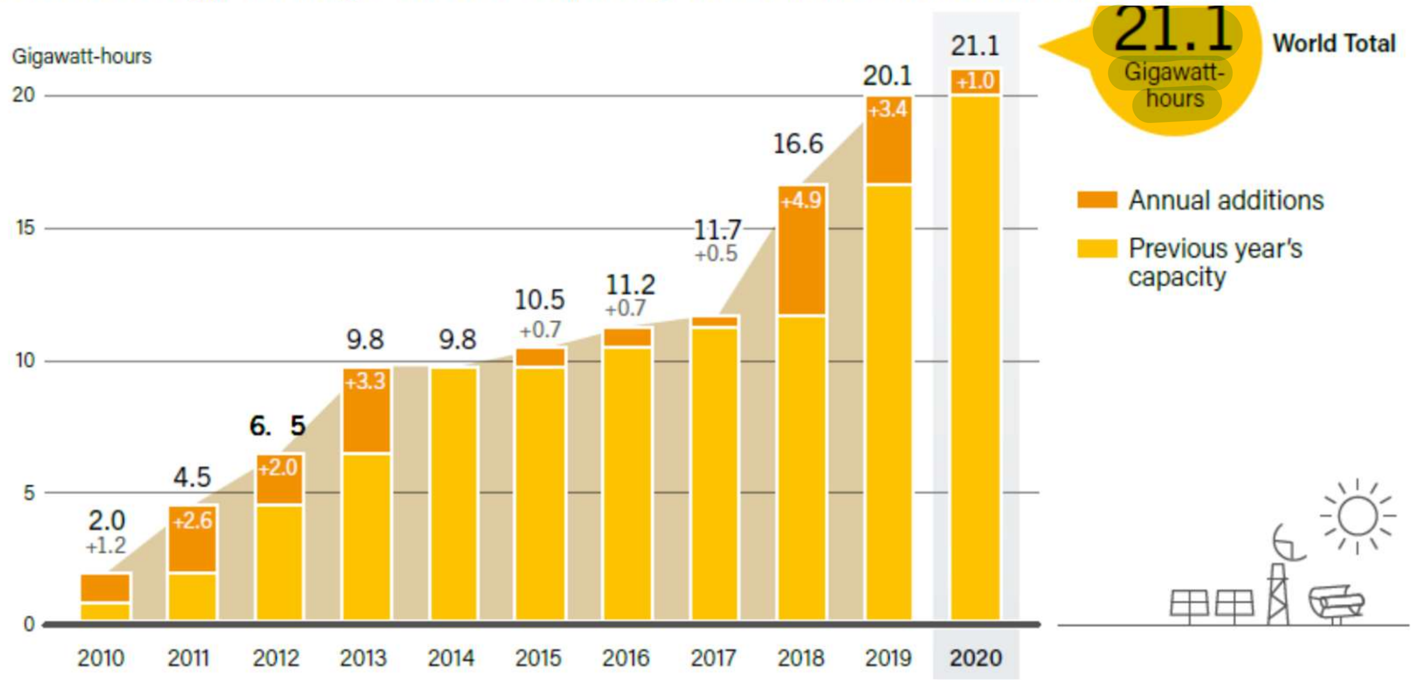
CSP project,

at 700 MW, was under construction in the United Arab Emirates.

Source: REN21's Renewables 2021 Global Status Report

Thermal Energy Storage is increasingly being added in CSP Systems

Thermal Energy Storage Global Capacity and Annual Additions, 2010-2020



More than 95% of thermal storage for CSP systems is based on molten salt technology. The remainder is steam based storage

Comparison of Major CSP Technologies
(Dish, Tower, Trough)

	Parabolic Dish	Parabolic Trough	Power Tower
			
Applications	Stand-alone small power systems; grid support	Grid-connected electric plants; process heat for industrial use.	Grid-connected electric plants; process heat for industrial use.
Advantages	Dispatchable electricity, high conversion efficiencies; modularity; hybrid (solar/fossil) operation.	Dispatchable peaking electricity; commercially available with 4,500 Gwh operating experience; hybrid (solar/fossil) operation.	Dispatchable base load electricity; high conversion efficiencies; energy storage; hybrid (solar/fossil) operation.

[Source: Status Report on Solar Thermal Power Plants. Pilkington Solar International GmbH: Cologne, Germany,1996.]
http://www.solardev.com/SEIA-makingelec.php

Economic Analysis

not tested yet

Assumptions:

- a technical lifetime of 25 years for all machine equipment & an interest rate of 4.5 %
- The installation of solar thermal plants only makes sense in areas with a high share of direct radiation:
- a reference site with a total annual global radiation on the horizontal surface of 2,300 kWh/m^2 and a direct radiation total of 2,700 kWh/m^2 has been defined.

Based on these site conditions a 30 MW solar tower power plant is assessed.

Technical data of the assessed 30 MW solar tower power plant

Nominal capacity	30 MW
Mirror surface	175,000 m^2
Full-load hours	2,100 h/a
Storage capacity	0.5 h
Solar share	100 %
Technical lifetime	25 a

Economic Analysis: Example

- Mean investment and operation costs, as well as, resulting power generation cost

Nominal capacity	30 MW
Investments	
heliostat field	30 Mio. €
receiver and steam generator system	20 Mio. €
tower	15 Mio. €
other components	20 Mio. €
assembly and commissioning	10 Mio. €
design, engineering, consulting, miscellaneous	5 Mio. €
Total	99 Mio. €
Operation and maintenance costs	1.5 Mio. €/a
Power generation costs	0.13 €/kWh

Concentrated Solar Power (CSP) prices have recently dropped by an astonishing 50%, to about 5-7 Euro cents!!

Environmental Impact Analysis

- Environmental effects related to solar thermal plants may already arise during production of the different plant components.
- However, **they are for limited duration**. Furthermore, these plants are primarily located in deserts and steppes where the population density is relatively low.

Factors to be considered:

- Space requirements
- Visual Impact
- Reflection
- Emission

Environmental Impact Analysis

Visual impact:

Due to their central tower, mainly tower and solar updraft power plants have a non-negligible impact on the appearance of the natural scenery; the disturbance of the scenery is static since no moving parts

Reflections:

Provided that power plants are operated properly, i.e. mirrors are precisely tracking, none of the known environmental effects will occur.

Emissions:

Since some solar thermal power plants also apply conventional power plant technology they are also potential sources of airborne emissions. However, greenhouse gas emissions as well as other types of emissions are only released into the atmosphere **during hybrid operation** involving fossil or biogenous combustibles.

Comparison of Major CSP Technologies
(Dish, Tower, Trough)

	Dish Stirling system	Power Tower	Parabolic Trough
			
Ratio of Solar Concentration (max upto)	3000	1500	400 suns
Annual efficiency (sunlight to electricity)	25-30%	16-35%	15%
Land area required	4 acres/MW	8 acres/MW	5 acres/MW
Cooling water requirements	Very little	Medium	High

BEST! (but still new, not industrialised)

Comparison of Major CSP Technologies

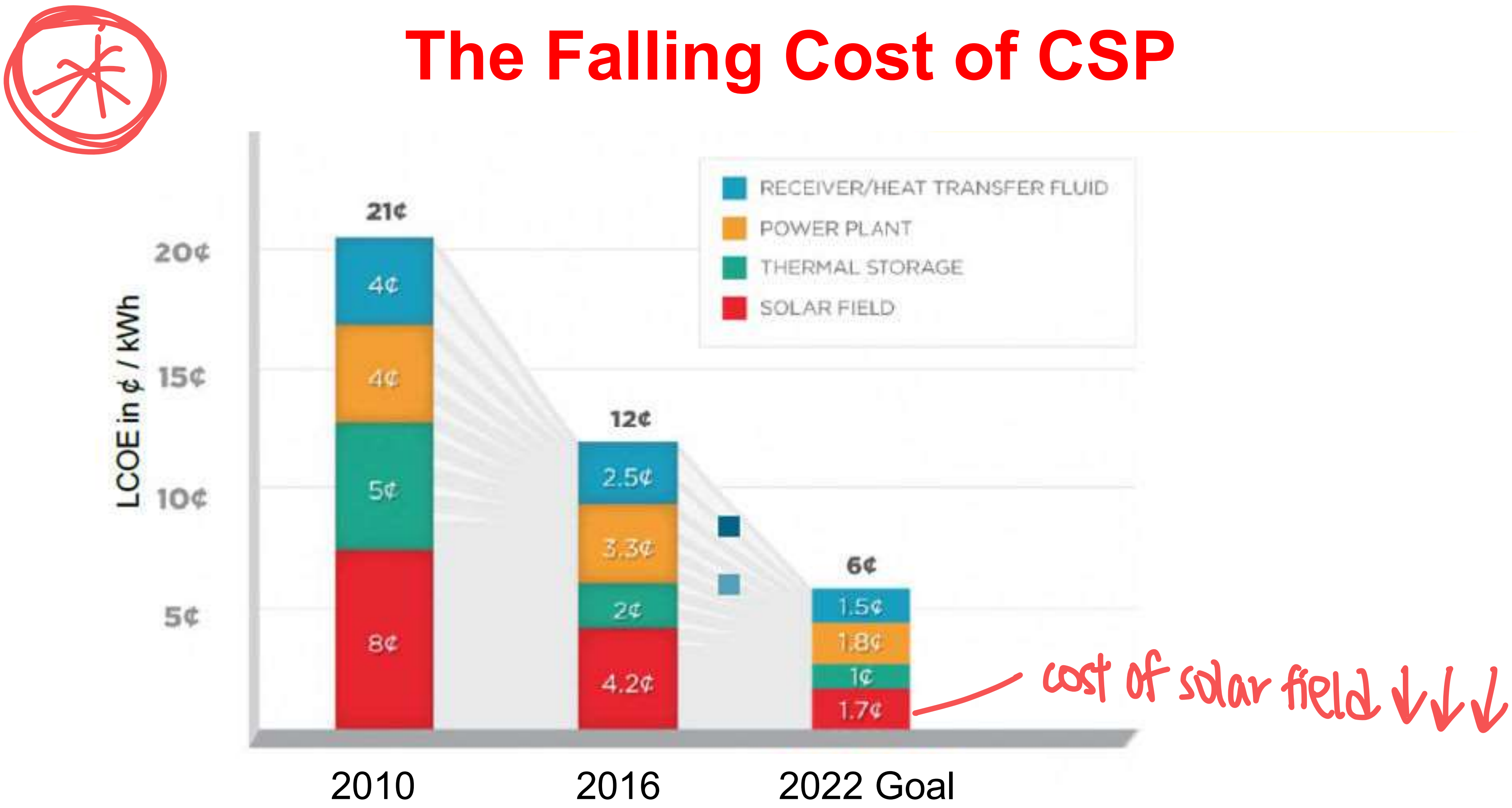
	Dish Stirling system 	Power Tower 	Parabolic Trough 
Mechanism	Dish focuses sunlight to single point , where thermal collector captures the heat .Engine converts heat into mechanical energy which drives generator to produce electricity	Circular array of mirrors concentrate s sunlight on receiver placed at top of central tower. Heat creates steam to power generator.	Curved trough reflects solar radiation onto tube and heats the oil inside it. A heat exchanger creates steam which runs a steam turbine .
Size (Scale)	**5 – 25 KW (per dish**	**10 – 200 (MW)**	**50 – 600 (MW)**
Commercial Status	**Embryonic - Pilot underway**	**Latest technology, several new commercial systems have started operating**	**Mature technology, 20 yr commercial track record**

Comparison of Other CSP Technologies
(Fresnel Reflector, Solar pond, Solar Up-draft tower)

	Fresnel Reflector	**Solar pond**	**Solar Up-draft tower**
Intensity of solar radiation	15 suns	1 sun	1 sun
Annual efficiency (sunlight to electricity)	9-16%	1%	1%
Typical capacity	10-200 MW	200 kW – 5 MW	30-200 MW

small...

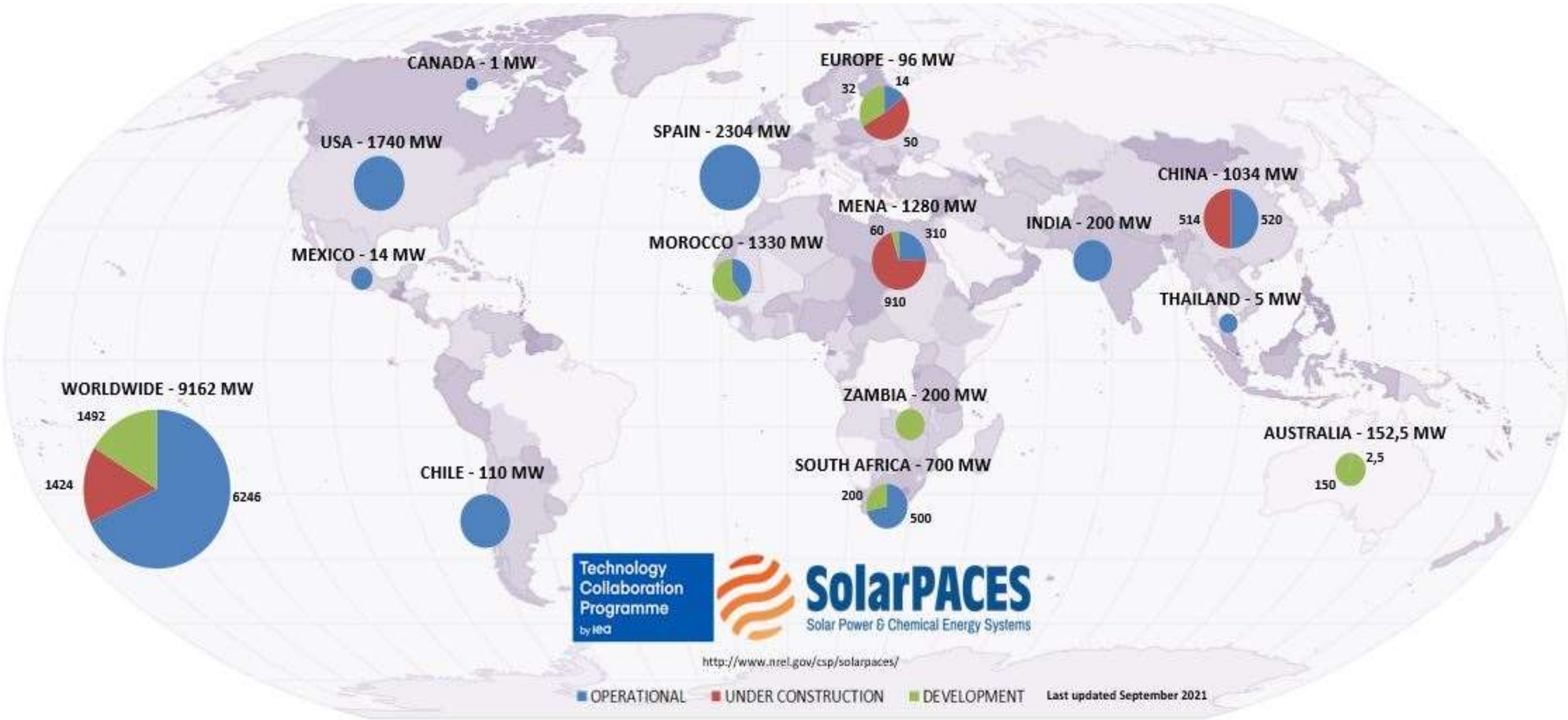
The Falling Cost of CSP



- The cost of trough and tower based systems is rapidly falling.
- The dispatchability offered by CSP with thermal storage has important benefits compared to PV and wind power.
- From the perspective of grid operators, CSP offers the critical ability to provide reliable energy and capacity specially during the hours when PV does not generate electricity.

CSP Projects Around the World (upto September 2021)

Concentrating solar power (CSP) projects around the world that have plants that are either operational, under construction, or under development.



CSP technologies include parabolic trough, linear Fresnel reflector, power tower, and dish/engine systems.

Source: NREL

CSP - Current Status

Ivanpah solar plant (California, USA)

- Ivanpah solar plant (California, USA) started energy feed to grid from Sept 2013
- Capacity: 392 MW
- Technology: Solar Tower

- Size: three power towers , 3,500 acres
- Uses over 300,000 software-controlled mirrors to track the sun across the sky

Ivanpah solar plant

CSP Current Status

Crescent Dunes (Nevada, USA)
Technology: Power Tower;
Thermal Storage

Size: 110 MW

Start date: Dec 2014
Size: 540- foot power tower, 100-foot molten salt receiver,
Approximately 10,000 heliostats

USA's first commercial-scale solar power tower facility with energy storage, as well as the largest power plant of its kind in the world.

CSP Current Status

Solana (Arizona, USA)
Technology: Parabolic
Trough; Thermal Storage

Size: 250 MW

Start date: Oct 2013
Size: 1921 Acres

Cerro Dominador Solar Project, Chile

- Total capacity: 210 MW (combines 100 MW of photovoltaic energy and 110 MW of solar concentrating power)

- CSP Technology: Molten Salt Tower

- First stage of 62 MW started delivering power to the grid in August 2017

This solar plant, with 17.5 hours of storage capacity, guarantees continuous production 24 hours per day, 365 days a year

Bokpoort, Northen Cape, South Africa

- Bokpoort 50 MW project is the first Concentrating Solar Power (CSP) plant in South Africa
- Technology: Parabolic trough plant
- Storage: Large capacity of storage (slightly above 9 hours), focused on 24/7 production

- Very high capacity factor (> 50%)
- Total reflective area: 588,600 m^2.
- Electricity delivery to 54,000 household
- CO_2 emission savings: 57,000 tons/year.

CSP puts end to Morocco electricity blackouts

- Ouarzazate CSP complex at the junction of the Atlas Mountains and Sahara Desert

- Largest CSP complex in the world upon completion in End 2018

- Noor 1 exceeded its objectives in year one and brought stability to the grid, drastic improvement on the quality of service, and an end to blackouts.

CSP puts end to Morocco electricity blackouts

Noor 1: 160 MW
Technology: parabolic trough,
Storage capacity: 3 hours thermal storage

Noor 2: 200 MW
Technology: parabolic trough
Storage capacity: 6 hours

Noor 3: 150 MW
Technology: 250m Molten Salt power tower,
Storage capacity: 7.5 hours

Together, they produce enough energy to power over one million homes and reduce carbon emissions by an estimated 760,000 tons per year

Source: CSP Focus

CSP Current Status - STEM

Solar Thermoelectric Magaldi (STEM)

- STEM is based on modular units rated 2 MW each
- Produces 24 hour industrial scale power for remote locations
- Generates superheated high-pressure steam at 520°C
- uses fluidized silica sand as a thermal storage and heat transfer medium for CSP systems

Heliostat panels surround a solar generation unit at a Solar Thermoelectric Magaldi (STEM) pilot plant, operated by Magaldi Group, in Buccino, Italy, on Monday, May 18, 2015.

Solar radiation captured by heliostats field is concentrated on a secondary reflector (beam down) and subsequently focused into a receiver, positioned at ground level

CSP Current Status

All new facilities that came online and under development incorporated thermal energy storage (TES), which is now seen as central to the value that CSP technology can add by providing dispatchable power to grids with high penetrations of variable renewables.

Parabolic trough and tower technologies continue to dominate the market.

CSP is receiving increased policy support in developing countries with limited oil and gas reserves, constrained power networks, and a need for energy storage.

Increasingly, solar thermal is being incorporated into district heating systems at significant scales, with several large projects in some European countries.

Denmark is in the lead and commissioned the world's largest plant for district heating (110 MW-thermal (MWth)) in 2016

CSP Technologies - Advantages

- **Free and secure resource**, widely available and highly predictable
- Uniquely suited for providing power during periods of peak demands
- Moderate net energy
- Moderate environmental impact
- No CO_2 emissions
- Steam is emitted rather than greenhouse gases
- Fast construction (1-2 years)
- Modern plants produce power at costs that are comparable to fossil fuels and wind power

Costs to produce facility:

- One-half **(50%)** the cost of solar power tower is associated with mirrors that focus light on the receivers,
- Less than one-third **(33%)** is associated with power cycle and heat storage
- Reduction in cost of mirrors will further reduce the overall costs

CSP - Challenges

Economical challenges:

- high cost of building facilities needed
- Funding will be needed to bring solar thermal electric into large scale development

Technological Obstacles:

- Needs back up or storage system - would typically need 16 hours of storage to continuously generate electricity
- Low efficiency - increasing efficiency by 20-30% could significantly reduce the cost of electricity

Land use issues:

- Takes lots of area requiring high land use
- Works best in desert or other areas with lots of sun
- Could potentially endanger wildlife

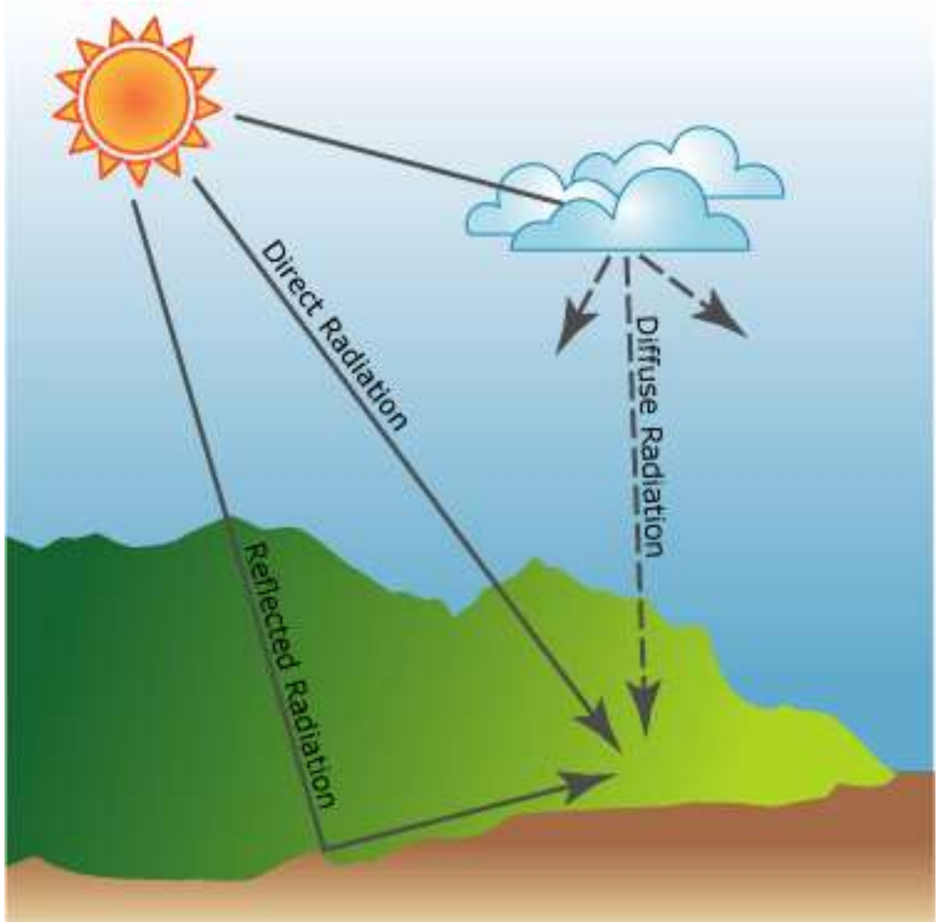
Solar PV Systems

Reference - Chapter 8: GM Master’s Book

Every hour the sun beams onto Earth more than enough energy to satisfy global energy needs for an entire year!

Solar Insolation

- Incoming solar radiation (**insolation**) is intercepted at the earth's surface as direct, diffuse, and reflected components.



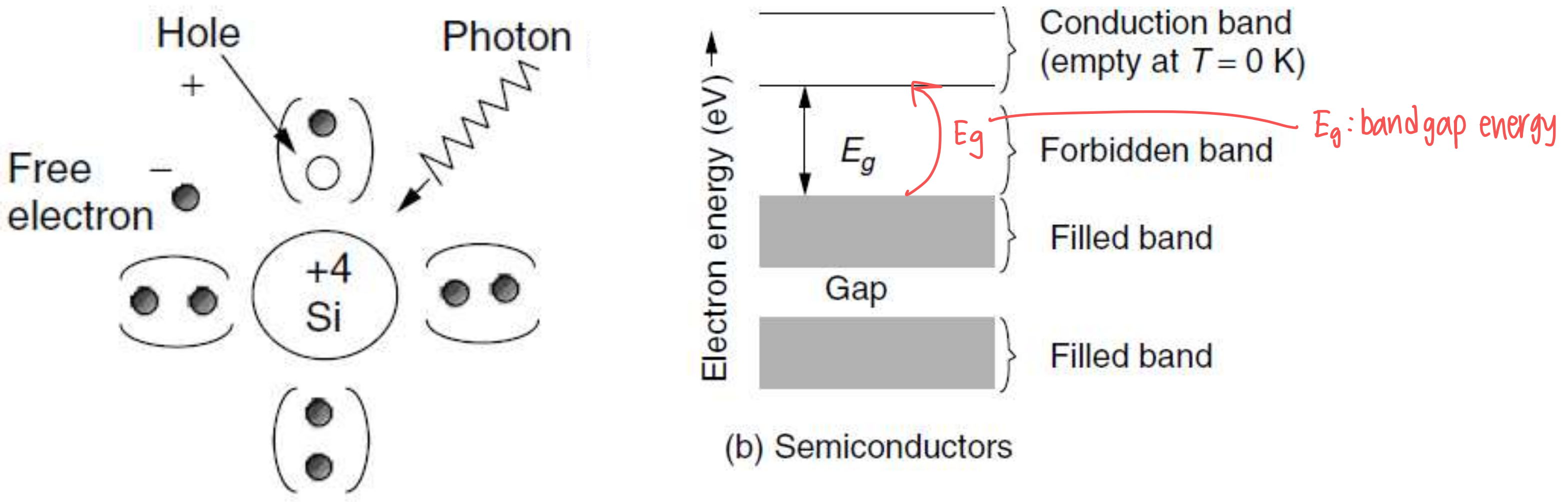
- *Solar insolation is a measure of solar radiation energy received on a given surface area in a given time*
- *It is commonly expressed as average irradiance Watts per square meter*

How does a semiconductor material convert sunlight into electricity?

Photovoltaic Effect

- In photovoltaics, the energy source is **photons** of electromagnetic energy from the sun.
- When a photon with more than **1.12 eV of energy** is absorbed by a solar cell, a single electron may jump to the conduction band.

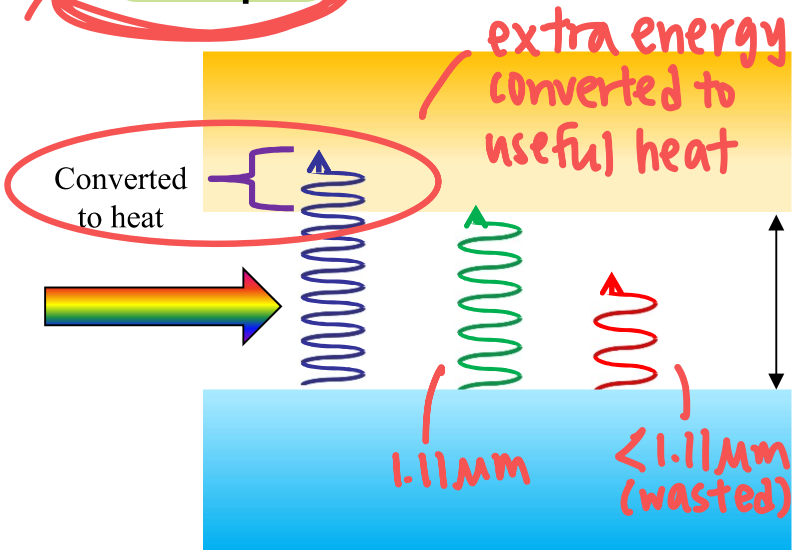
One photon can excite only one electron

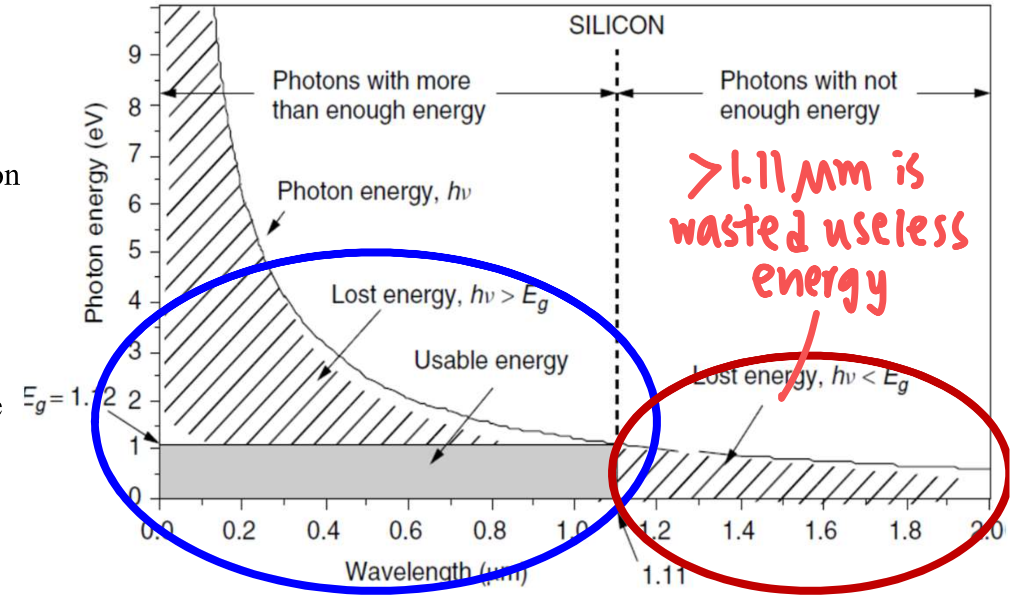


Refer to Chapter 8: GM Master's book

Bandgap energy for Silicon

- Band gap of silicon : 1.12 eV corresponds to wavelength of 1.11μm

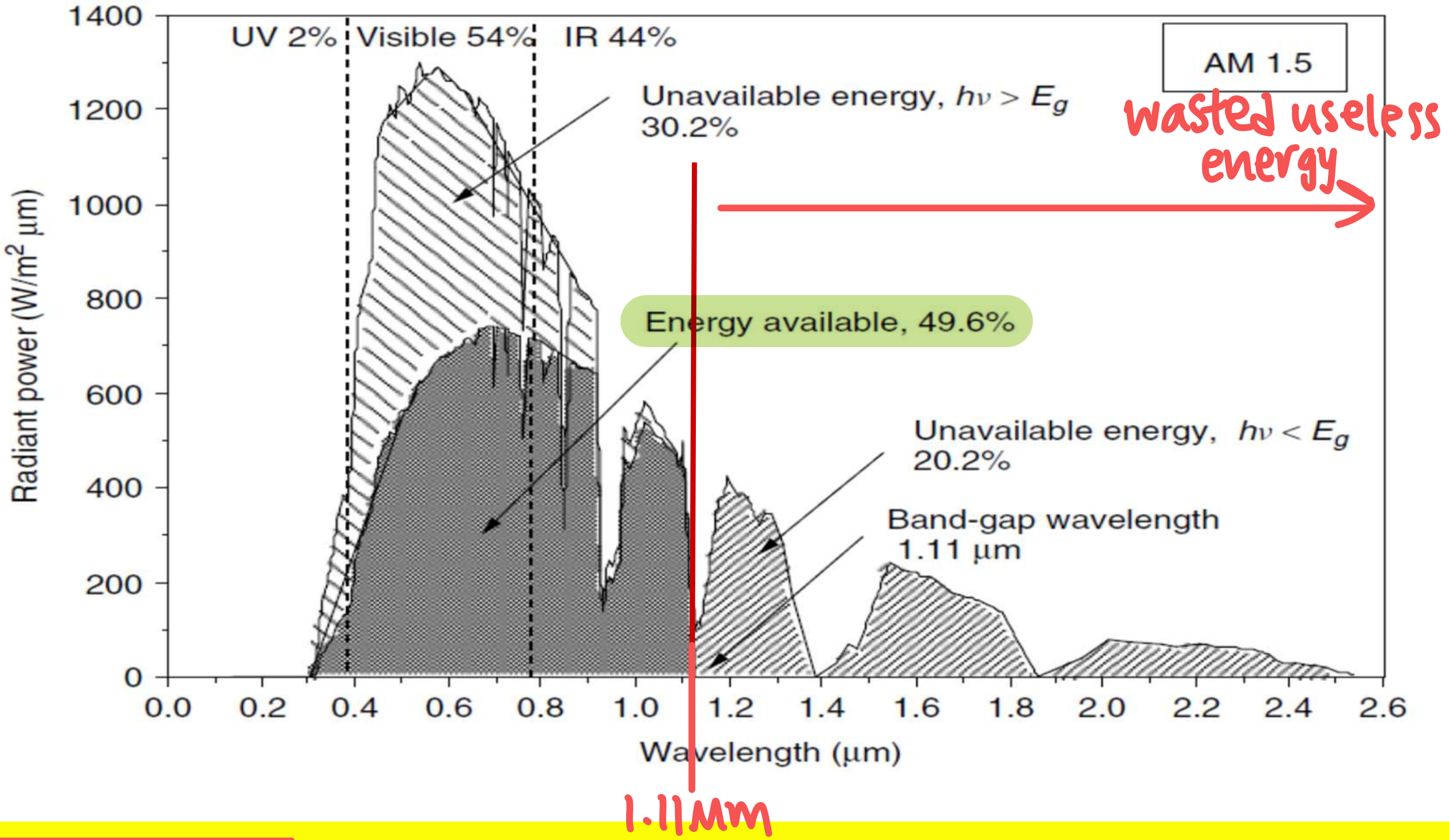




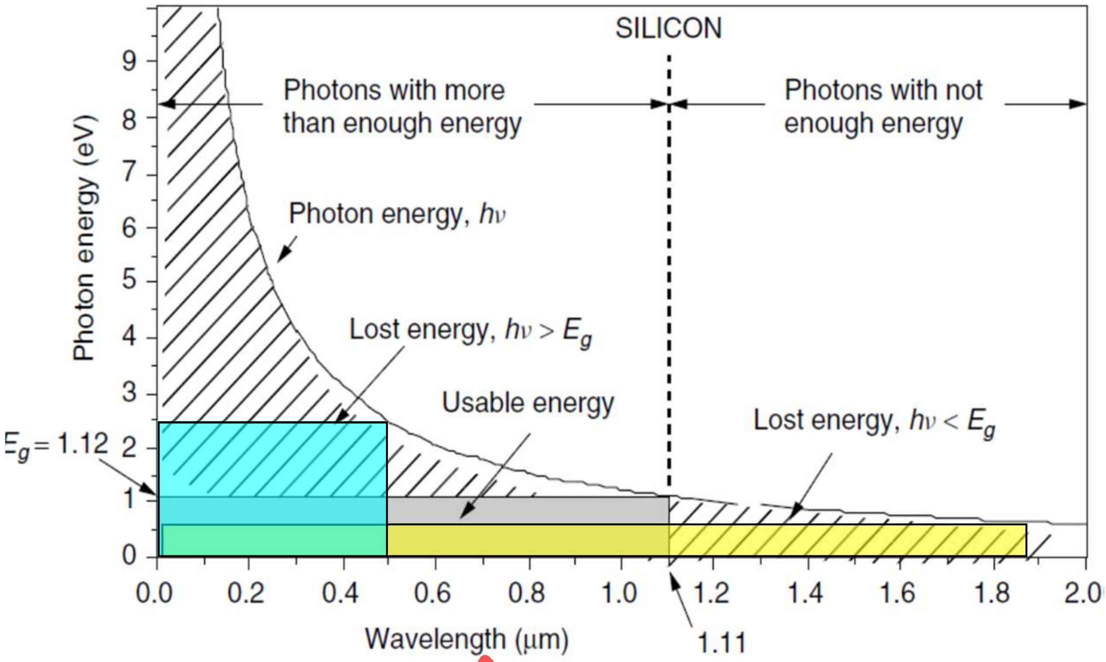
Photons with wavelength < 1.11μm waste their extra energy

Photons with wavelength > 1.11μm cannot send electrons to conduction band

Band gap impact on Photovoltaic Efficiency



The maximum possible fraction of the sun's energy that could be collected with a silicon solar cell is 49.6%!



more e⁻.

↑λ

the yellow graph

Important consideration for selection of materials

- With smaller bandgap, more photons cross the gap, and high current can be generated but voltage is low
- With larger bandgap, fewer photons cross the gap, which results in higher voltage and lower current

Efficiency of PV Cell

Efficiency drops to 49.6% due to losses caused by photons with **insufficient or too much energy**.

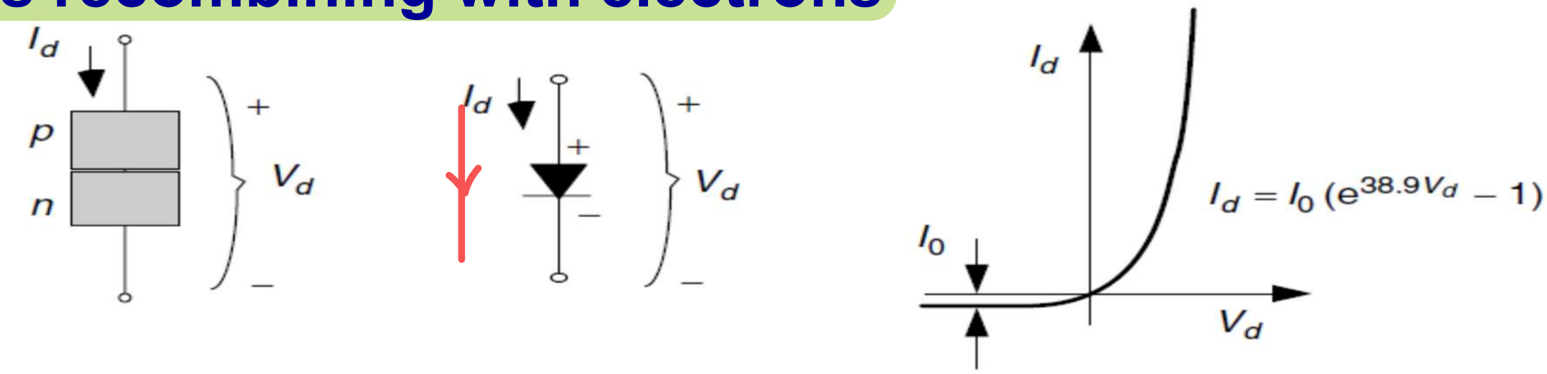
- **Further drop in efficiency due to:**

1. **Recombination** of holes and electrons before they can contribute to current flow.
2. Only about half to two-thirds of the full **band-gap voltage** across the terminals of the solar cell.
3. Photons that are **not absorbed** in the cell
4. **Internal resistance** within the cell, which dissipates power.

P-N junction diode

current only flows in 1 direction.

- Photovoltaics use p-n junction semiconductor to avoid holes recombining with electrons



(a) p–n junction diode

(b) Symbol for real diode

(c) Diode characteristic curve

in K.

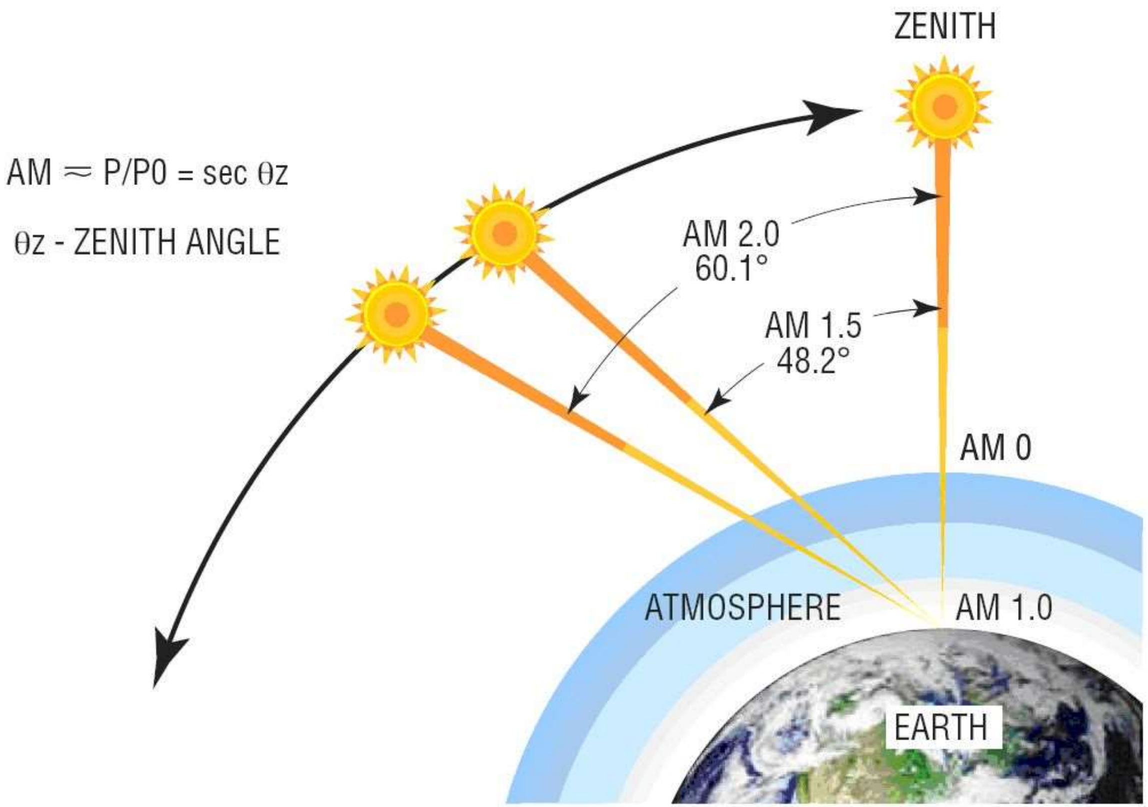
$$I_d = I_0(e^{qV_d/kT} - 1)$$

$$\boxed{I_d = I_0(e^{38.9V_d} - 1) \qquad \text{(at } 25^\circ\text{C)}}$$

where I_d is the diode current in the direction of the arrow (A), V_d is the voltage across the diode terminals from the p-side to the n-side (V), I_0 is the reverse saturation current (A), q is the electron charge (1.602×10^{-19}C), k is Boltzmann's constant (1.381×10^{-23} J/K), and T is the junction temperature (K).

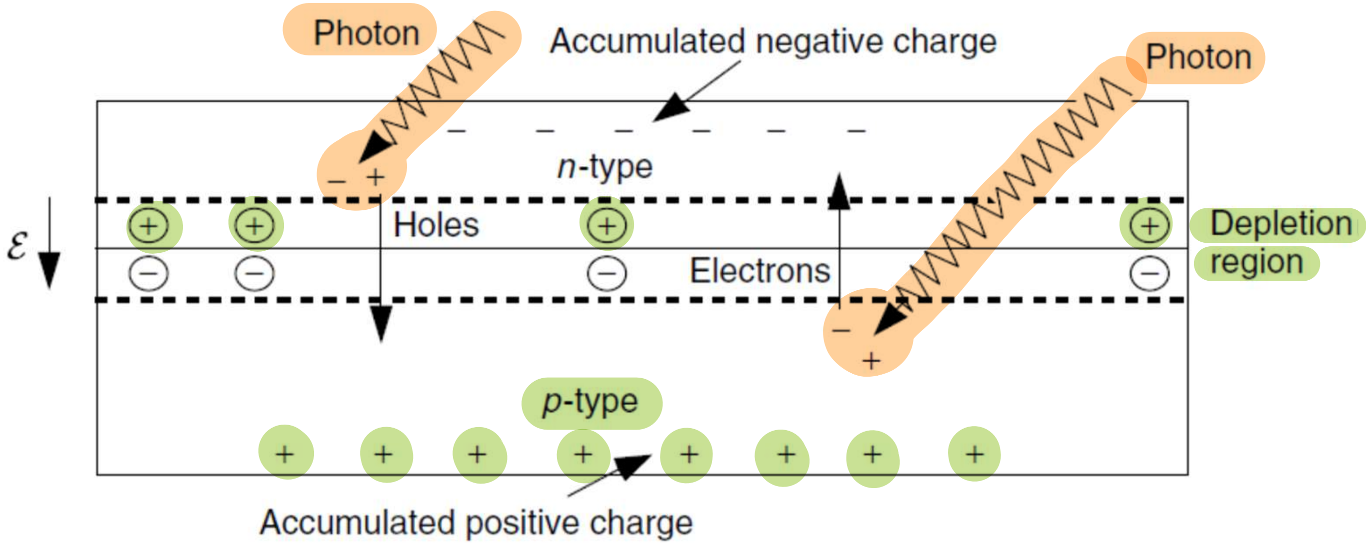
What is meant by "1 Sun"?

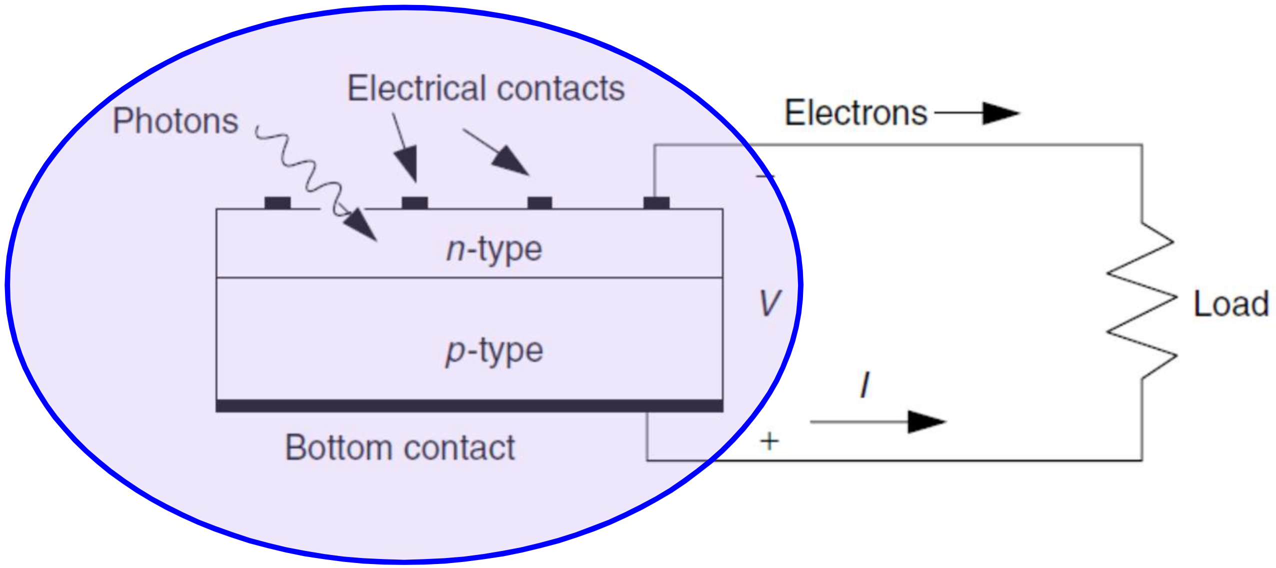
At air mass AM 1.5, 1 sun is defined as equal to $1kW/m^2$ of irradiance

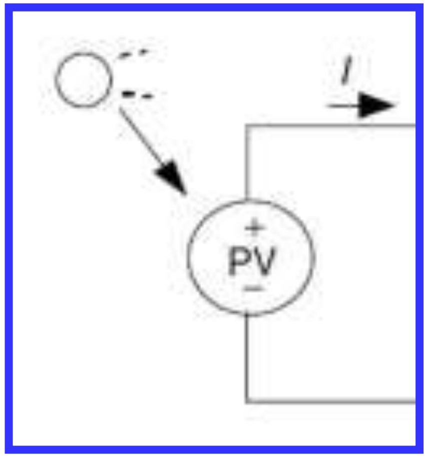


1 sun = $1kW/m^2$ irradiance

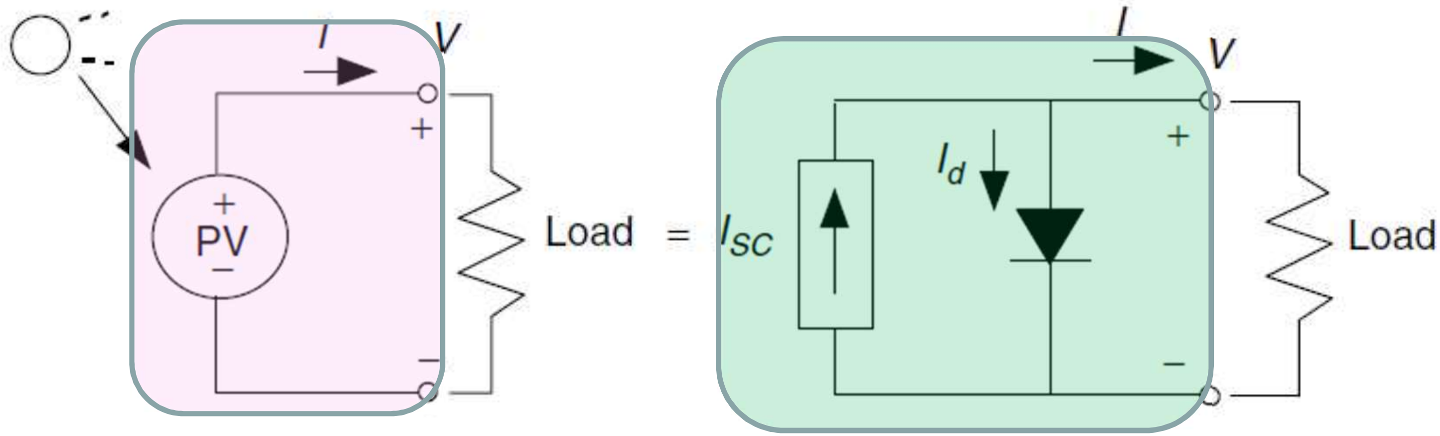
Equivalent Circuit for a Photovoltaic Cell



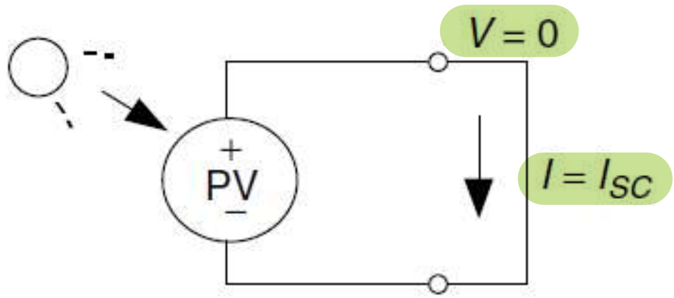




Equivalent Circuit for a Photovoltaic Cell



Voltage and current equations for the PV cell



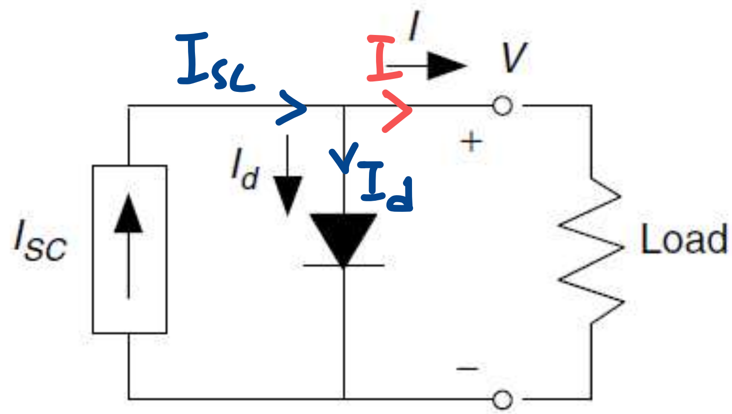
(a) Short-circuit current

Hence the magnitude of ideal current source = I_{SC} — ALL current collected (ideal)

$I_{sc} = I$

Voltage and current equations for the PV cell

Current ***I***: $I = \underbrace{I_{SC} - I_d}$ current drop due to losses

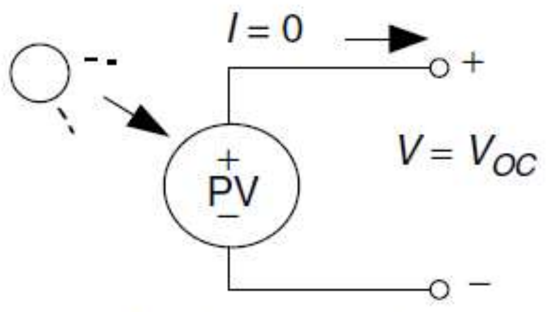


From the diode characteristics, substituting for I_d:

$$I = I_{SC} - I_0 \left(e^{qV/kT} - 1\right)$$

Voltage and current equations for the PV cell

$$I = I_{SC} - I_0\left(e^{qV/kT} - 1\right)$$



(b) Open-circuit voltage

Open circuit voltage (when I = 0):

$$V_{OC} = \frac{kT}{q}\ln\left(\frac{I_{SC}}{I_0} + 1\right)$$

At 25^0 C, the equations become:

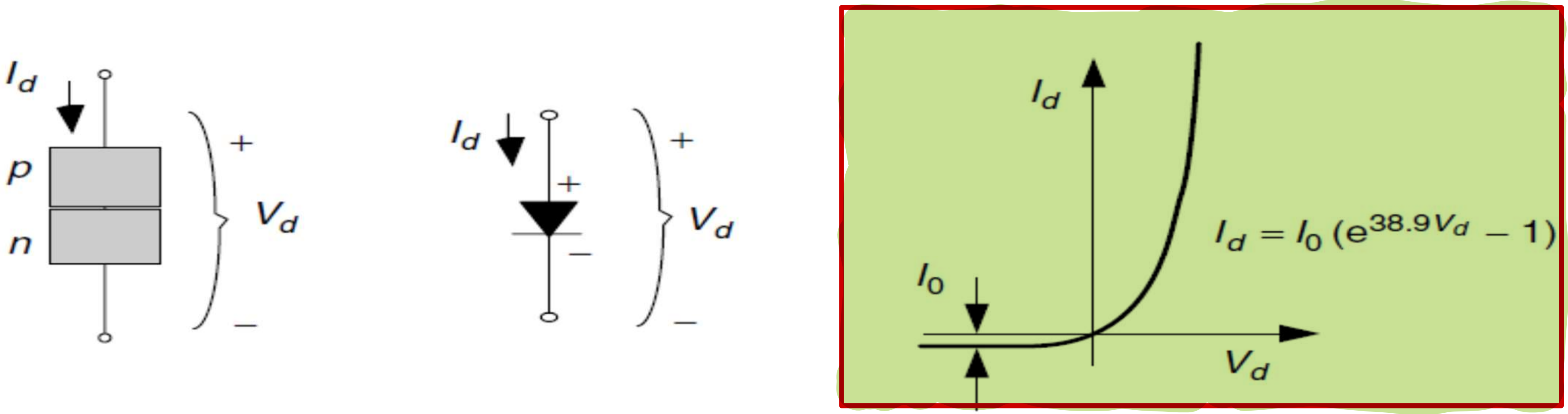
$$\boxed{I = I_{SC} - I_0(e^{38.9\ V} - 1)} \qquad \boxed{V_{OC} = 0.0257\ln\left(\frac{I_{SC}}{I_0} + 1\right)}$$

under OPEN CIRCUIT conditions!!

↳ $I = 0$

↳ $V = V_{oc}$

P-N junction diode



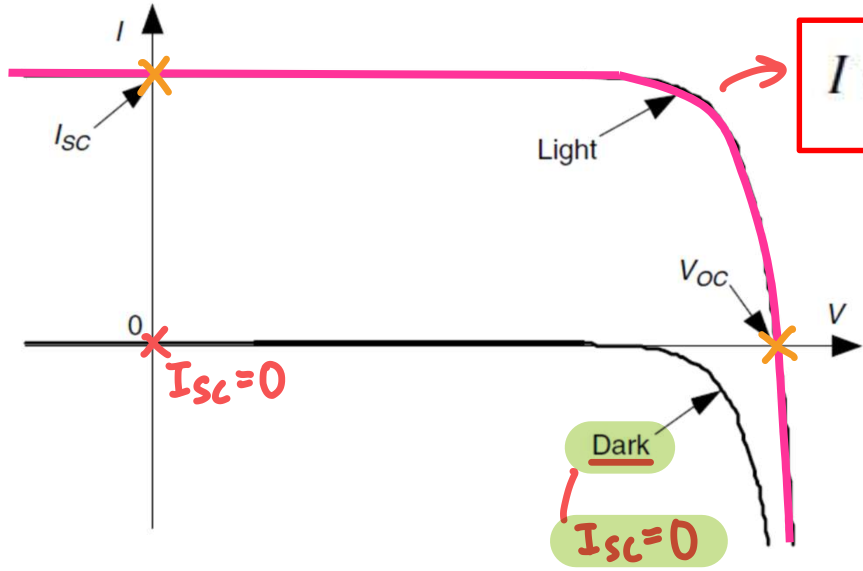
(a) p–n junction diode

(b) Symbol for real diode

(c) Diode characteristic curve

Photovoltaic current–voltage relationship

- In both these equations, **short circuit current is directly proportional to solar insolation**, hence we can now plot current-voltage curves for varying sunlight.
- The dark (no sunlight) curve is just the diode curve turned upside-down. The light (illuminated cell) curve is the dark curve plus I_{SC}



$$I = I_{SC} - I_0(e^{38.9\ V} - 1)$$

Example **The $I-V$ Curve for a Photovoltaic Cell.** Consider a 100-cm^2 photovoltaic cell with reverse saturation current $I_0 = 10^{-12}$ A/cm^2. In full sun, it produces a short-circuit current of 40 mA/cm^2 at 25°C. Find the open-circuit voltage at full sun and again for 50% sunlight. Plot the results.

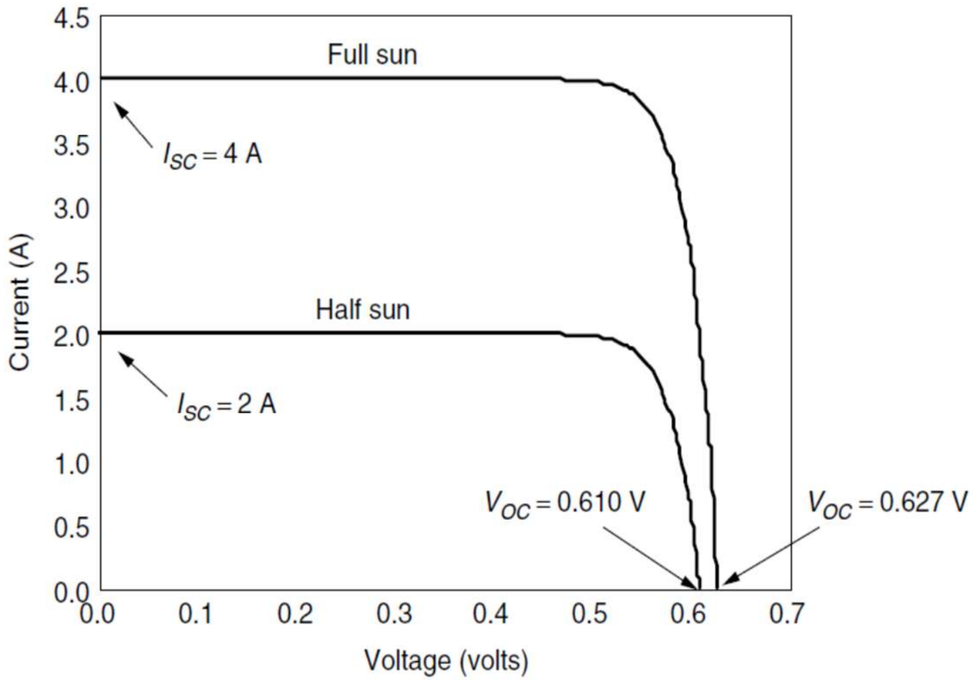
Solution. The reverse saturation current I_0 is 10^{-12} A/cm^2 $\times$ 100 cm^2 $= 1 \times 10^{-10}$ A. At full sun I_{SC} is 0.040 A/cm^2 $\times$ 100 cm^2 $=$ 4.0 A.

$$V_{OC} = 0.0257 \ln\left(\frac{I_{SC}}{I_0} + 1\right) = 0.0257 \ln\left(\frac{4.0}{10^{-10}} + 1\right) = 0.627 \text{ V}$$

Since short-circuit current is proportional to solar intensity, at half sun $I_{SC} = 2$ A and the open-circuit voltage is

$$V_{OC} = 0.0257 \ln\left(\frac{2}{10^{-10}} + 1\right) = 0.610 \text{ V}$$

$I_{sc} \propto$ sunlight intensity

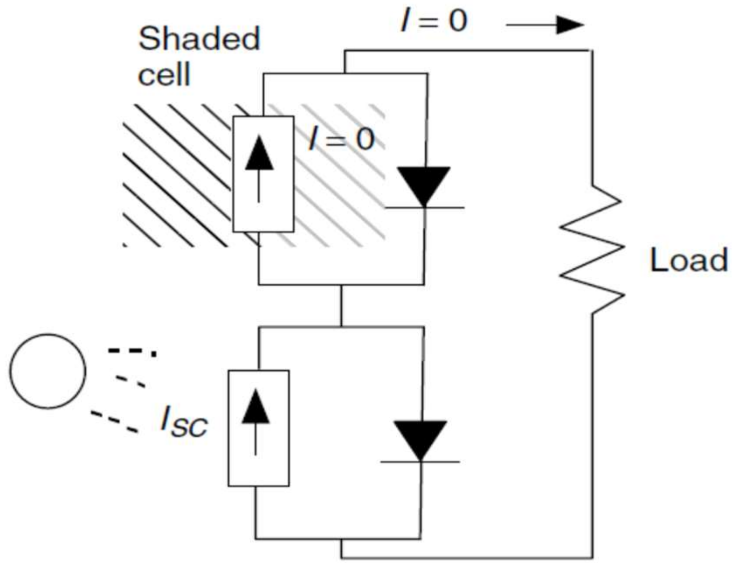


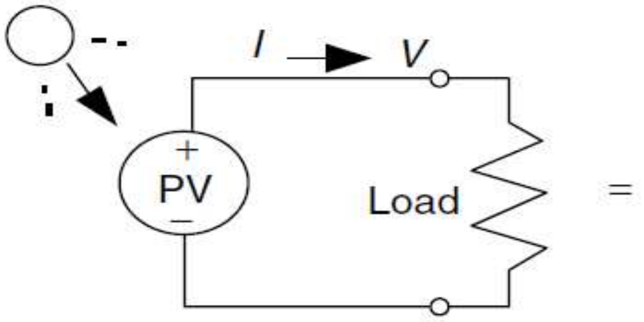
A more accurate Equivalent Circuit for a PV Cell

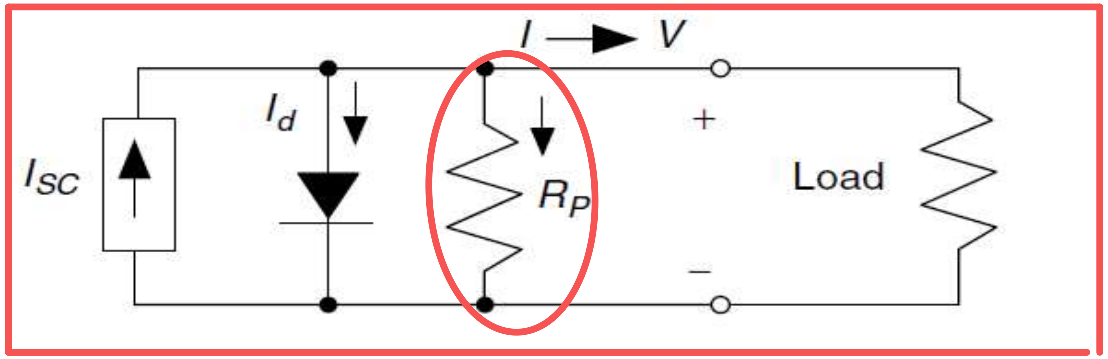
Equivalent circuit of a PV cell…

The simple equivalent circuit of a string of cells in series suggests no current can flow to the load if any cell is in the dark (shaded).

A more complex model can deal with this problem.





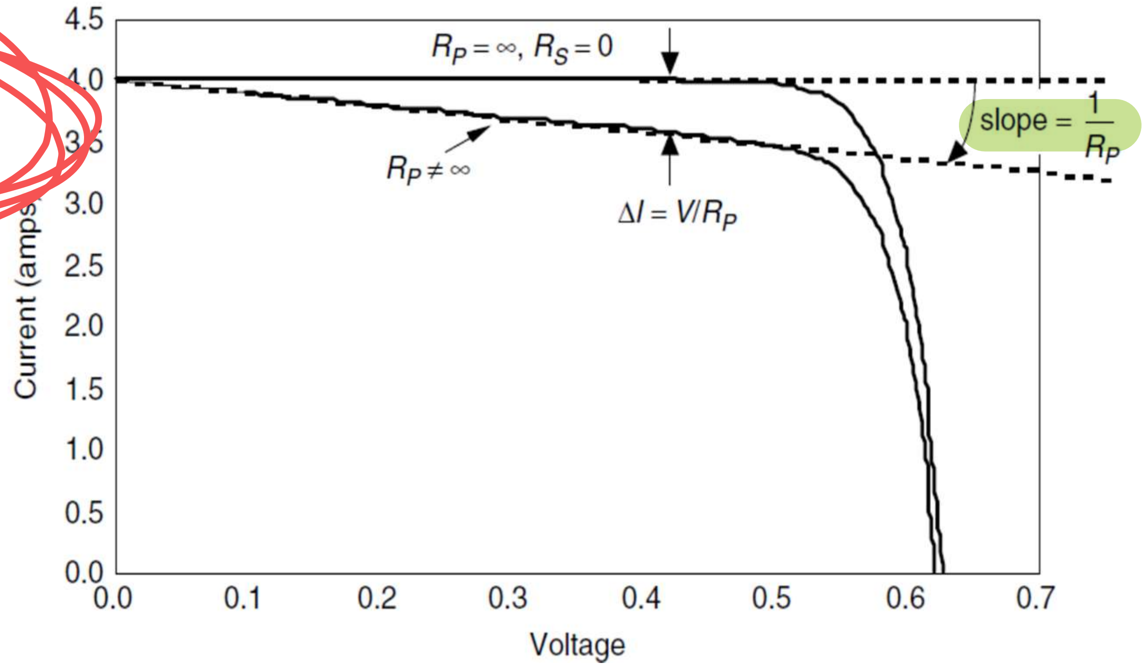


$$I = (I_{SC} - I_d) - \frac{V}{R_p}$$

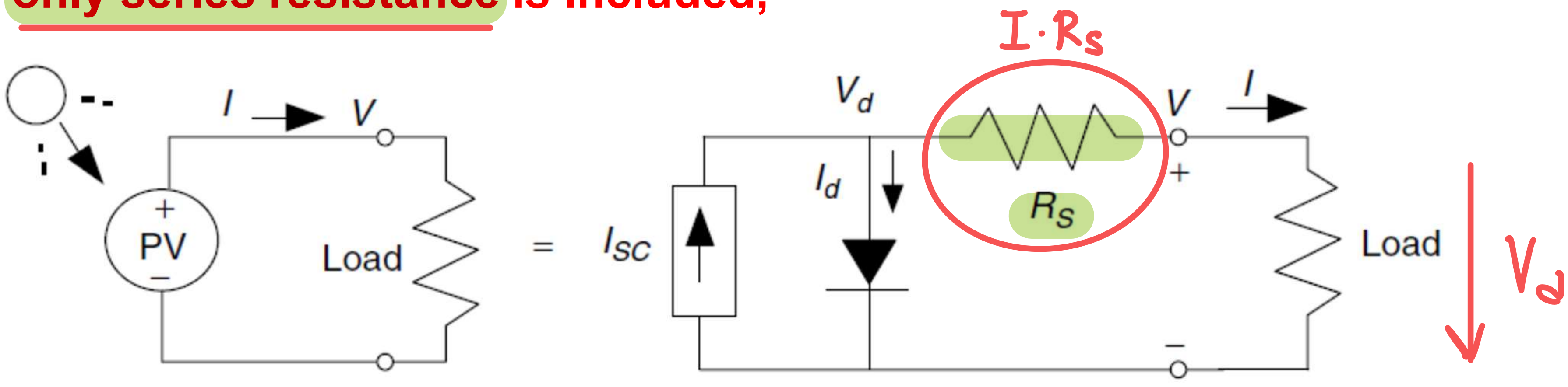
Simple PV equivalent circuit with an added parallel resistance

- Modifying the idealized PV equivalent circuit by adding parallel resistance causes the current at any given voltage to drop by V/R_P .

$$I = (I_{SC} - I_d) - \frac{V}{R_p}$$



- A more accurate equivalent circuit includes series resistance to incorporate other losses
- **If only series resistance is included,**



The original equation: $I = I_{SC} - I_d = I_{SC} - I_0\left(e^{qV_d/kT} - 1\right)$

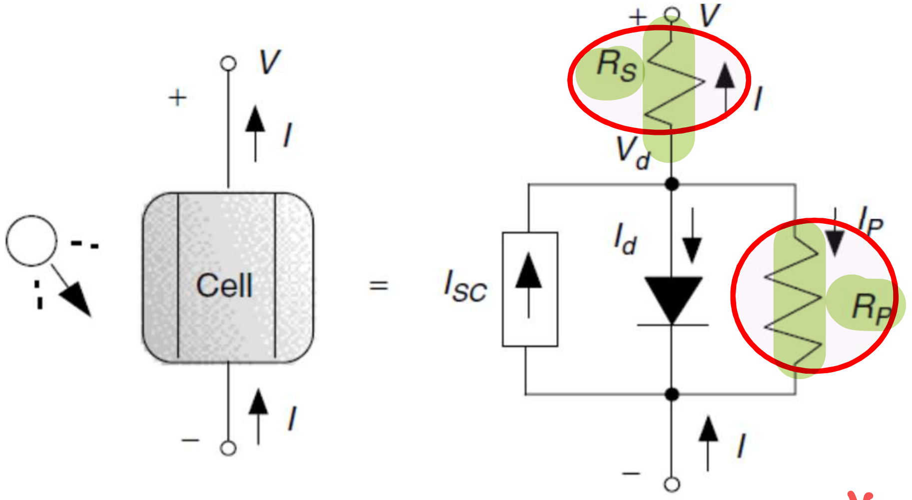
Modified to include R_s gives $V_d = V + I \cdot R_S$

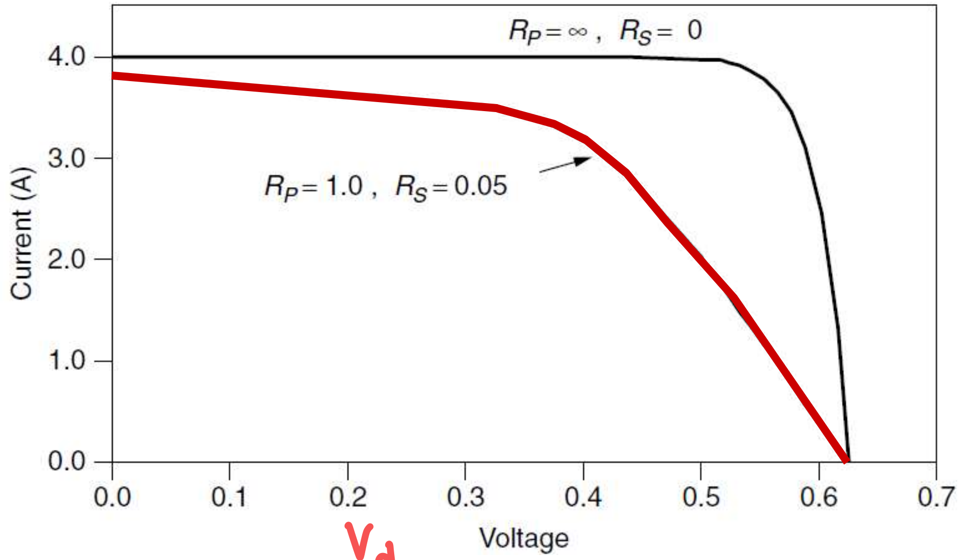
to give

$$I = I_{SC} - I_0 \left\{ \exp\left[\frac{q(V + I \cdot R_S)}{kT}\right] - 1 \right\}$$

Equivalent circuit of a Solar Cell

- A more accurate equivalent circuit includes both series and parallel resistance





$$I = I_{SC} - I_0 \left\{ \exp\left[\frac{q\overbrace{(V + I \cdot R_S)}^{V_d}}{kT} \right] - 1 \right\} - \left(\frac{\overbrace{V + I \cdot R_S}^{V_d}}{R_P} \right)$$

$$I_{SC} = I + I_d + I_P$$

Under the standard test conditions of 25º cell temp,

$$I = I_{SC} - I_0 \left[e^{38.9(V+IR_S)} - 1 \right] - \frac{1}{R_P}(V + IR_S) \qquad \text{at } 25^\circ\mathrm{C}$$

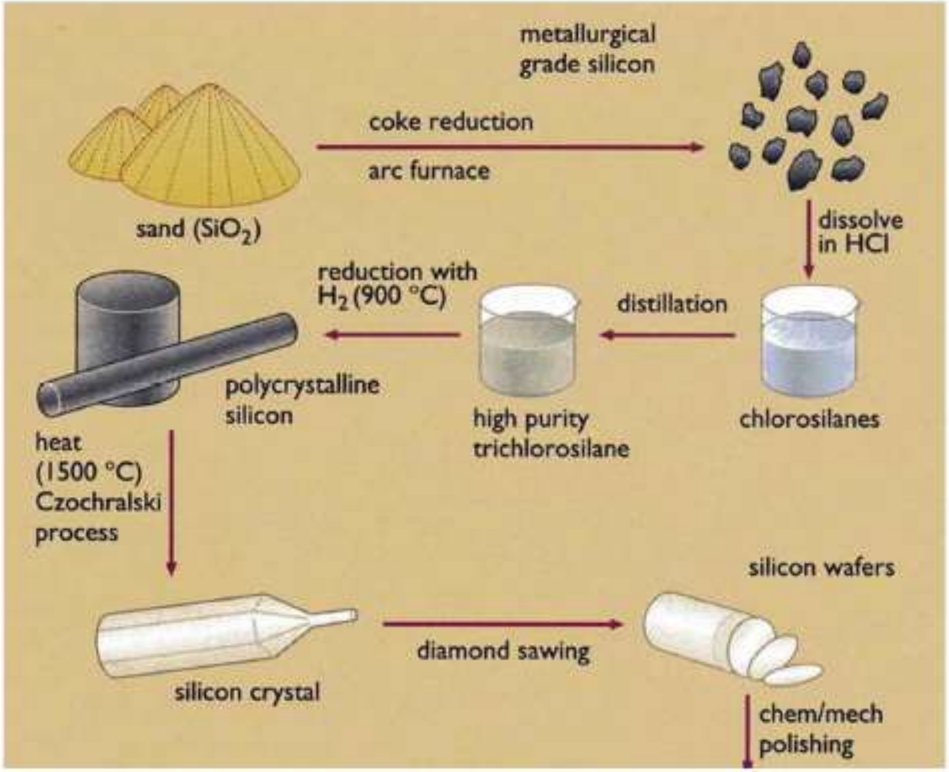
How Solar Cells are made?

Solar Cell Construction

- Materials
  - Crystalline Silicon or Gallium Arsenide (more expensive)
- Grown into large single-crystal ingots
- Sawed into thin wafers

Czochralski Process

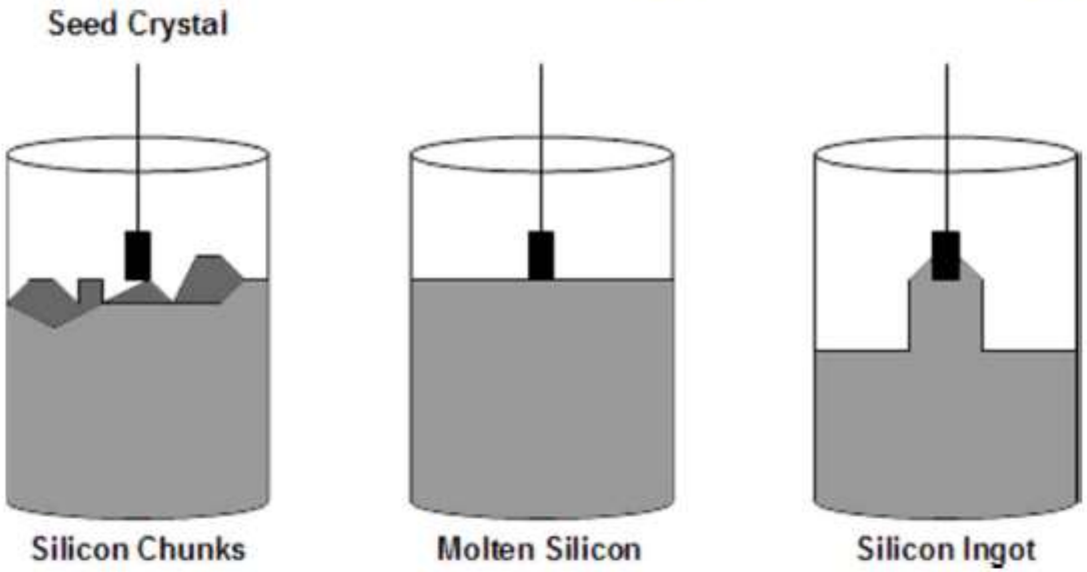
↳ wafers are sliced up to 20-30cm wide, 2m long, few hundreds kg



- 2 wafers are bonded together (p-n junction)
- Wafers grouped into panels or arrays

http://en.wikipedia.org/wiki/Solar_panel

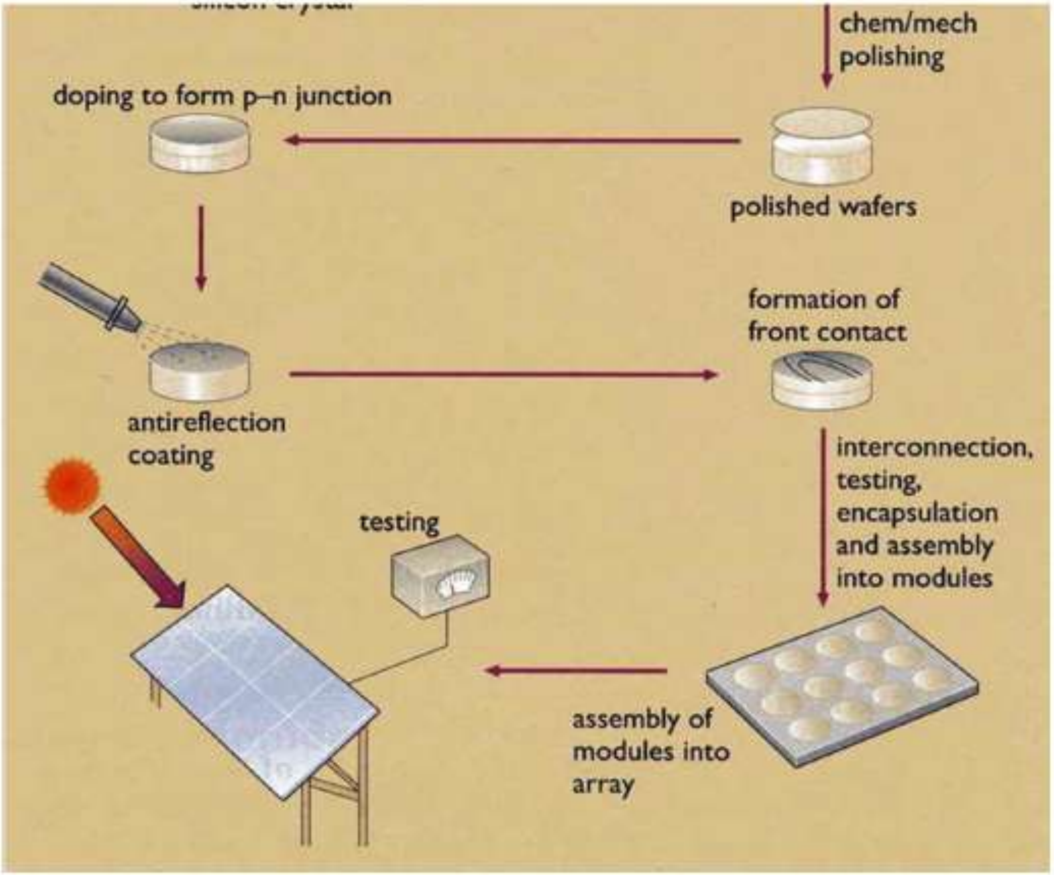
Growing Silicon Ingots



Czochralski Process

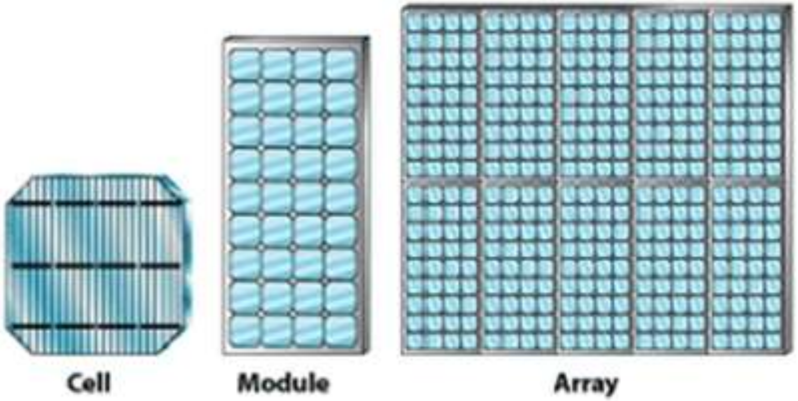
Creating PV Cells

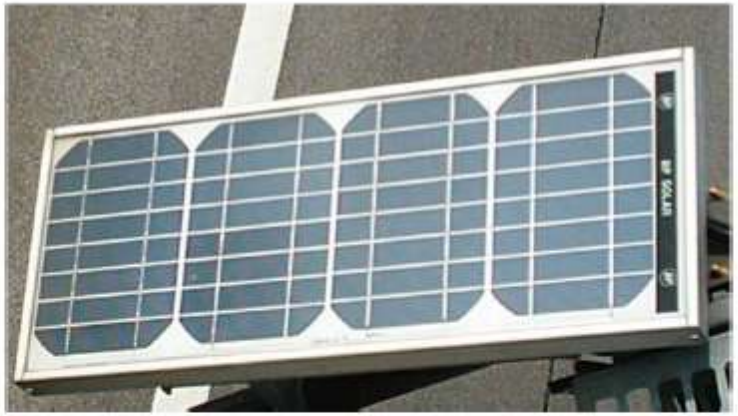
generates a lot of CO_2 & emissions in the making process ..



Solar PV Systems

- **Cells** are the building block of PV systems
  - Typically generate 1.5 - 3 watts of power
- ~36x cells **Modules** or panels are made up of multiple cells
- **Arrays** are made up of multiple modules (panels) that comprises the complete PV generating system





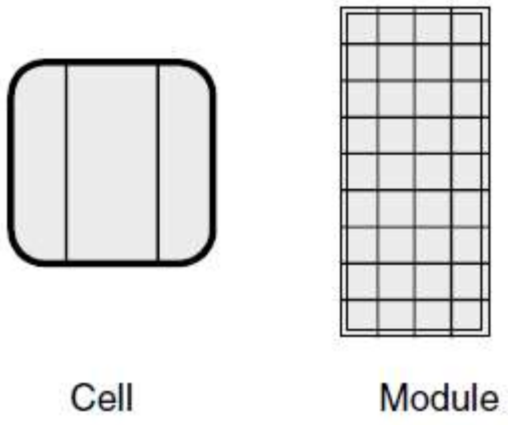
Solar panel by BP Solar at a German autobahn bridge

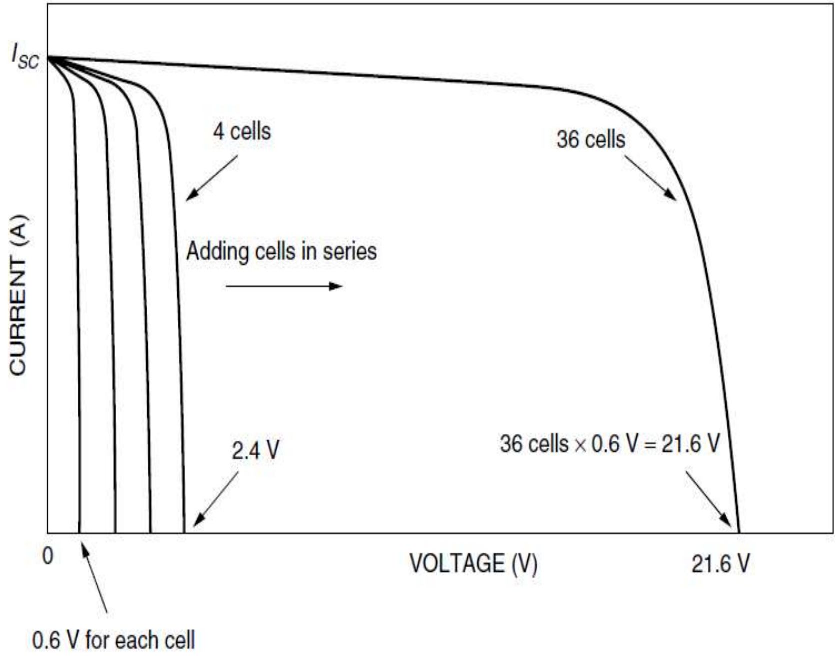
From cells to a module

- A typical module has 36 cells
- Often designated as 12-V module
- When wired in series, they carry the same current, but voltages add
- Overall module voltage for n cells

$$V_{\text{module}} = n(V_d - IR_S)$$

n=no. of cells





Voltage and current from a PV module

Example: A PV module is made up of 36 identical cells, all wired in series.

With 1-sun insolation (1 kW/m^2), each cell has short-circuit current $I_{SC} = 3.4\ A$

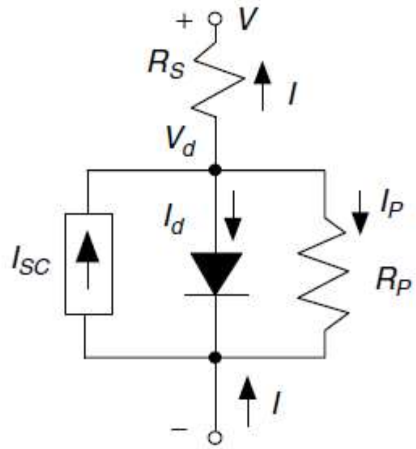
and at 25°C its reverse saturation current is $I_0 = 6 \times 10^{-10}\ A$.

Parallel resistance $R_P = 6.6\Omega$ *and*

series resistance $R_S = 0.005\Omega$.

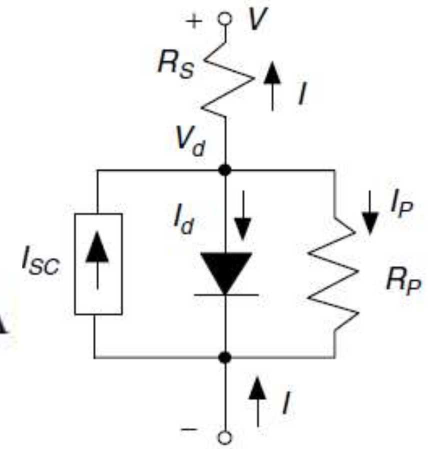
Find the voltage, current, and power delivered when the junction voltage of each cell is 0.50 V

V_d



Voltage and current from a PV module

Example: A PV module is made up of 36 identical cells, all wired in series. With 1-sun insolation (1 kW/m^2), each cell has short-circuit current I_{SC} = 3.4 A and at 25°C its reverse saturation current is $I_0 = 6 \times 10^{-10}$ A. Parallel resistance R_P = 6.6 Ω and series resistance R_S = 0.005 Ω. Find the voltage, current, and power delivered when the junction voltage of each cell is 0.50 V



Using the given data, and V_d = 0.5V,

$$I = I_{SC} - I_0(e^{38.9V_d} - 1) - \frac{V_d}{R_P}$$

$$= 3.4 - 6 \times 10^{-10}(e^{38.9\times0.50} - 1) - \frac{0.50}{6.6} = 3.16 \text{ A}$$

For a 36-cell module, voltage produced

$$V_{\text{module}} = n(V_d - IR_S) = 36(0.50 - 3.16 \times 0.005) = 17.43 \text{ V}$$

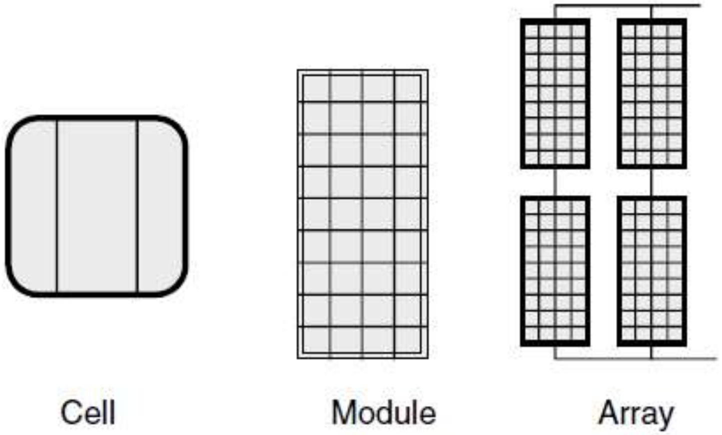
Power delivered is therefore

$$P(\text{watts}) = V_{\text{module}}\, I = 17.43 \times 3.16 = 55.0 \text{ W}$$

$$\eta = \frac{\text{output P}}{\text{input P}}$$

From modules to arrays

- Modules can be wired in series to increase voltage
- Modules can be connected in parallel to increase current
- Series and parallel connection increases power

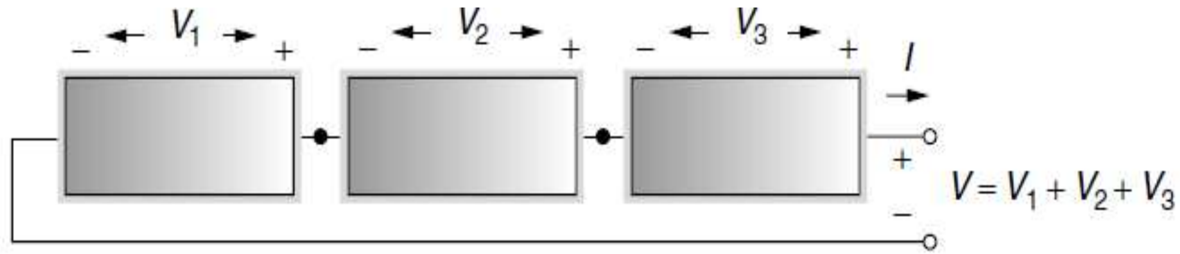


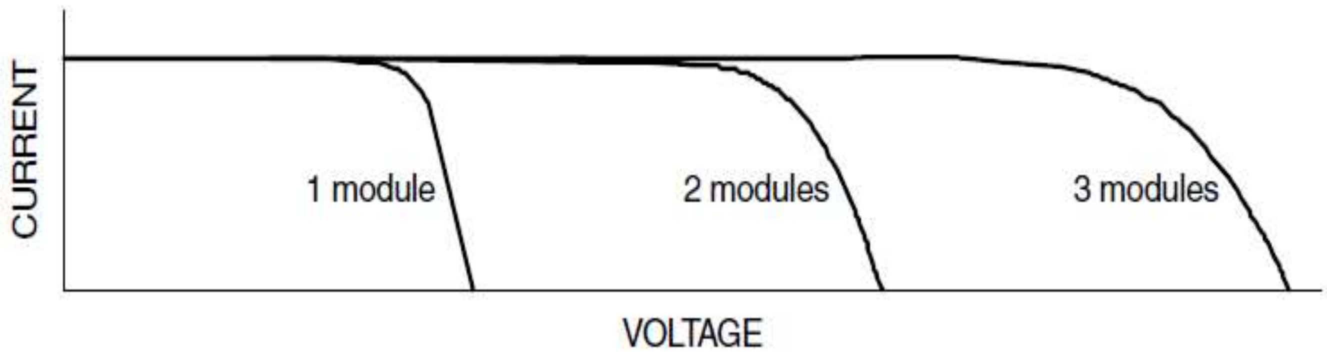
series : ↑V

parallel : ↑I

Modules connected in series

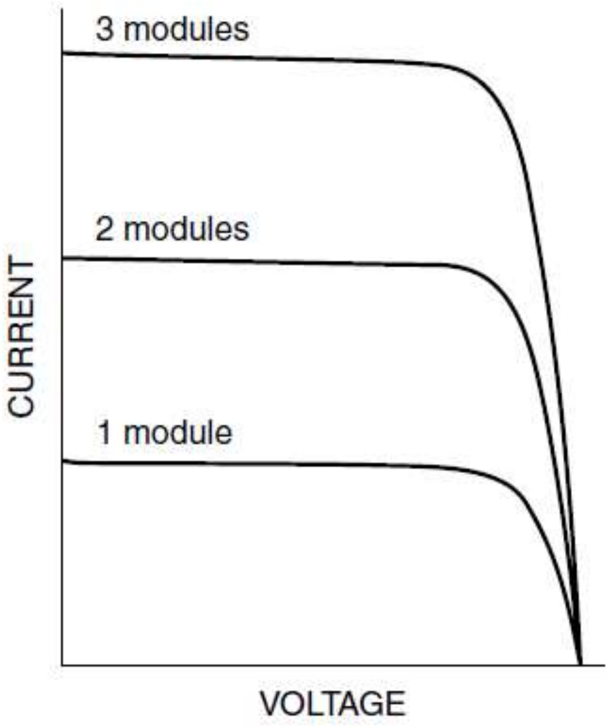
- The voltages produced are added
- Same current flows through all

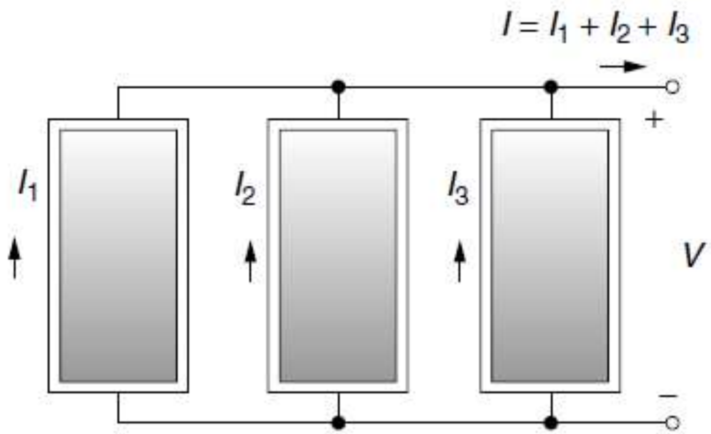




Modules connected in parallel

- Currents add, while voltage remains the same

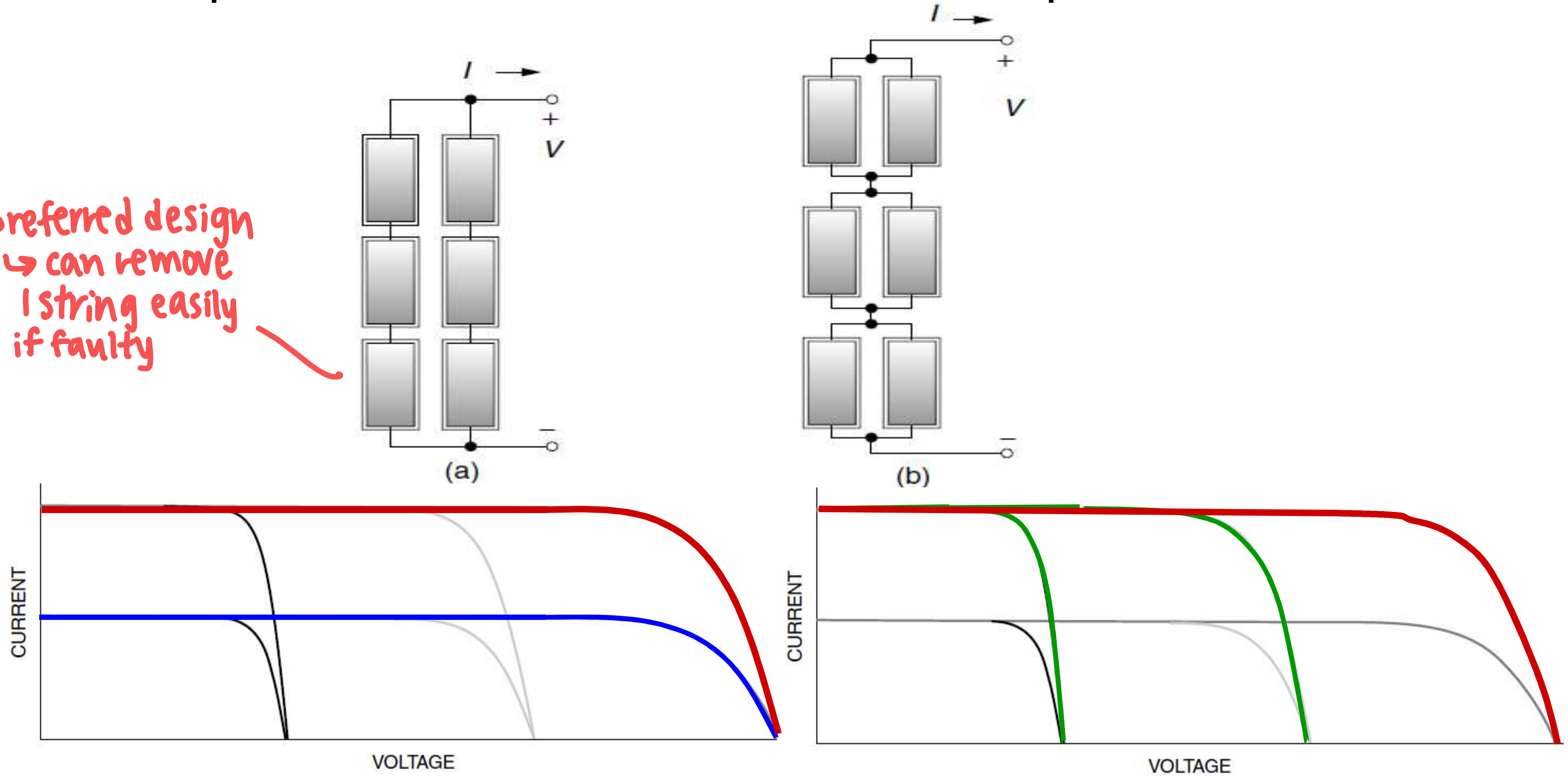




Modules in series-parallel configuration

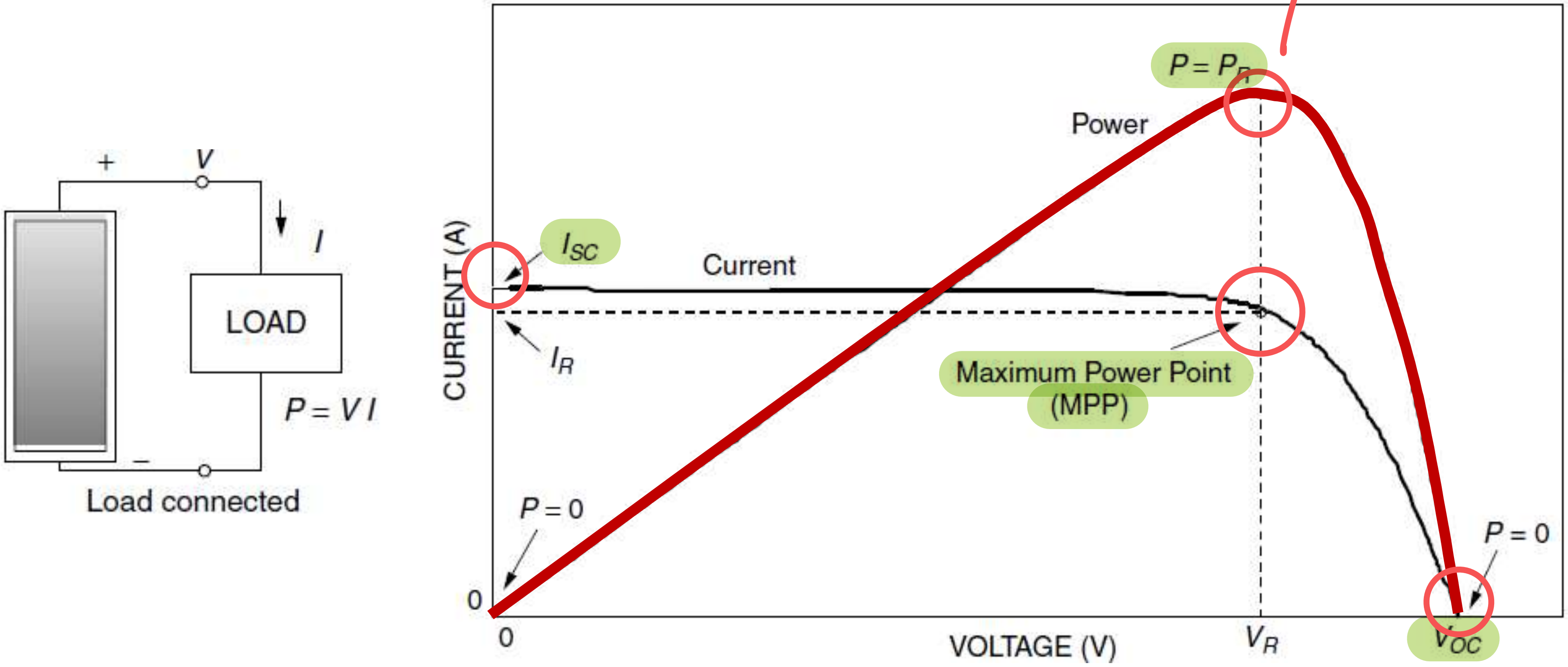
- Example: Three modules in series, two in parallel

preferred design
↳ can remove
1 string easily
if faulty



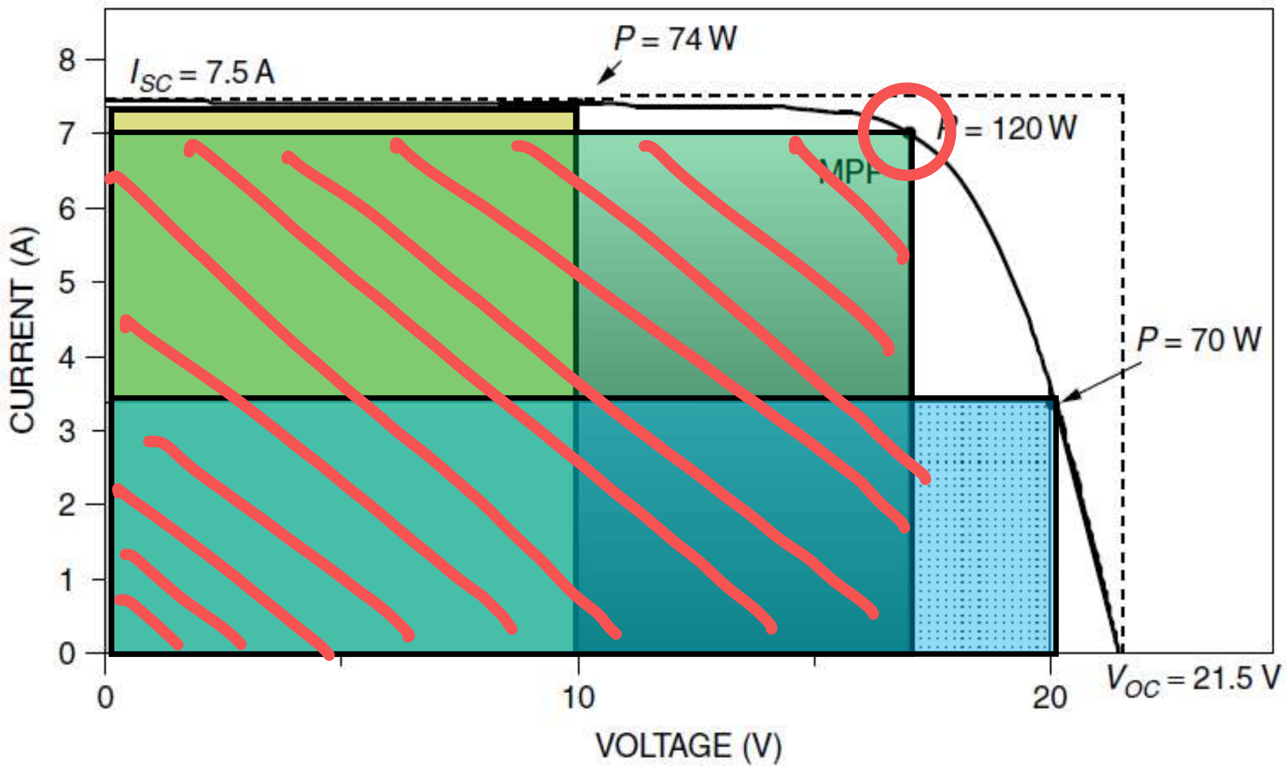
Voltage, Current and Power Curves

rated power operating at MPP!



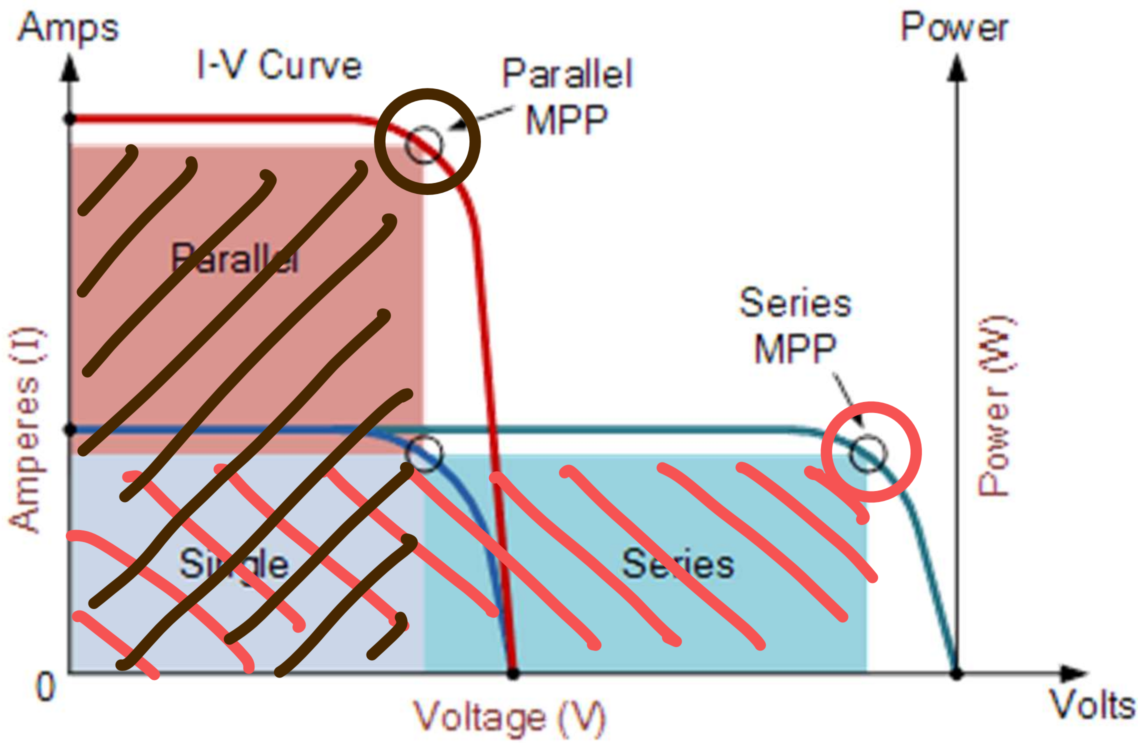
Maximum Power Point (MPP)

- At the maximum power point (MPP) the module delivers the most power that it can under the conditions of sunlight and temperature for which the $I - V$ curve has been drawn



- **MPP corresponds to the biggest rectangle that can fit beneath the $I - V$ curve**

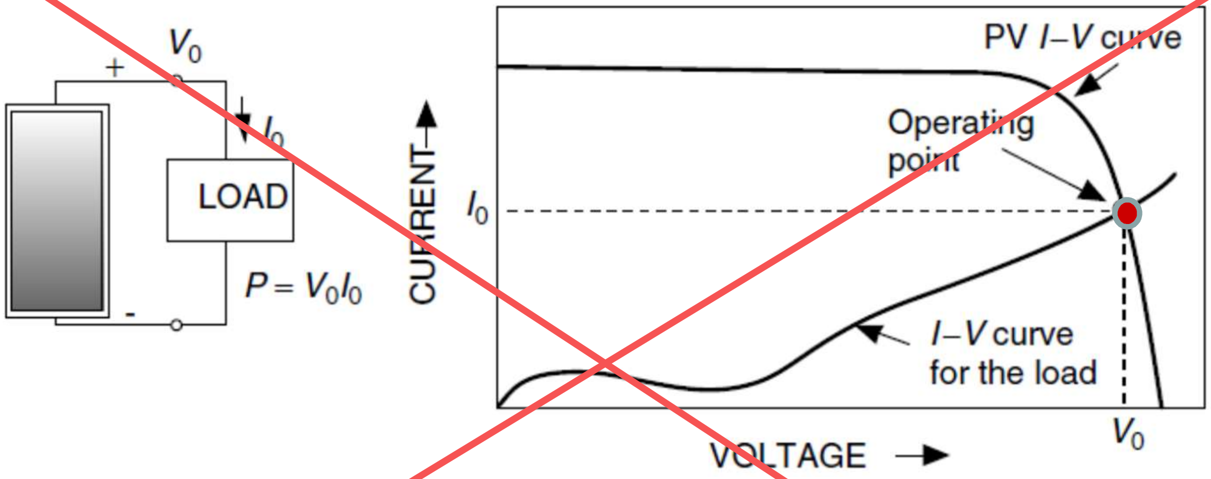
Maximum Power Point (MPP)



What factors can influence the performance of a Solar PV Cell?

Current-Voltage Curve for Load

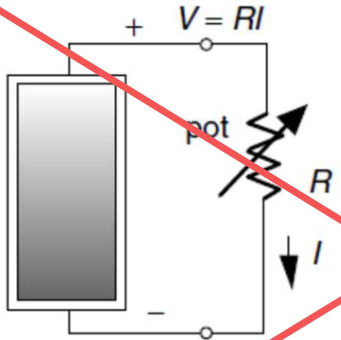
- **Operating point** – intersection of curves where the system will finally operate at

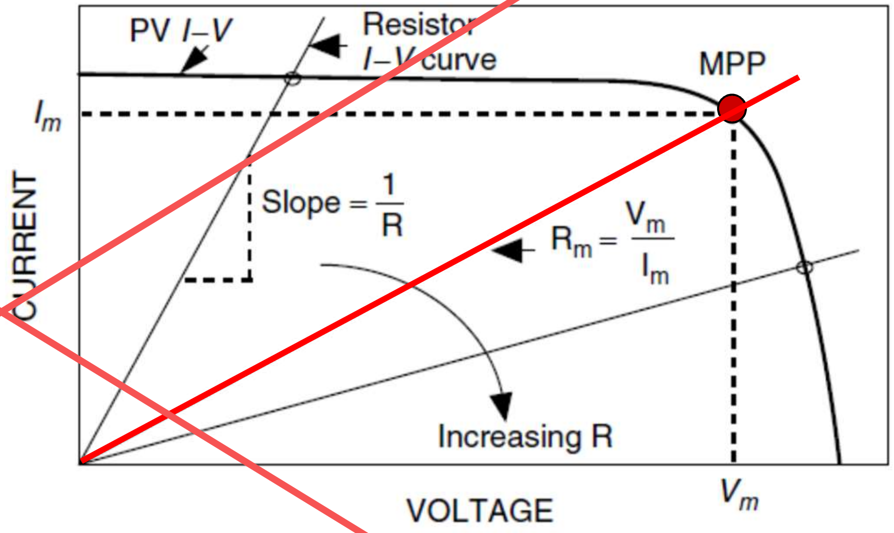


Current-Voltage Curve for Load

Resistance corresponding to maximum power:

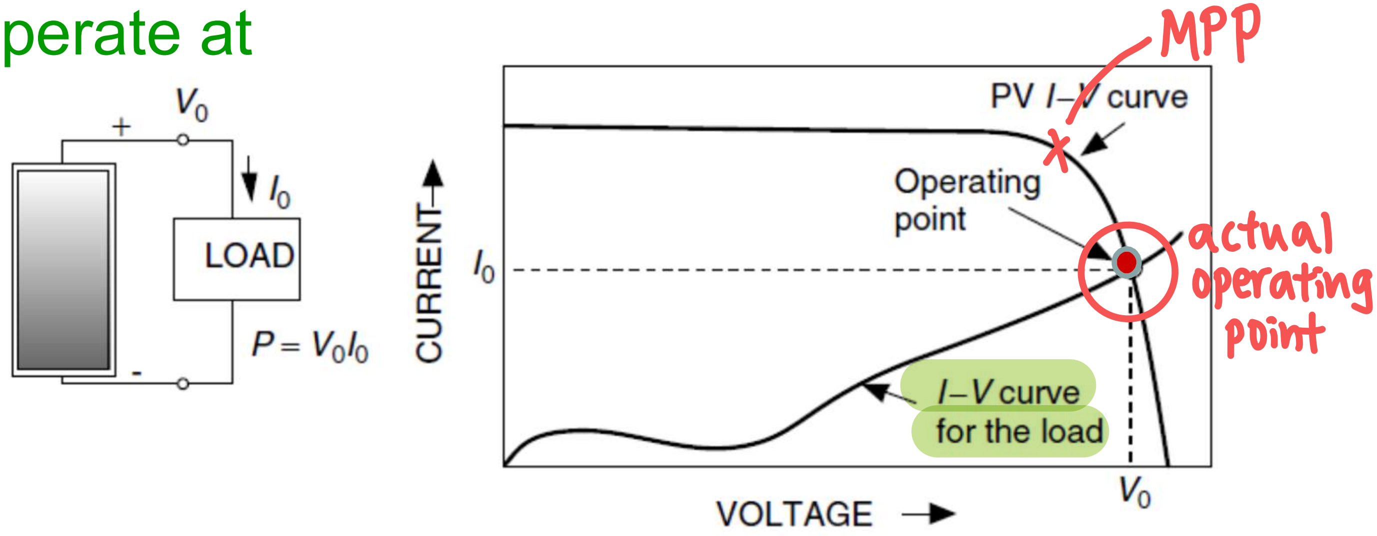
$$R_m = \frac{V_m}{I_m}$$





Current-Voltage Curve for Load

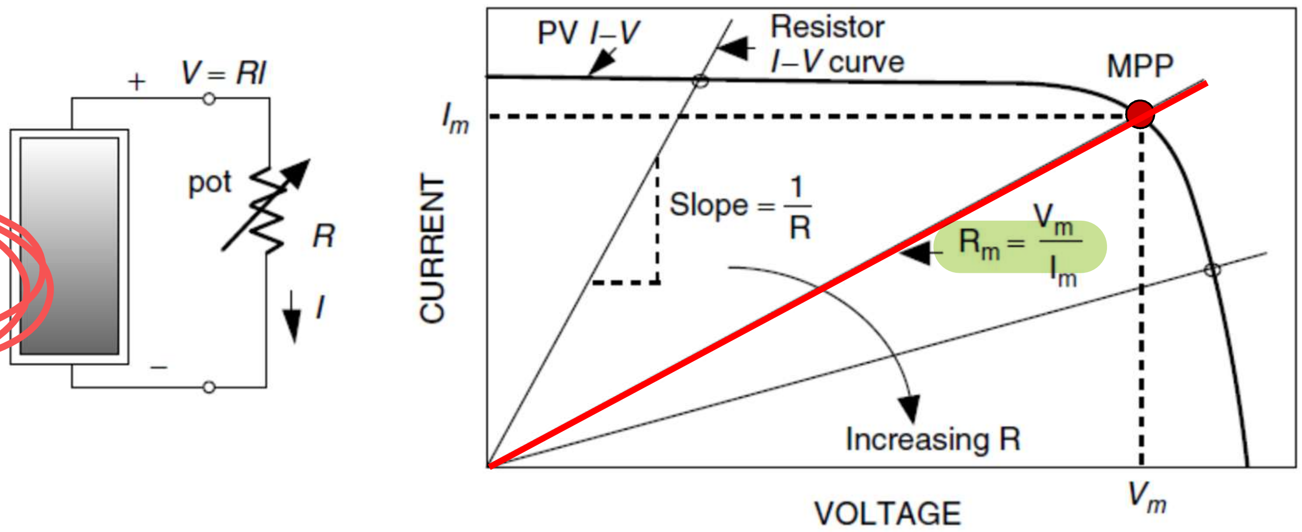
- **Operating point** – intersection of curves where the system will finally operate at



Resistance corresponding to maximum power:

$$R_m = \frac{V_m}{I_m}$$

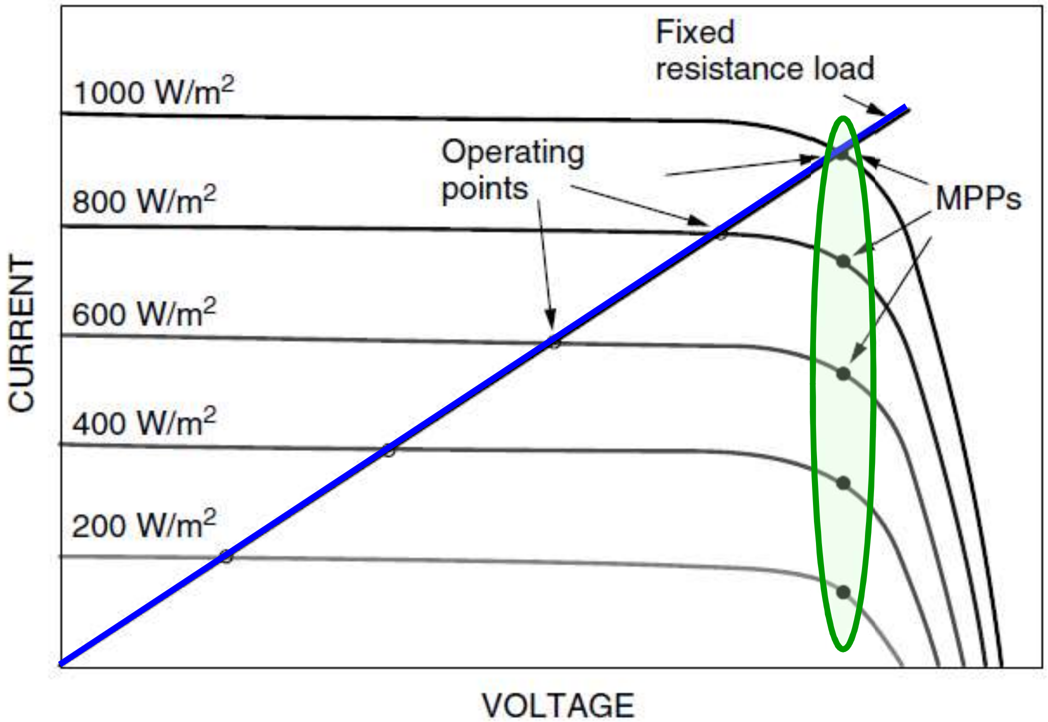
↳R at MPP



Efficiency of a PV module with fixed resistance load

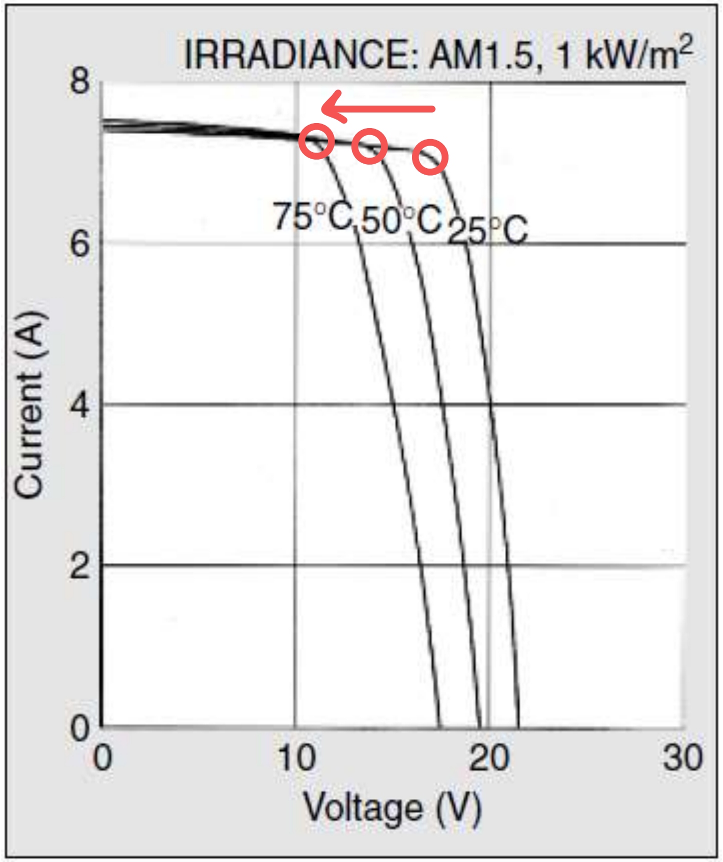
- The best value of resistance for maximum power transfer under 1-sun, 25°C, 1.5 AM conditions would be V_R/I_R hence varying R would be good
- **The operating point however, slips off MPP if resistance is fixed**

Max power point tracker (MPPT) ensures the module operates at highest efficiency point



Effect of temperature

- **With increase in temperature, voltage reduces while current increases very slightly**
- For crystalline Silicon cells, V_{OC} drops by 0.37% per degree C, and I_{SC} increases by 0.05% per degree C
- **MPP drops by approx 0.5% per deg C**

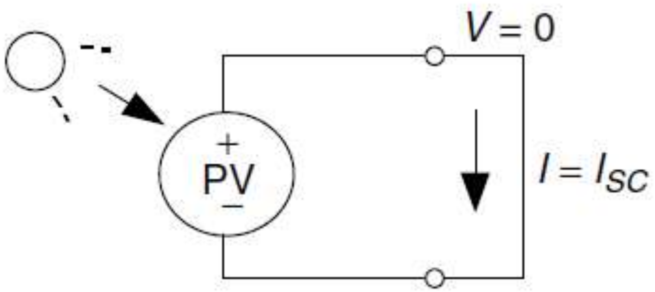


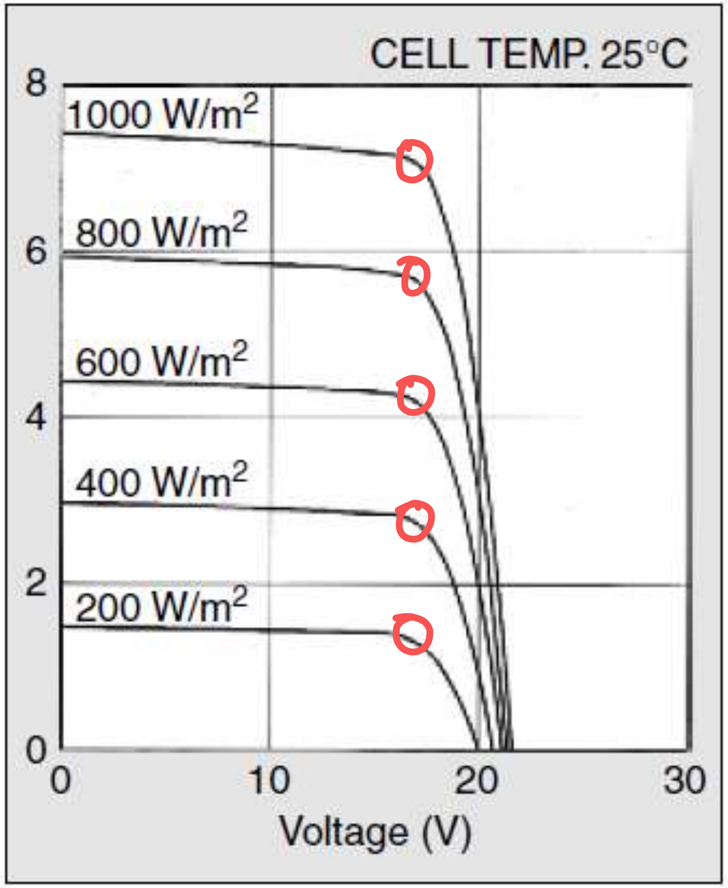
Efficiency drops as the temperature increases

$\uparrow T, \downarrow \eta$

Effect of Insolation

- **As insolation drops, I_{sc} drops proportionately**
- V_{OC} drops very slightly

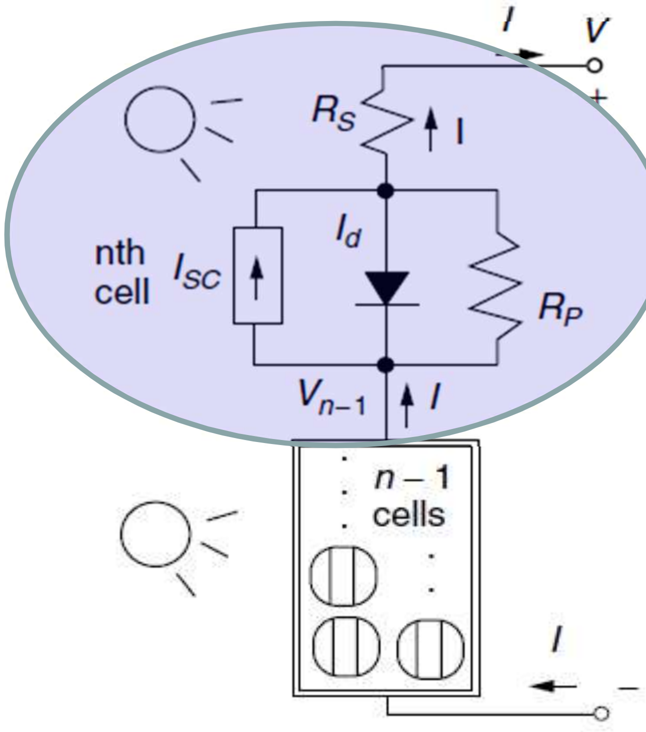




$I_{sc} \propto$ insolation

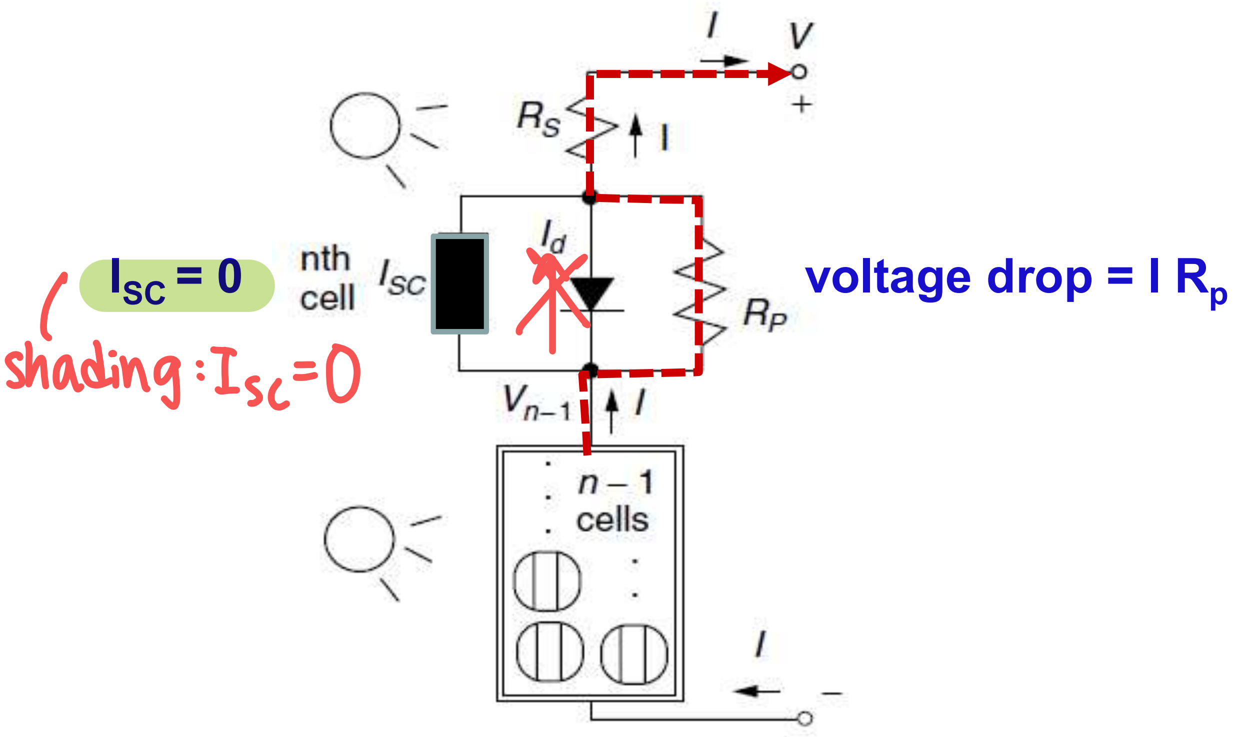
$\downarrow$ insolation, $\downarrow I_{sc}$

Effect of Shading



(a) All cells in the sun

Effect of Shading



(a) All cells in the sun

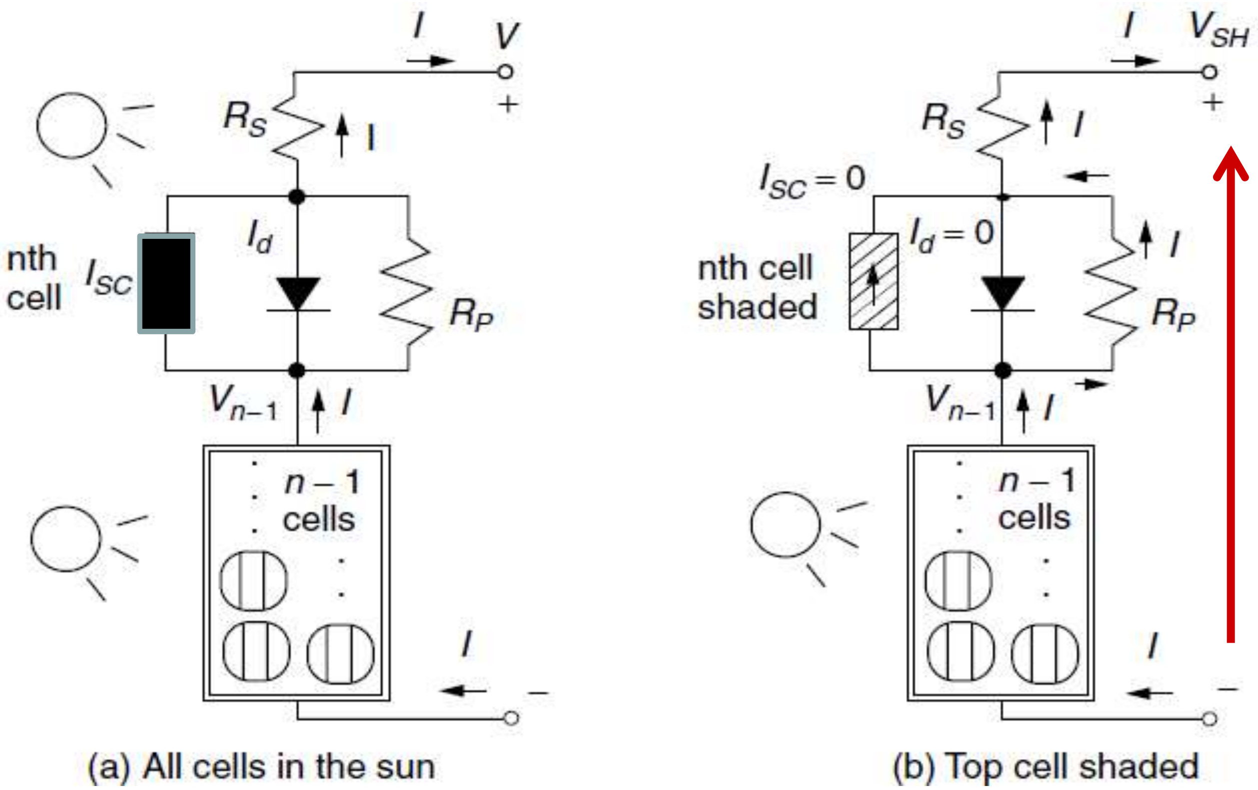
$I_{sc} = 0$

- Even if one cell is shaded, since its short circuit current is now zero, the main current I causes the diode to be reserve biased, hence $I_d = 0$ and total voltage is reduced by IR_p

$I_d = 0$

I cannot pass through!

Effect of Shading



- Even if one cell is shaded, since its short circuit current is now zero, the main current I causes the diode to be reserve biased, hence $I_d = 0$ and total voltage is reduced by IR_p

Effect of shading

Output voltage of the module becomes

$$V_{SH} = V_{n-1} - \underbrace{I(R_P + R_S)}$$

V drop due to shading

For the remaining cells, $V_{n-1} = \left(\frac{n-1}{n}\right) V$

Substituting, $$V_{SH} = \left(\frac{n-1}{n}\right) V - I(R_P + R_S)$$

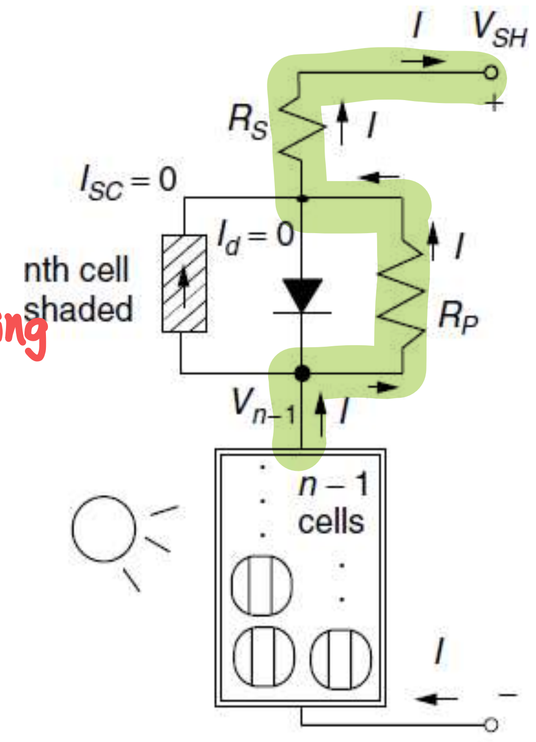
The **drop in voltage** due to shading of one cell:

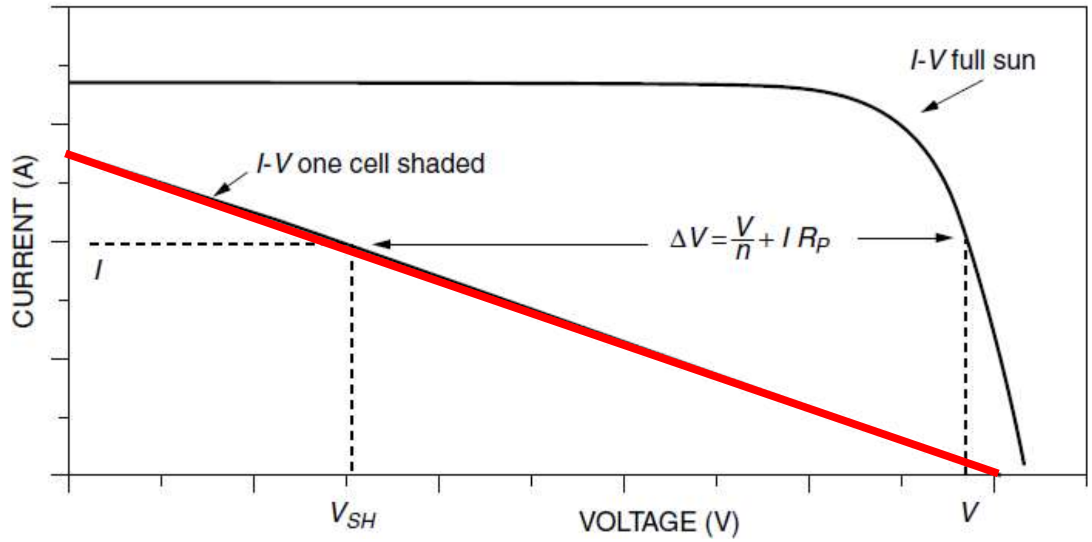
$$\Delta V = V - V_{SH} = V - \left(1 - \frac{1}{n}\right) V + I(R_P + R_S)$$

$$\Delta V = \frac{V}{n} + I(R_P + \cancel{R_S})$$

Since R_s is very small,

$$\Delta V \cong \frac{V}{n} + IR_P$$





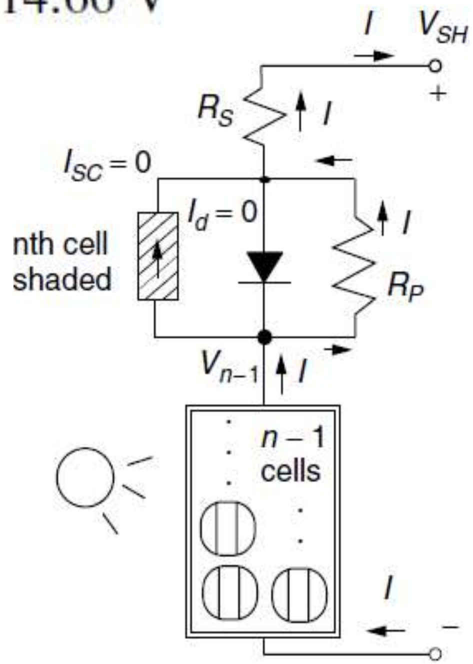
Example: The 36-cell PV module described in previous example had a parallel resistance per cell of R_P = *6.6 Ω. In* full sun and at current *I = 2.14 A the output voltage was found to be V* =19*.41 V.* If one cell is shaded and this current somehow stays the same, then:

- a. What would be the new module output voltage and power?
- b. What would be the voltage drop across the shaded cell?

The drop in module voltage will be $\Delta V = \frac{V}{n} + IR_P$

$$= \frac{19.41}{36} + 2.14 \times 6.6 = 14.66 \text{ V}$$

The new output voltage will be $19.41 - 14.66 = 4.75$ V



Example: The 36-cell PV module described in previous example had a parallel resistance per cell of R_P = *6.6 Ω. In* full sun and at current *I = 2.14 A the output voltage was found to be V* =19*.41 V.* If one cell is shaded and this current somehow stays the same, then:

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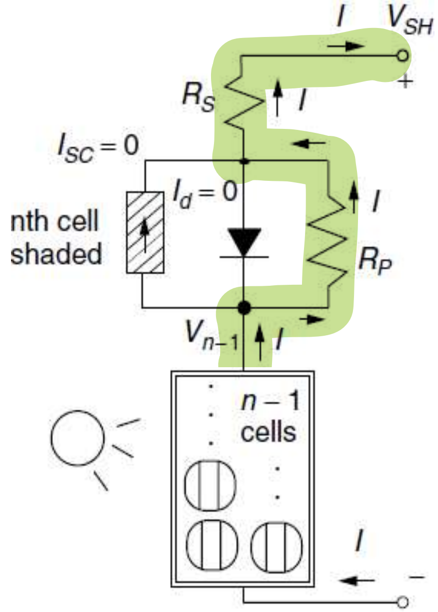


Power delivered by the module with one cell shaded would be

P lost is converted to heat
↳ might damage the PV cell

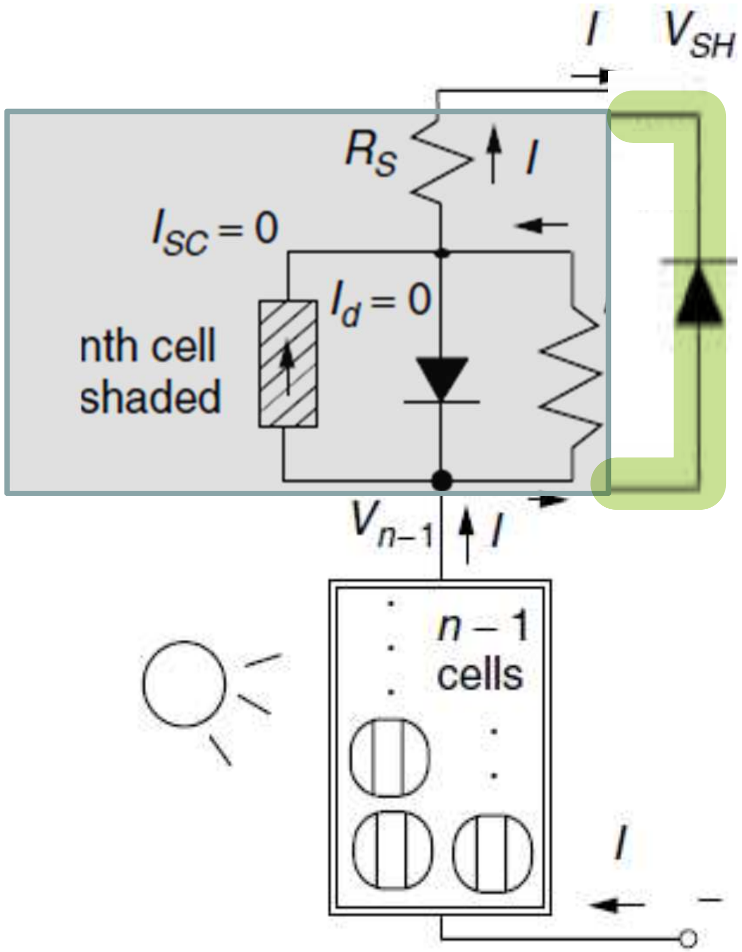
$$P_{\text{module}} = VI = 4.75 \text{ V} \times 2.14 \text{ A} = 10.1 \text{ W}$$

For comparison, in full sun the module was producing 41.5 W

All of that 2.14 A of current goes through the parallel plus series resistance (0.005 Ω) of the shaded cell, so the drop across the shaded cell will be

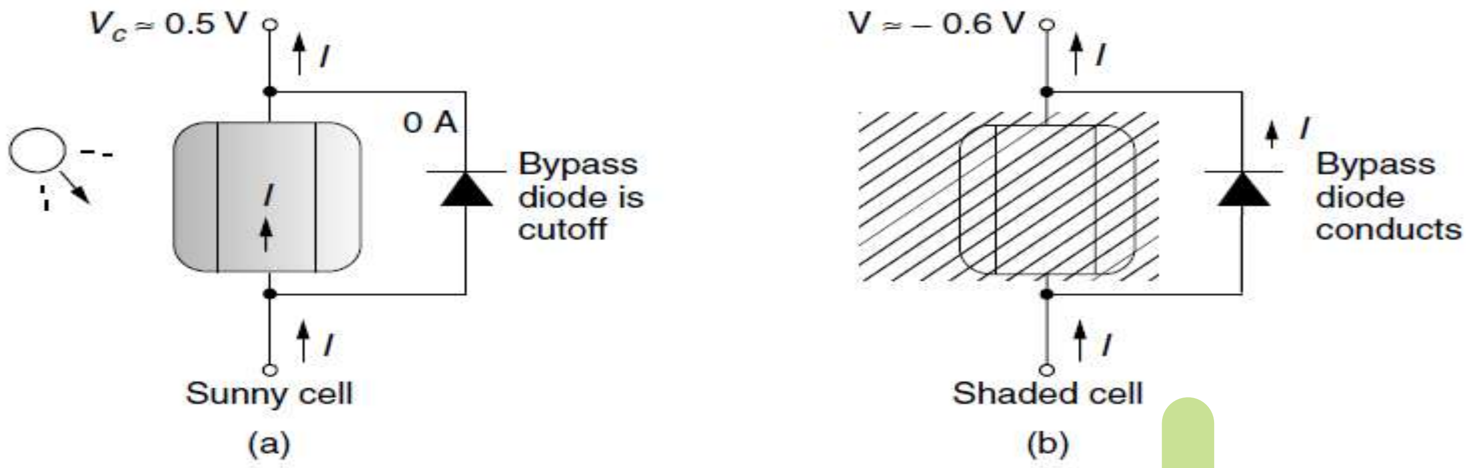
$$V_c = I(R_P + R_S) = 2.14(6.6 + 0.005) = 14.14 \ V$$

Bypass Diode to mitigate effect of shading

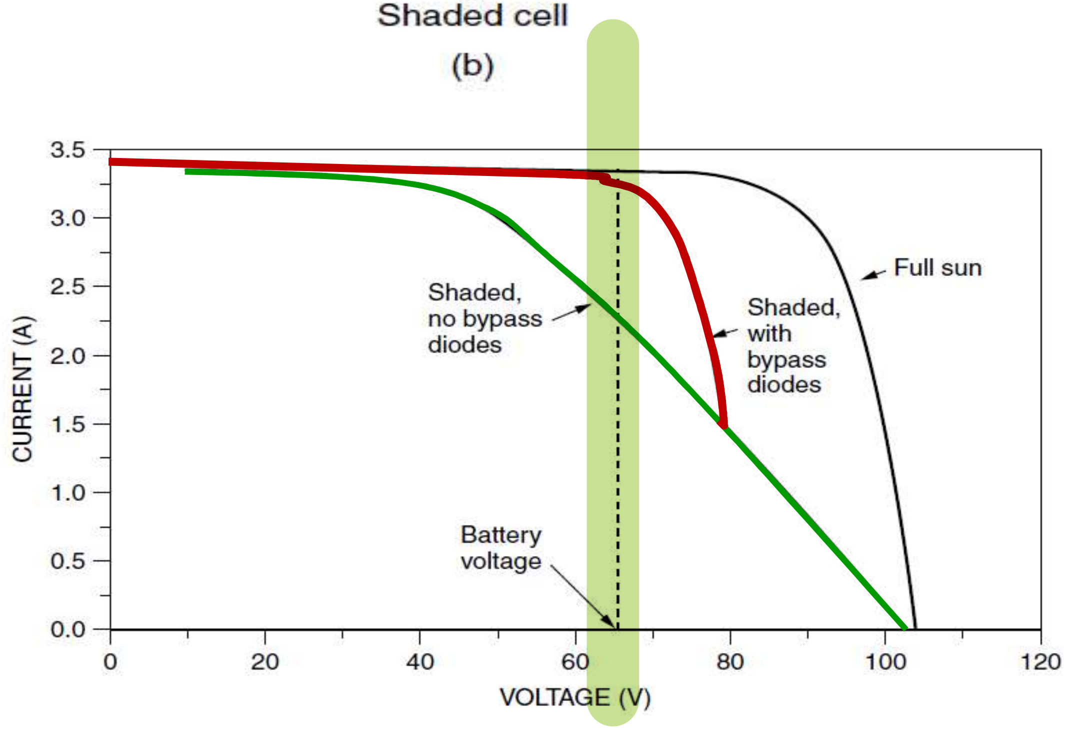


Bypass diode
↳ current passes through this diode instead of the shaded cell
↳ prevents overheating of shaded cell

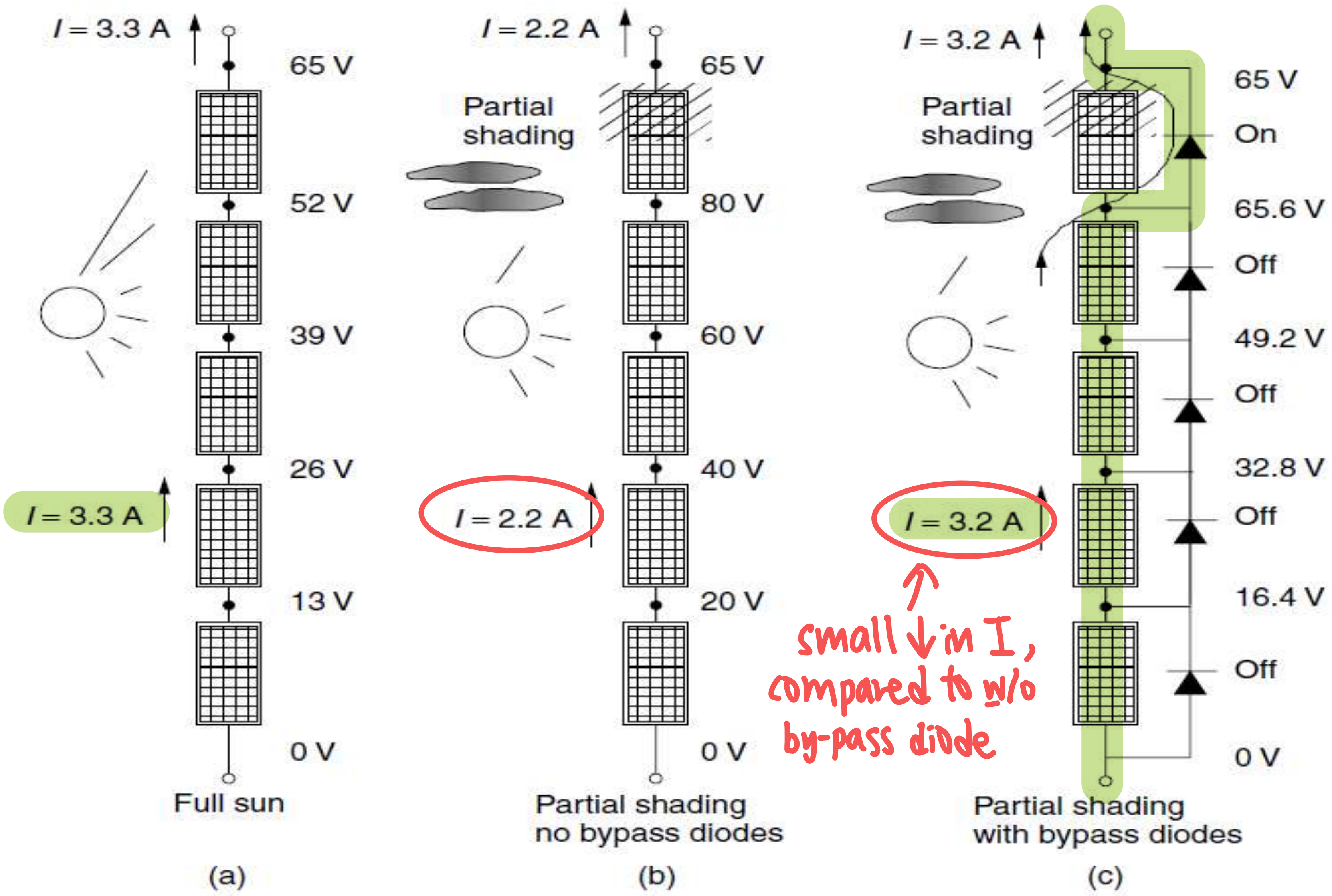
Bypass Diode to mitigate effect of shading



- Typically one bypass diode is provided for each module
- Example I-V curve for a string of 5 modules when one module has two cells completely shaded

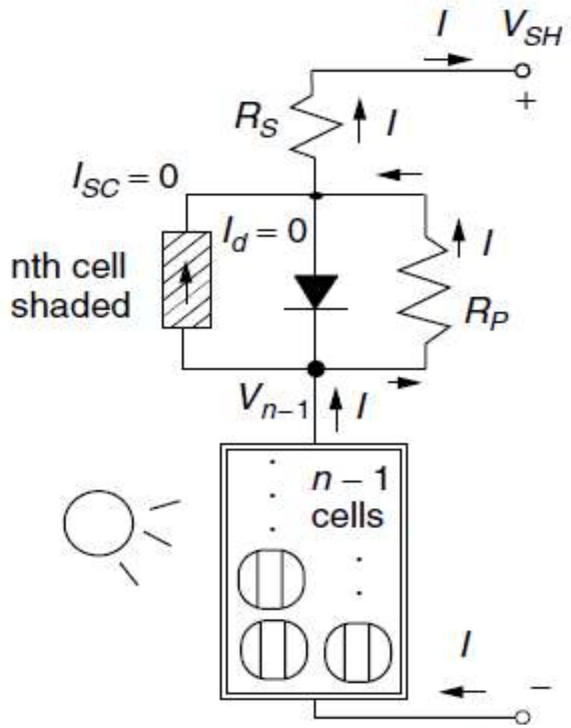


With bypass diodes, current is diverted around the shaded module

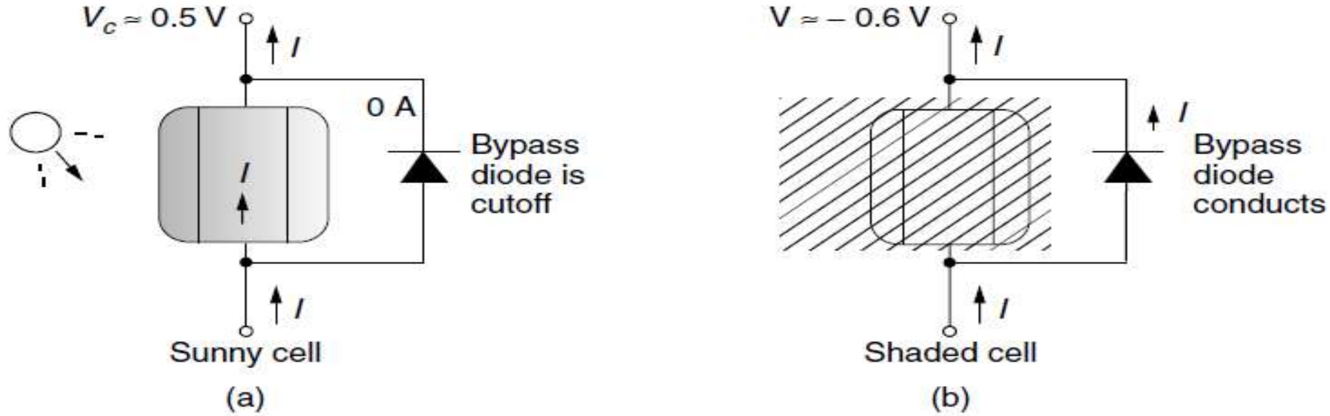


Effect of shading

Shading of even one cell in a module causes severe drop in module voltage and power

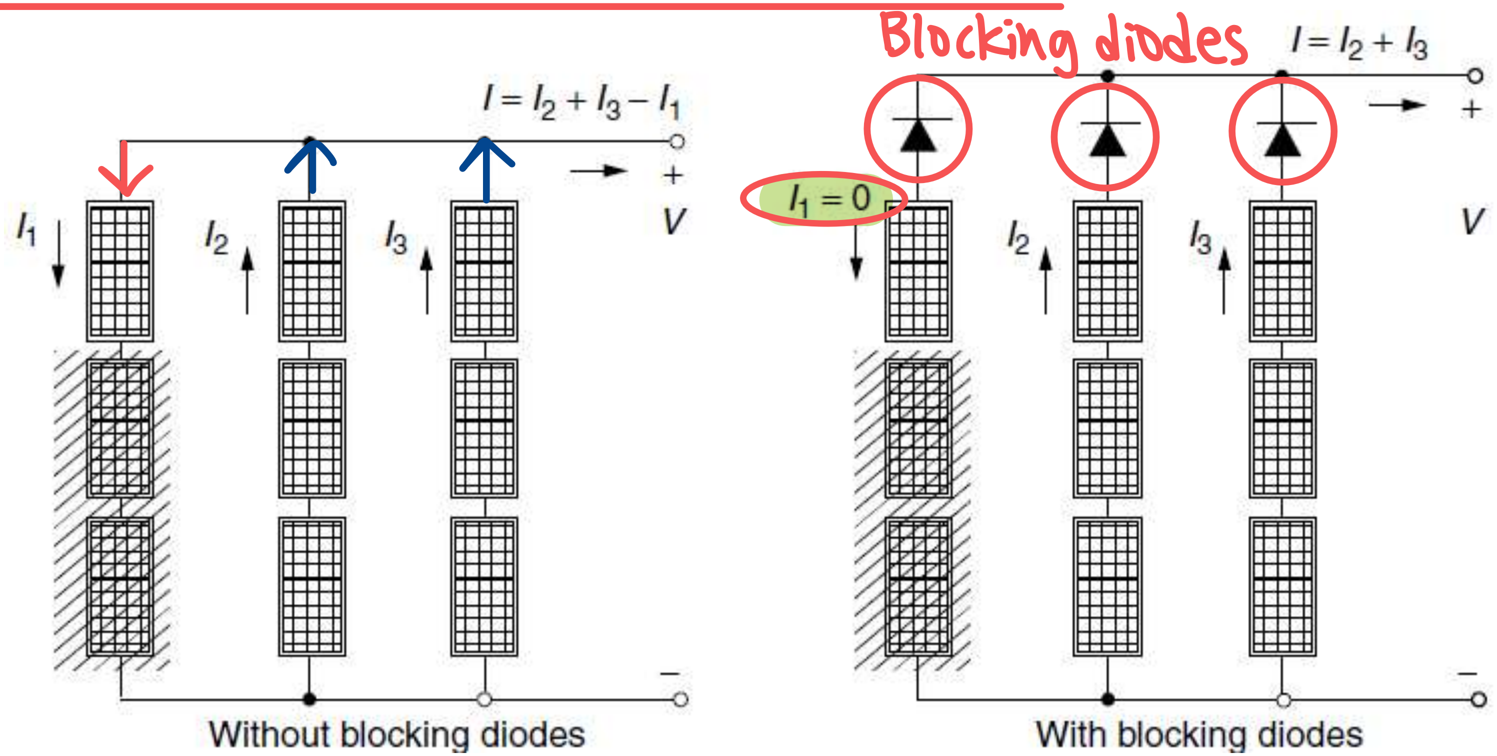


Bypass diode can mitigate the effect of shading



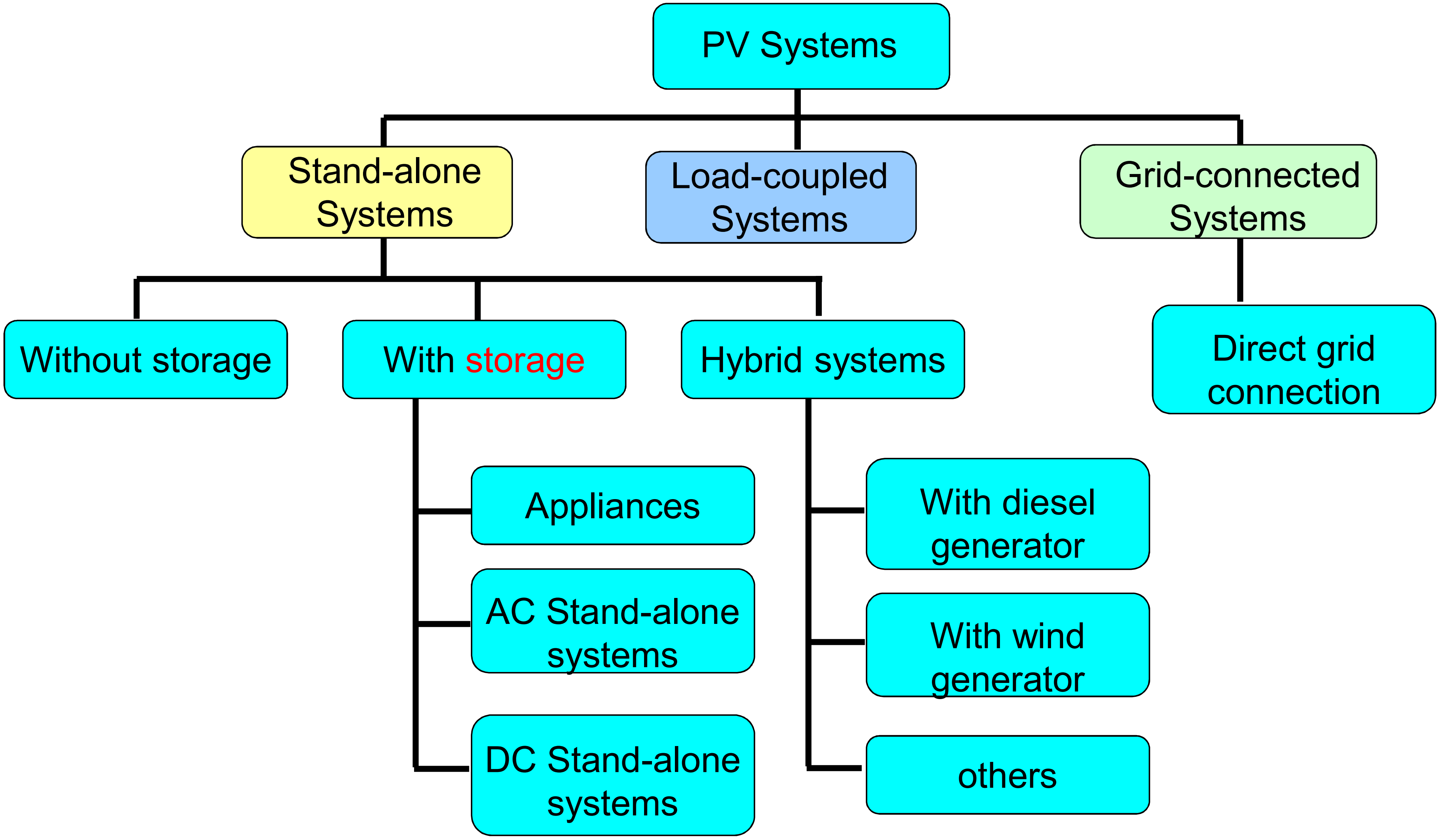
Blocking Diodes

- For strings of modules connected in parallel, if one of the strings is not performing well, it tends to draw current
- **Blocking diodes** can prevent the reverse current drawn by shaded string

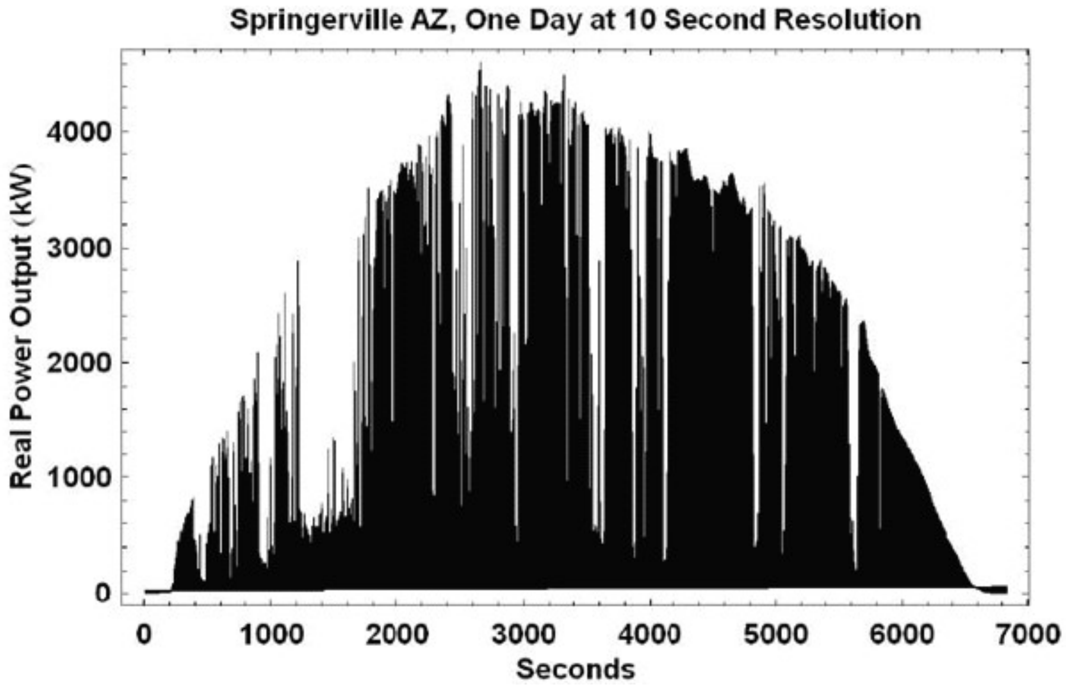


Solar PV Systems

Types of Solar PV Systems



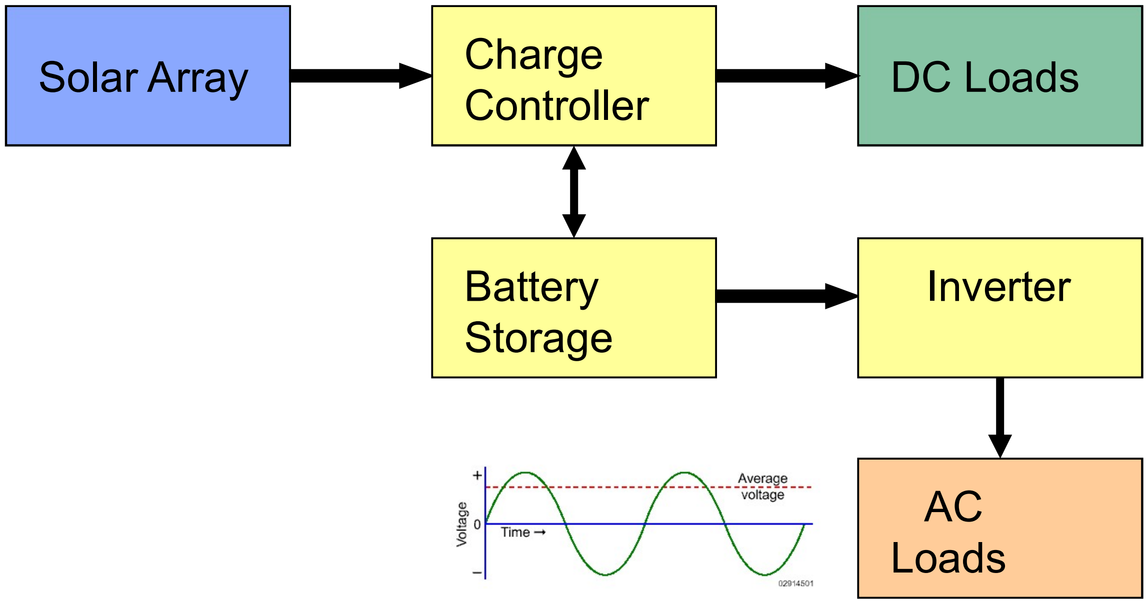
Variability of solar power output – Motivation for Storage



- **Variations in power generating capacity – temporal fluctuations are large on a daily and seasonal basis**
- Without energy storage, solar power will only be available when the sun is shining
- **Storage allows optimal operation and utilization of energy**

Stand-alone solar power systems

Typical stand-alone system powering DC and AC loads:

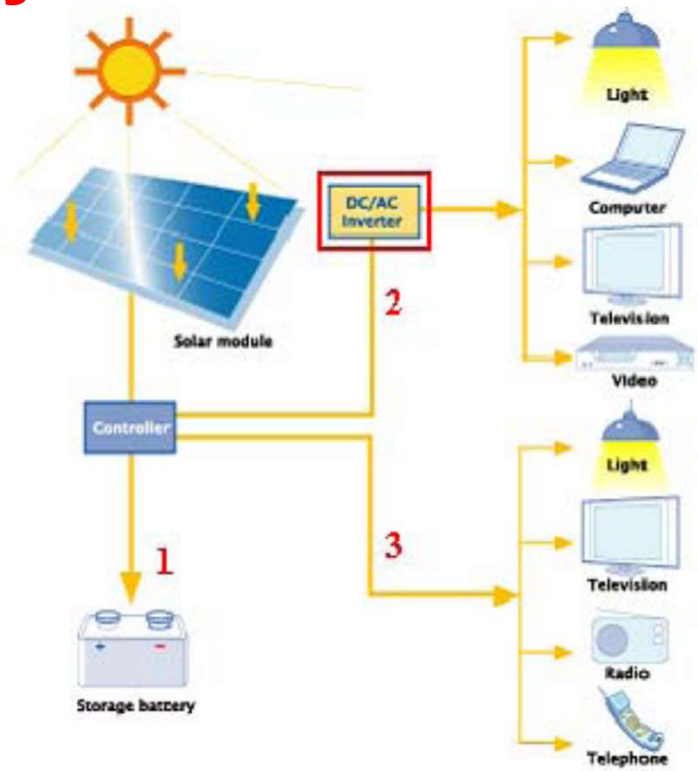


A PV system has these main components:

- One or more PV modules, which are connected to an inverter
- The inverter, which converts the system's direct-current (DC) electricity to alternating current (AC)
- Batteries to provide energy storage or backup power in case of a power interruption
- *Charge controller regulates the battery charging/discharge*

Stand-alone PV System

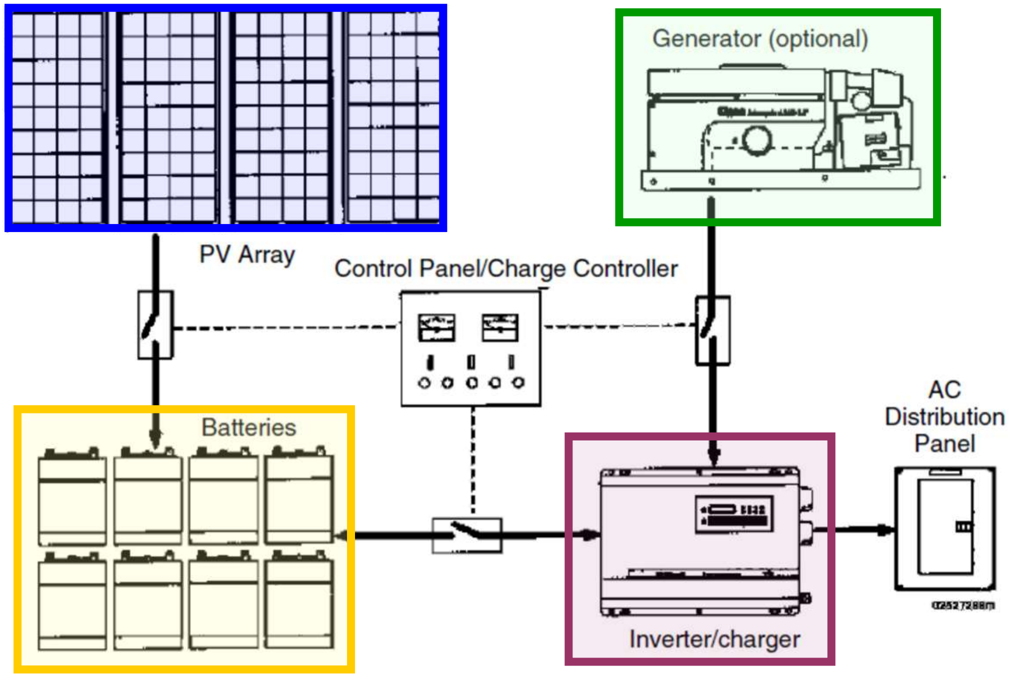
- In simple systems, all loads can be directly run on DC and no inverter may be necessary
- Cost effective in remote locations
- Some loads may run on AC – inverter is therefore needed



Stand-alone PV systems

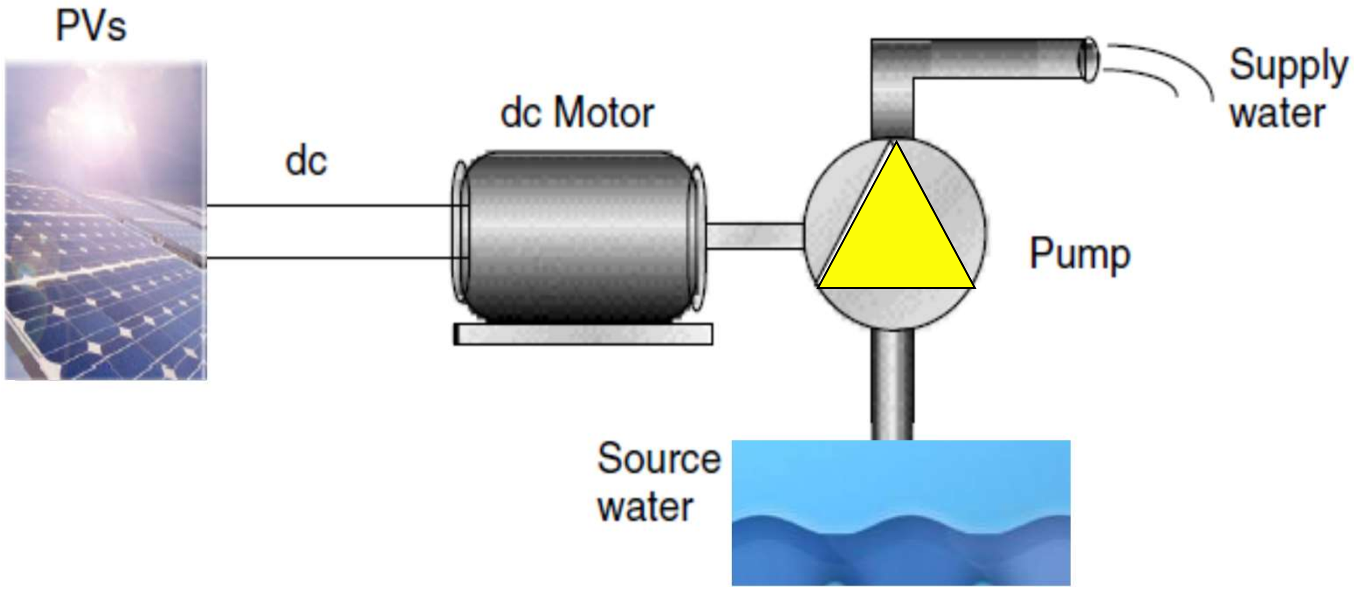
Inefficiencies due to:

- Battery losses
- Operating point typically not the most efficient one
- Steep tilt angle
- Uneven availability of power due to weather variations



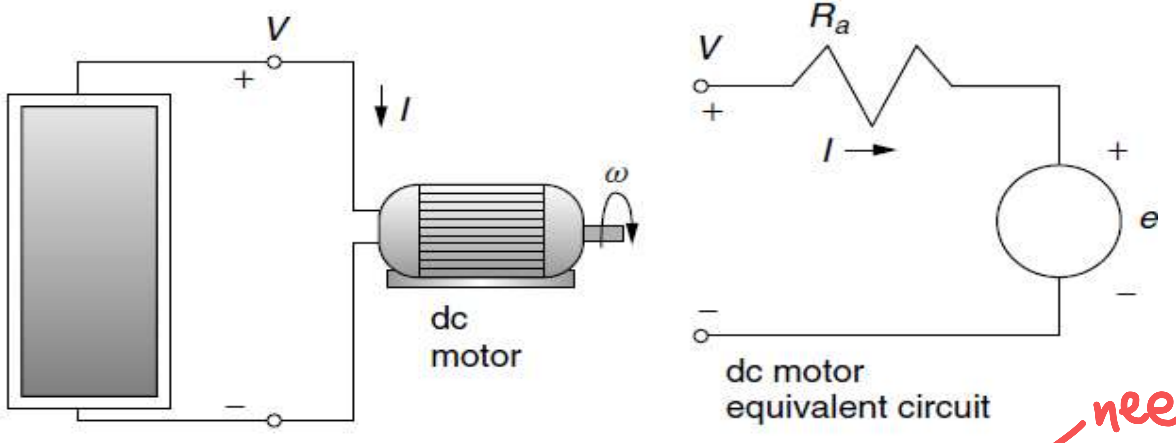
Load-coupled PV Systems

- PV modules are directly connected to their loads
- No batteries or power conditioning equipment
- Most common – for water pumps
- No electric storage (storage in terms of potential energy of water pumped)
- Very simple and reliable



Load-coupled PV Systems – DC Motor for pumps

- Typical motor for water pumping applications



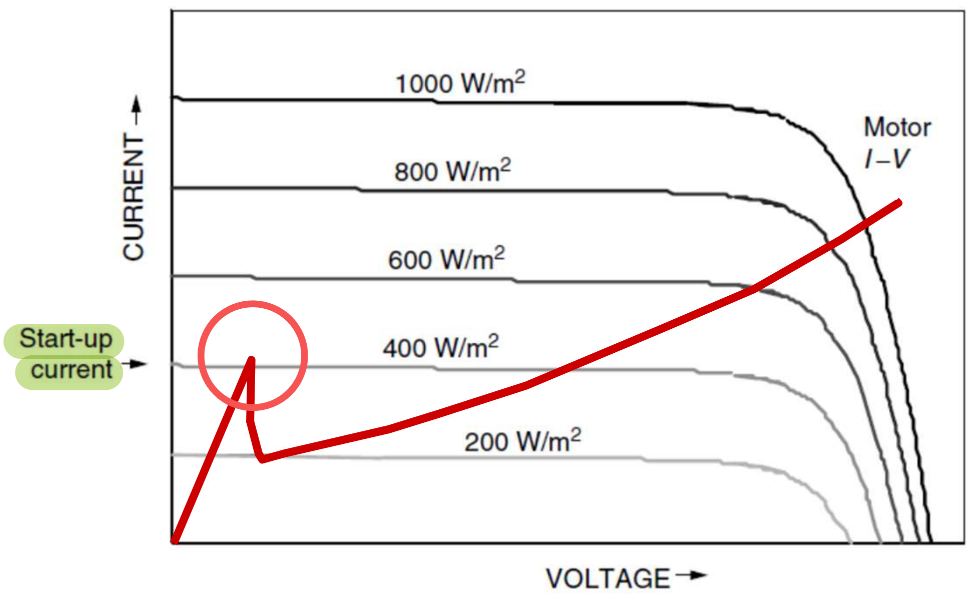
$V = I\,R_a + E_b$

needs enough insolation

- **The motor will not start pumping until insolation reaches 400 W/m²**

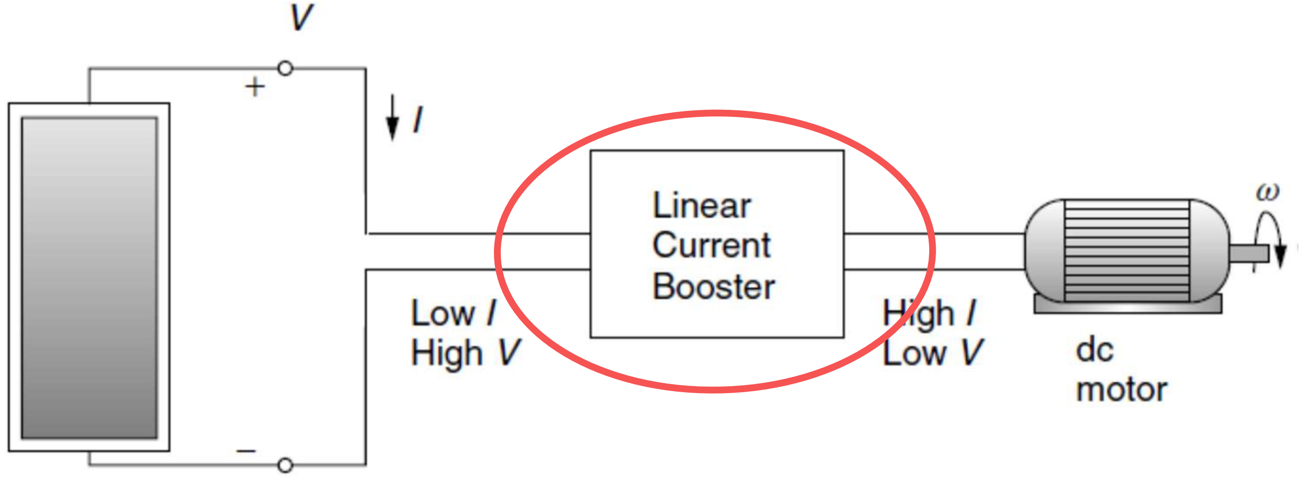
The system has to be carefully designed!

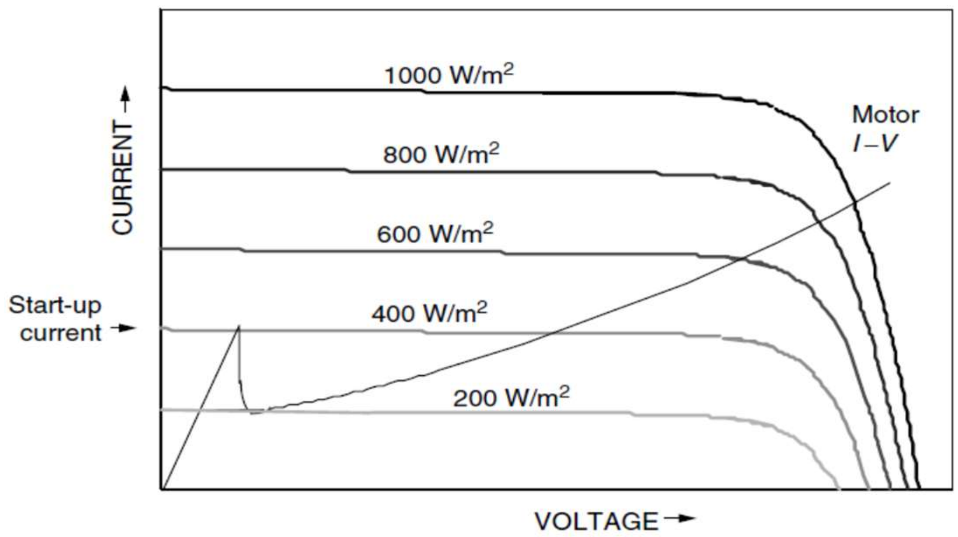
Insufficient insolation in the mornings results in lower efficiency



Load-coupled PV Systems – DC Motor for pumps

- A **linear current booster (LCB)** increases current to help start or keep the motor running in low sunlight





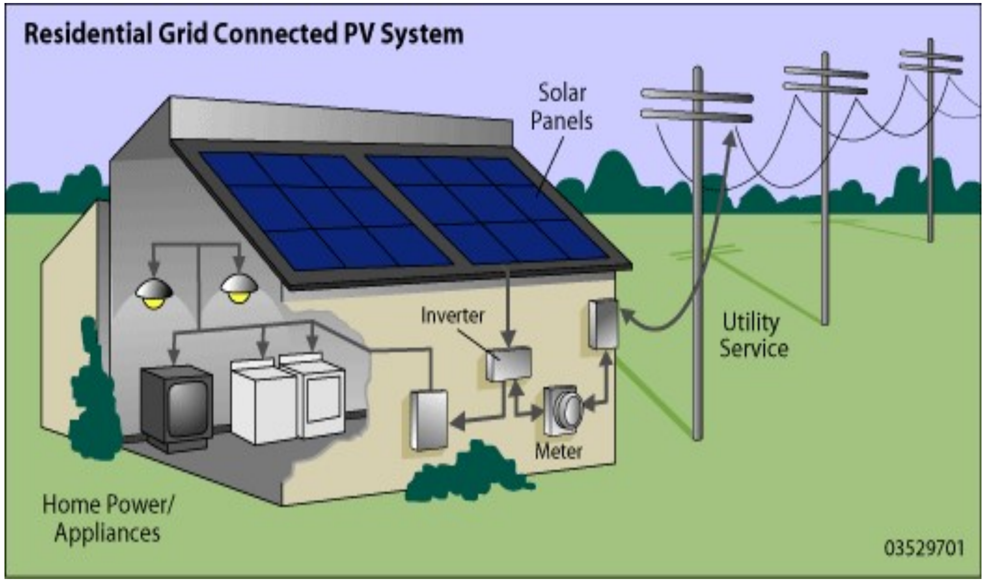
↳ needs inverter : DC → AC!!

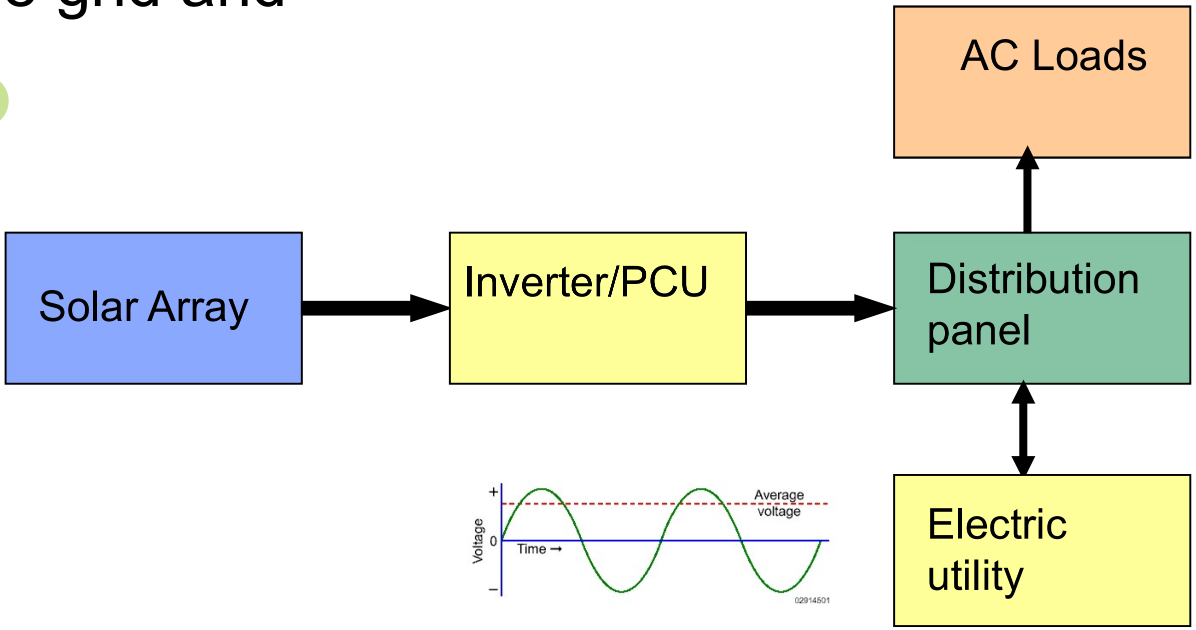
Grid-connected PV Systems

The components of a grid-connected PV system include:

- PV modules/arrays
- An inverter and power conditioning unit (PCU)
- A safety device to power down at failures in the grid and
- an electricity meter

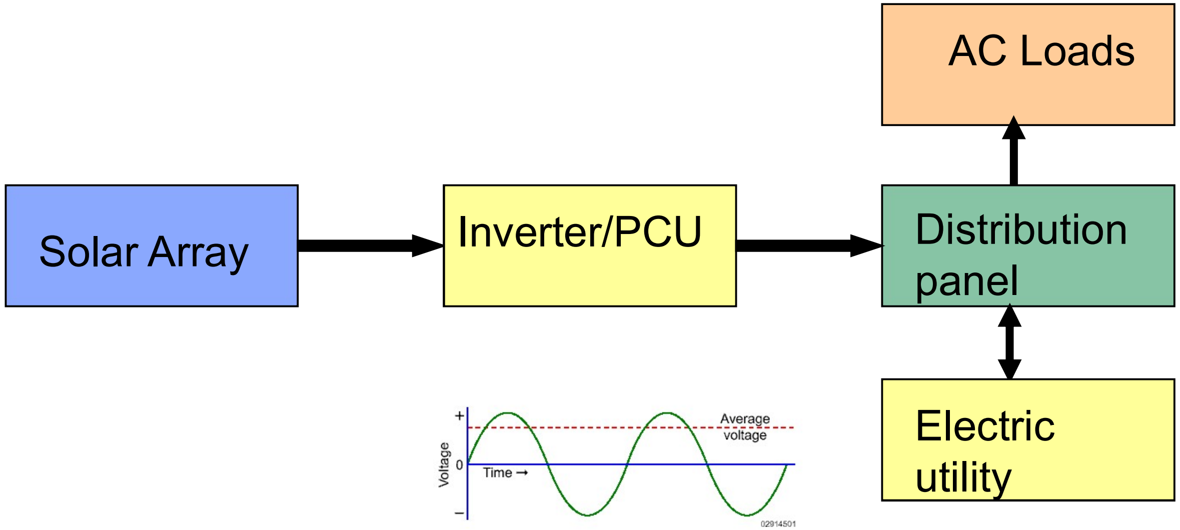
↳ no need external energy storage system





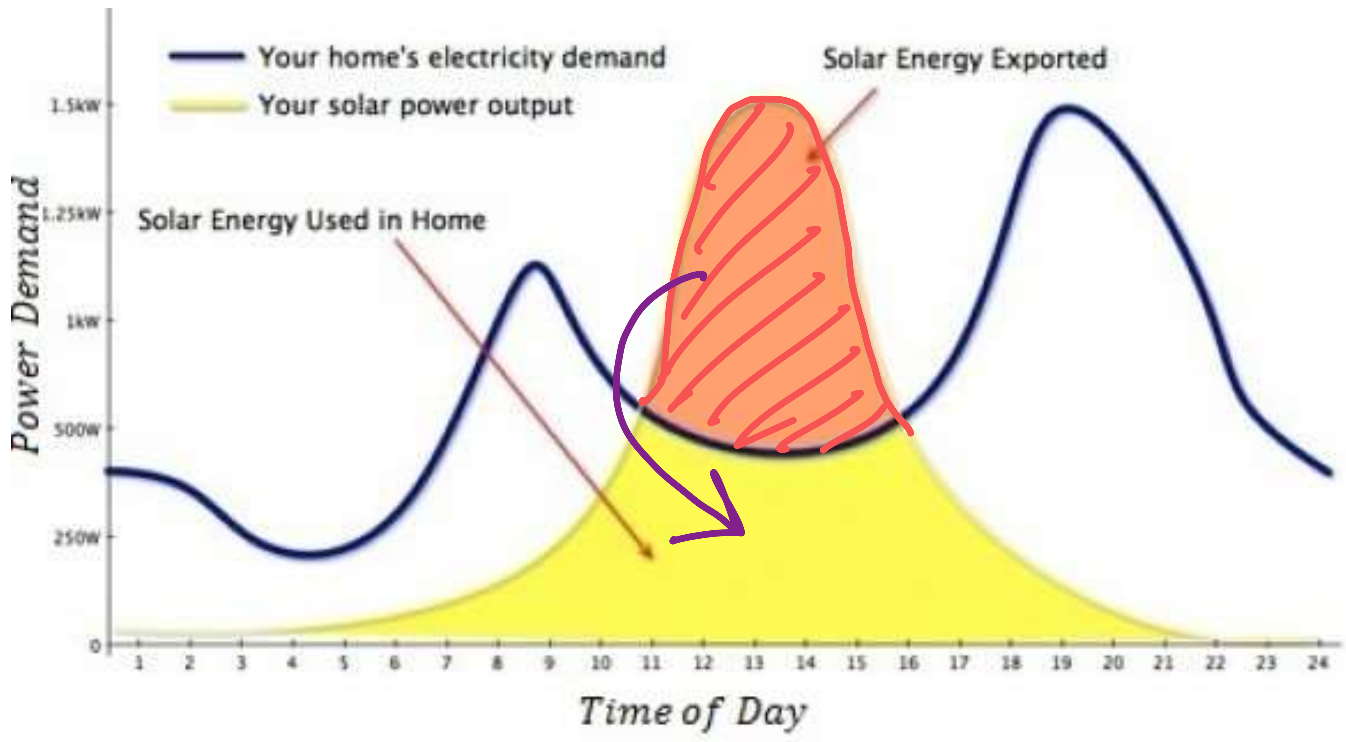
Grid-connected PV Systems

- Designed to operate in parallel with, and interconnected, with the electric utility grid
- The primary component in grid-connected systems is the **inverter**
- **PCU** converts the DC power into AC power consistent with the voltage and power quality requirements of the utility grid
- PCU **automatically stops** supplying power to the grid when the utility grid is not energized.



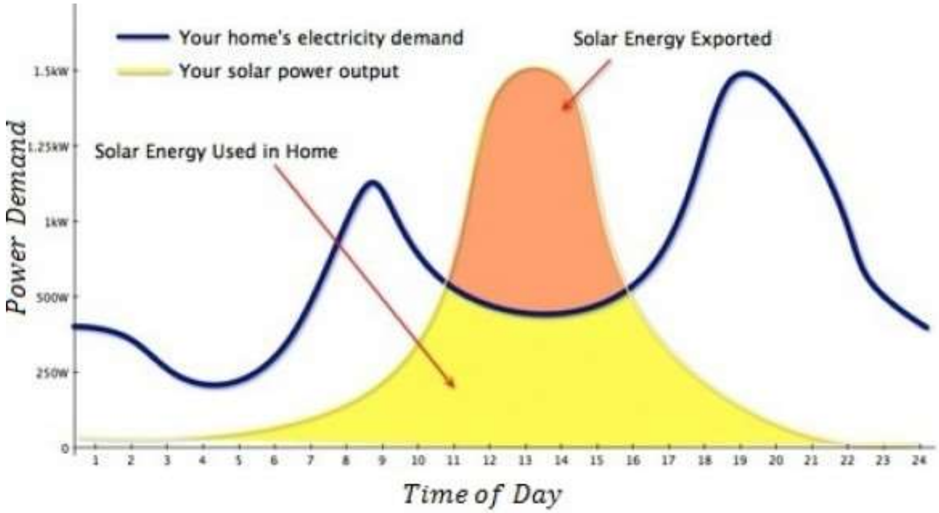
Grid-connected PV Systems

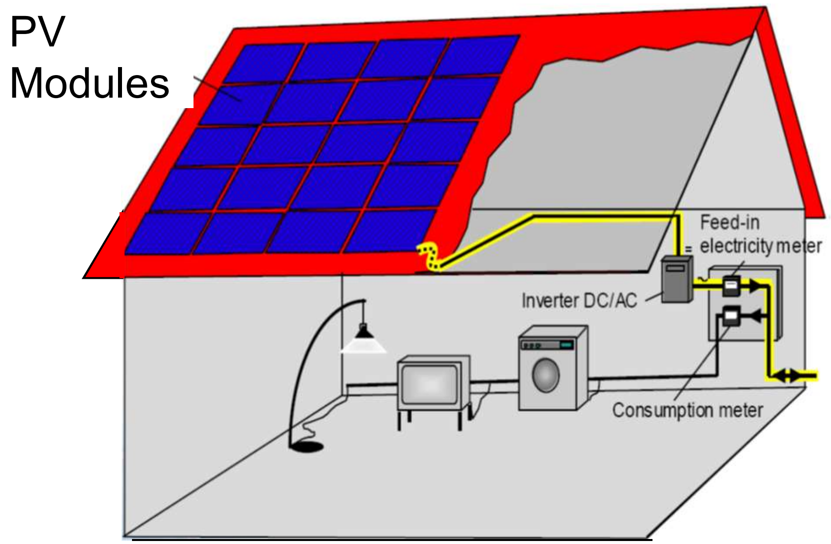
- Solar power system **back-feeds the grid** when the solar power system output is greater than the on-site load demand.



Grid-connected PV Systems

- At night and during other periods when the electrical loads are greater than the solar power system output, the balance of power required by the loads is received from the electric utility.
- **The system requires two meters to keep track of these**

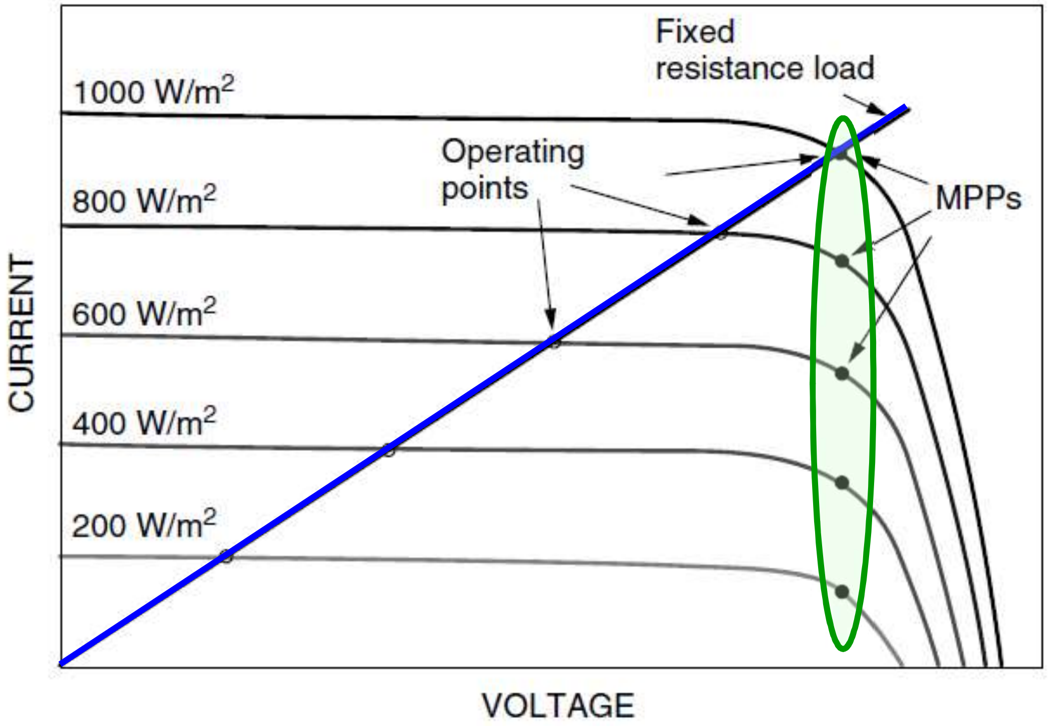




(Source: BSW)

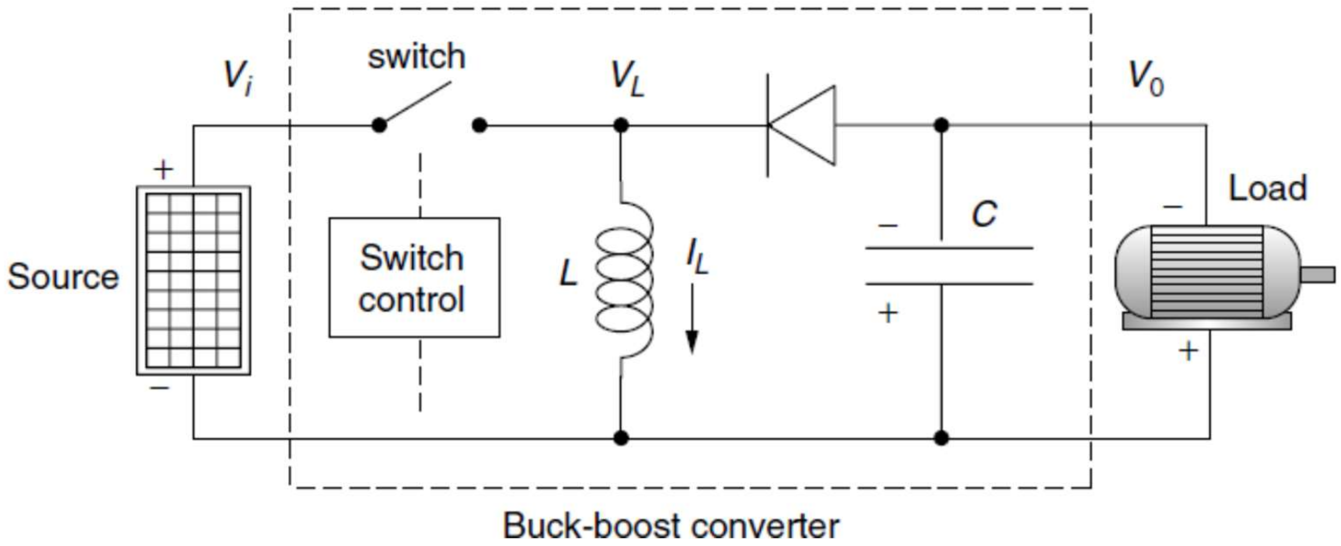
Maximum Power Point Trackers (MPPT)

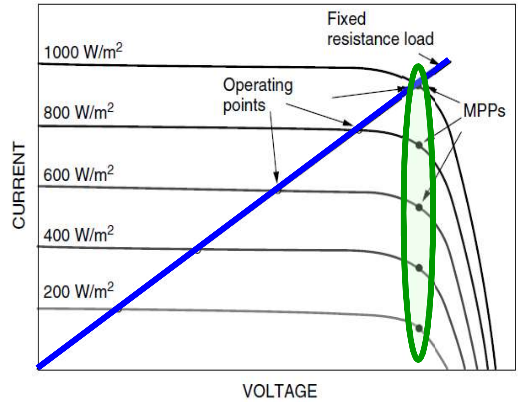
Max power point tracker (MPPT) ensures the module operates at highest efficiency point



Maximum Power Point Trackers (MPPT)

- Standard part of most grid-connected systems
- Commonly use a buck-boost converter (also used in linear current boosters)

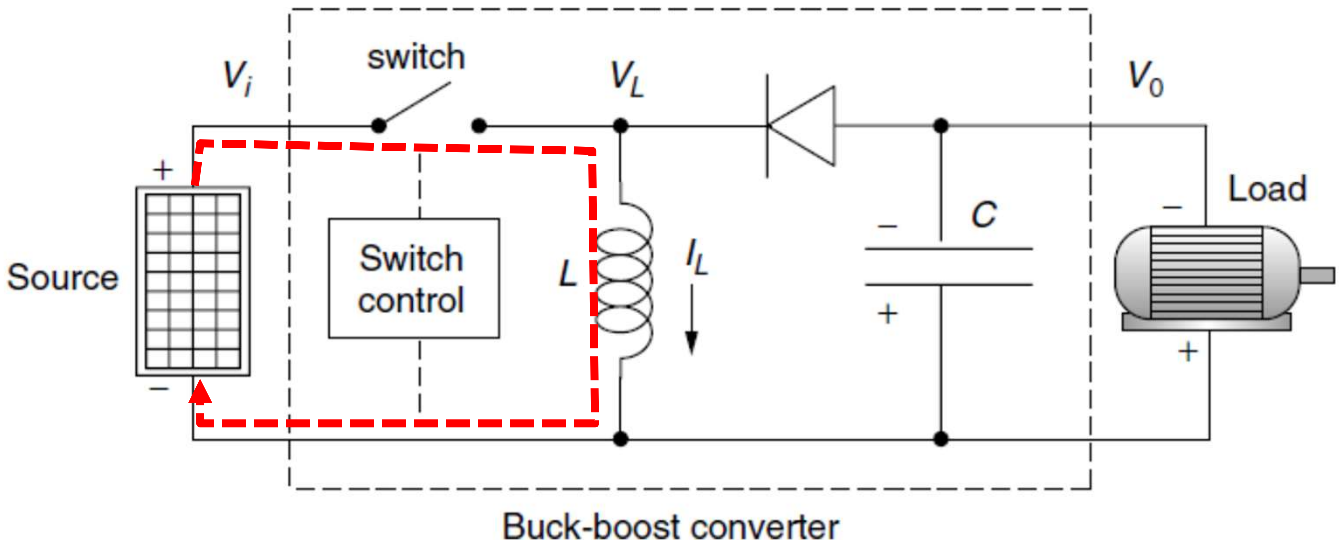




Raises or lowers the voltage to the desired value needed by load

Maximum Power Point Trackers (MPPT)

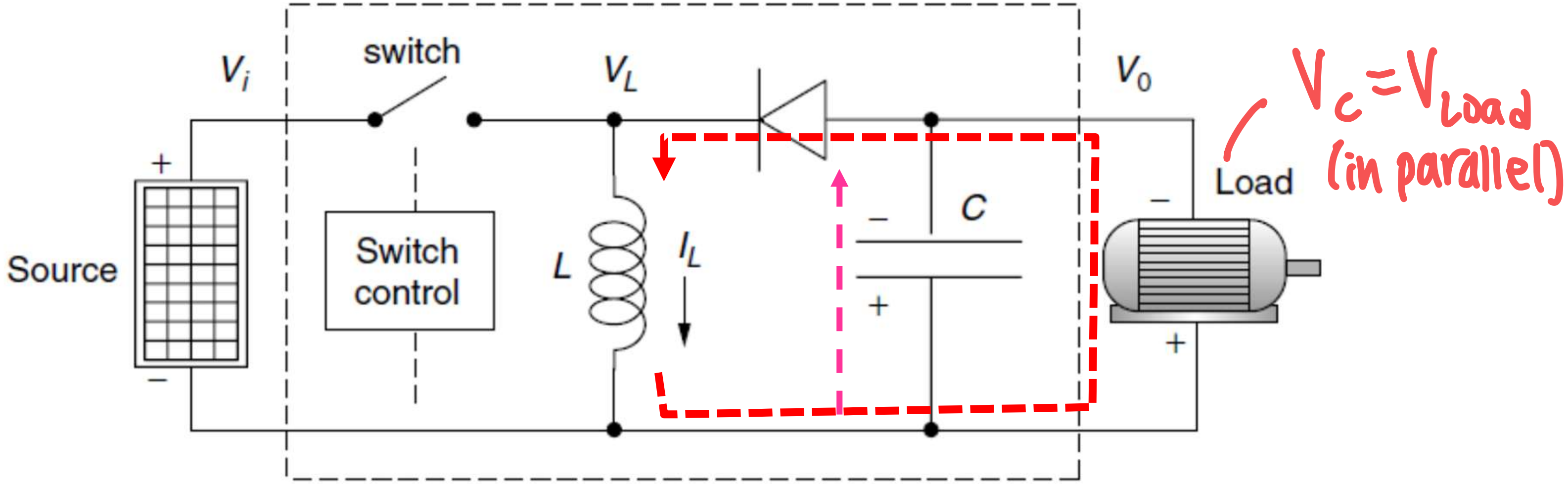
- When switch is **CLOSE**: energy is supplied to inductor, and I_L builds up



Typically, the on-off switch in this switched-mode dc-dc converter is an IGBT transistor

Maximum Power Point Trackers (MPPT)

- When switch is **CLOSE**: energy supplied to inductor, and I_L builds up
- When switch is **OPEN**: Inductor current flows through C, load and diode
- With fast switching, inductor current and output voltage are **CONSTANT**

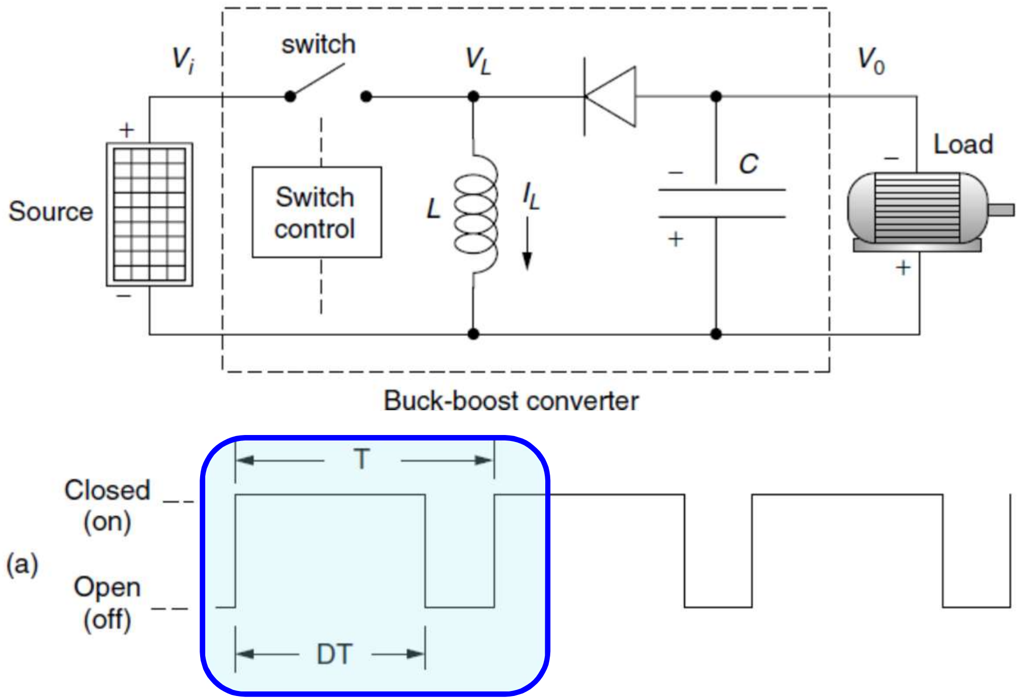


Buck-boost converter

Typically, the on-off switch in this switched-mode dc-dc converter is an IGBT transistor

Maximum Power Point Tracker (MPPT)

Duty cycle: the **fraction** of time the switch is closed



Duty cycle = DT/T

(assume fast charging)

Under the assumption that inductor current is constant, the average power into the inductor is

$$\overline{P}_{L,\text{in}} = \frac{1}{T} V_i I_L \int_0^{DT} dt = V_i I_L D$$

Maximum Power Point Tracker (MPPT)

power into the inductor

$$\overline{P}_{L,\text{in}} = \frac{1}{T} V_i I_L \int_0^{DT} dt = V_i I_L D$$

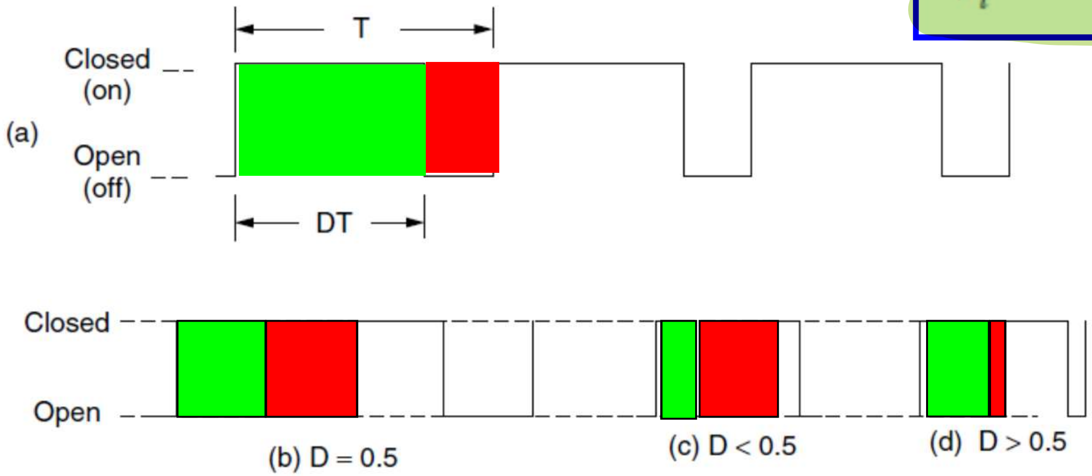
power delivered by the inductor is
output

$$\overline{P}_{L,\text{out}} = \frac{1}{T} V_0 I_L (T - DT) = V_0 I_L (1 - D)$$

Over a complete cycle, the two are equal. Therefore:

$$\boxed{\frac{V_0}{V_i} = -\left(\frac{D}{1-D}\right)}$$

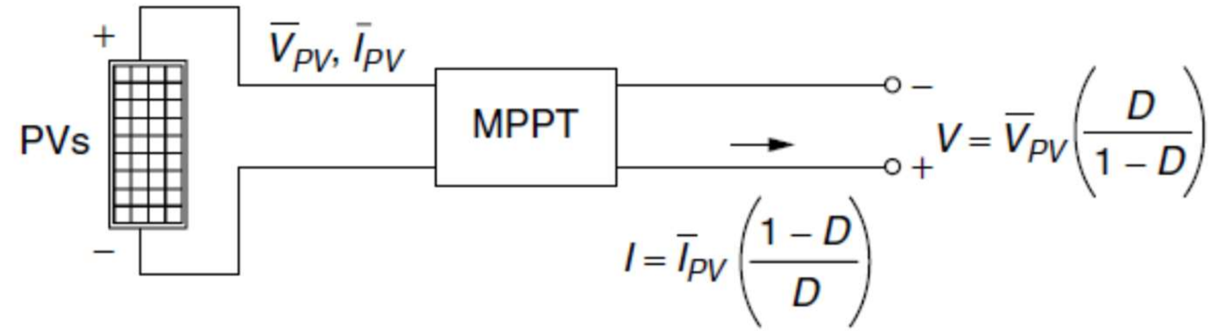
fraction of time that switch is closed

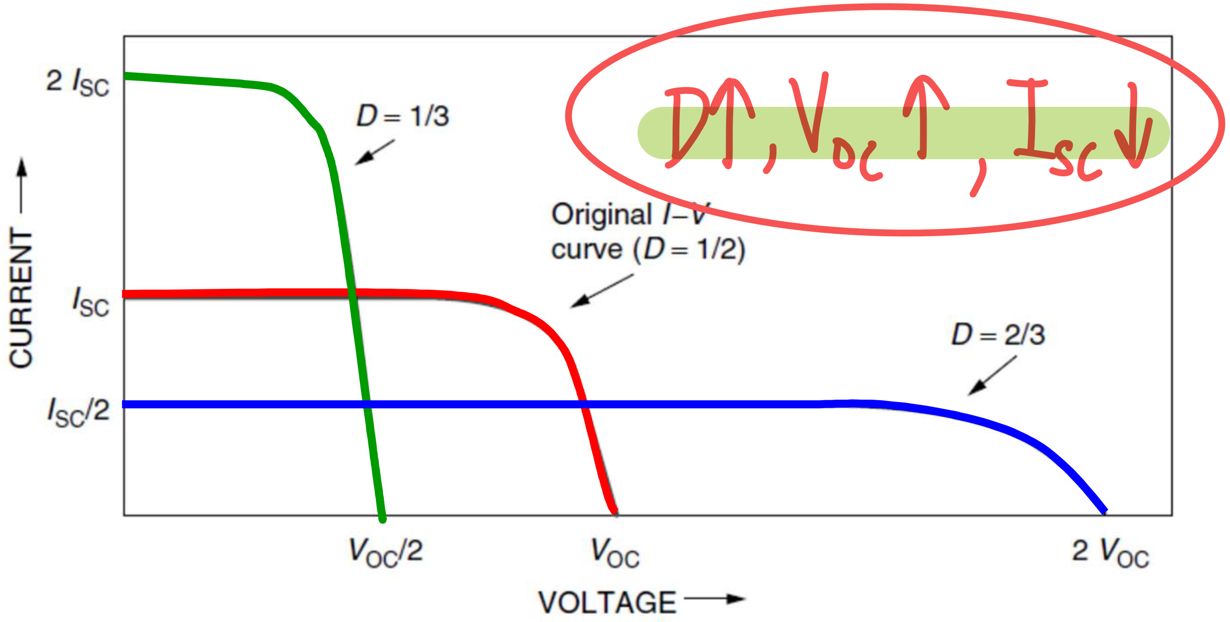


Voltage can be increased or decreased just by varying the duty cycle!

Maximum Power Point Tracker (MPPT)

- PV current-voltage curve with MPPT





I-V curves drawn using D as a parameter

Example: Under certain ambient conditions, a PV module has its maximum power point at V_m = 17 volts and I_m =6 A.

What duty cycle should an MPPT have if the module is delivering power to a 10 Ω resistance?

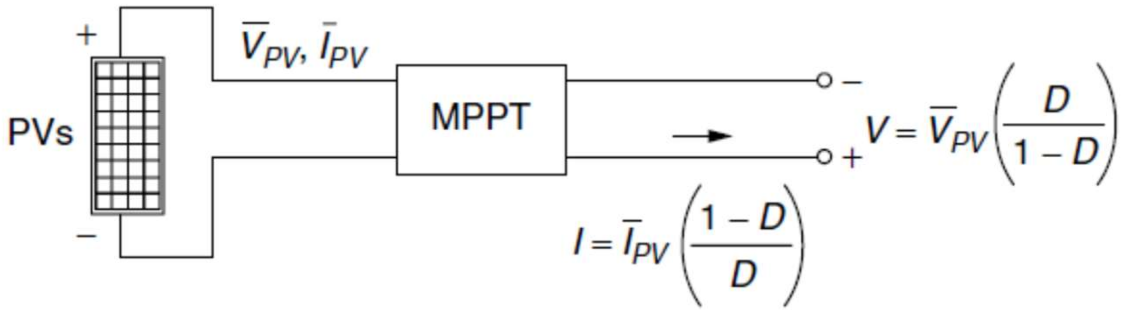
Solution: The maximum power delivered by the PVs is:

P = 17 V × 6 A = 102 W.

To deliver all of that 102 W to the 10 Ω resistor means the resistor needs a voltage of

$$P = \frac{V_R{}^2}{R} \Rightarrow 102 = \frac{V_R{}^2}{10}$$

$$V_R = \sqrt{102 \cdot 10} = 31.9 \text{ V}$$

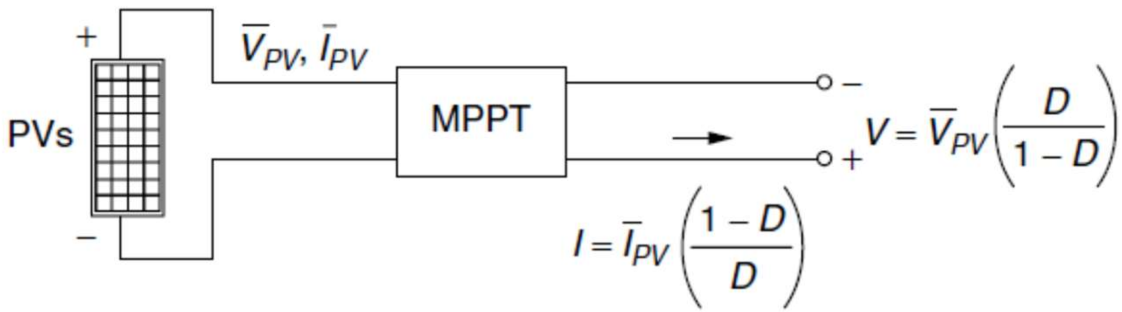


The MPPT must bump the 17-V PV voltage to the desired 31.9-V resistor voltage.

$$\frac{V_i}{V_o} \quad \frac{31.9}{17} = \left(\frac{D}{1-D}\right) = 1.88$$

$$D = 1.88 - 1.88D$$

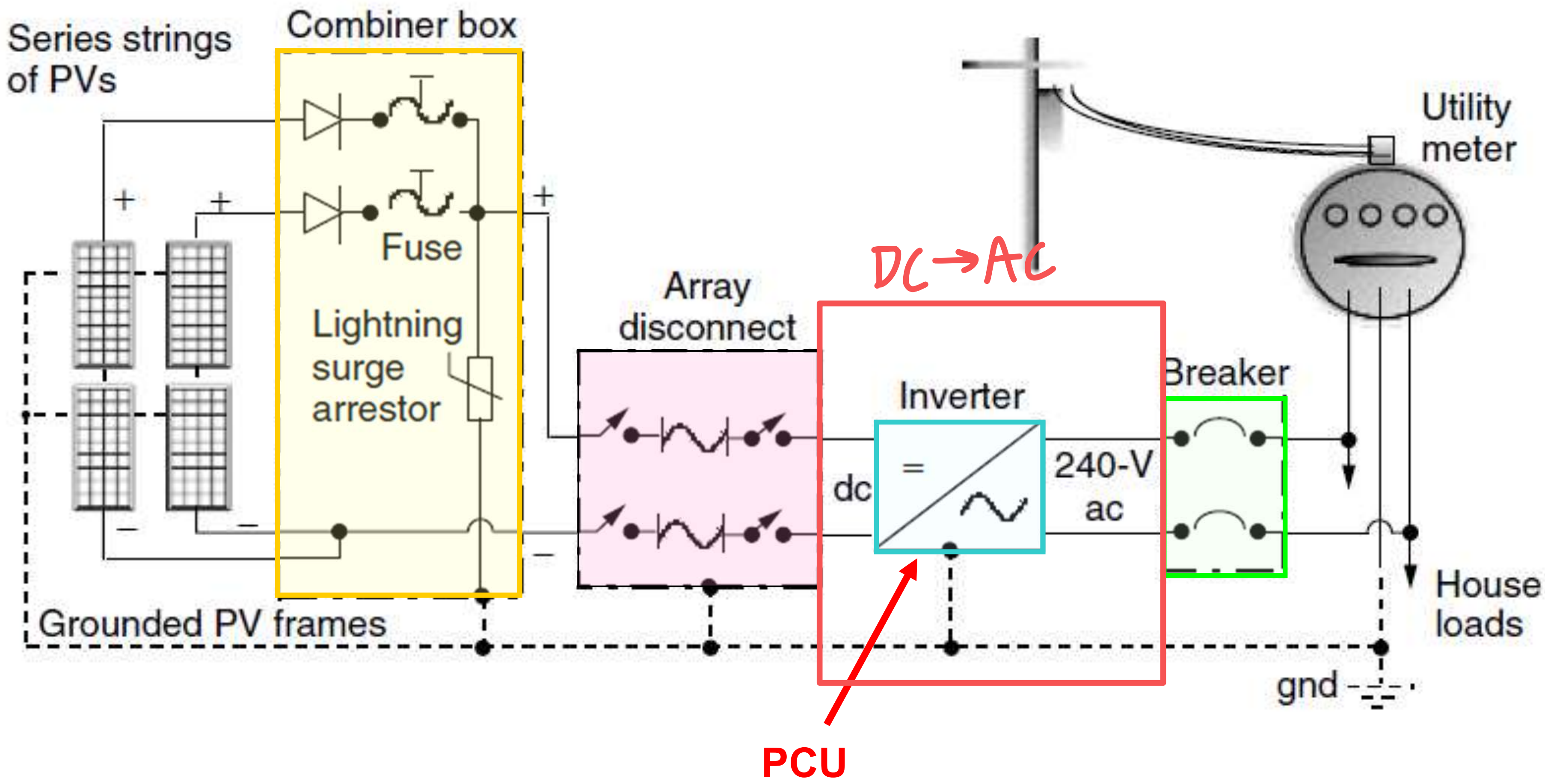
$$D = \frac{1.88}{2.88} = 0.65$$



Grid-connected PV Systems

Grid-connected system using a single inverter

(MPPT, protection circuitry and battery bank are not shown)

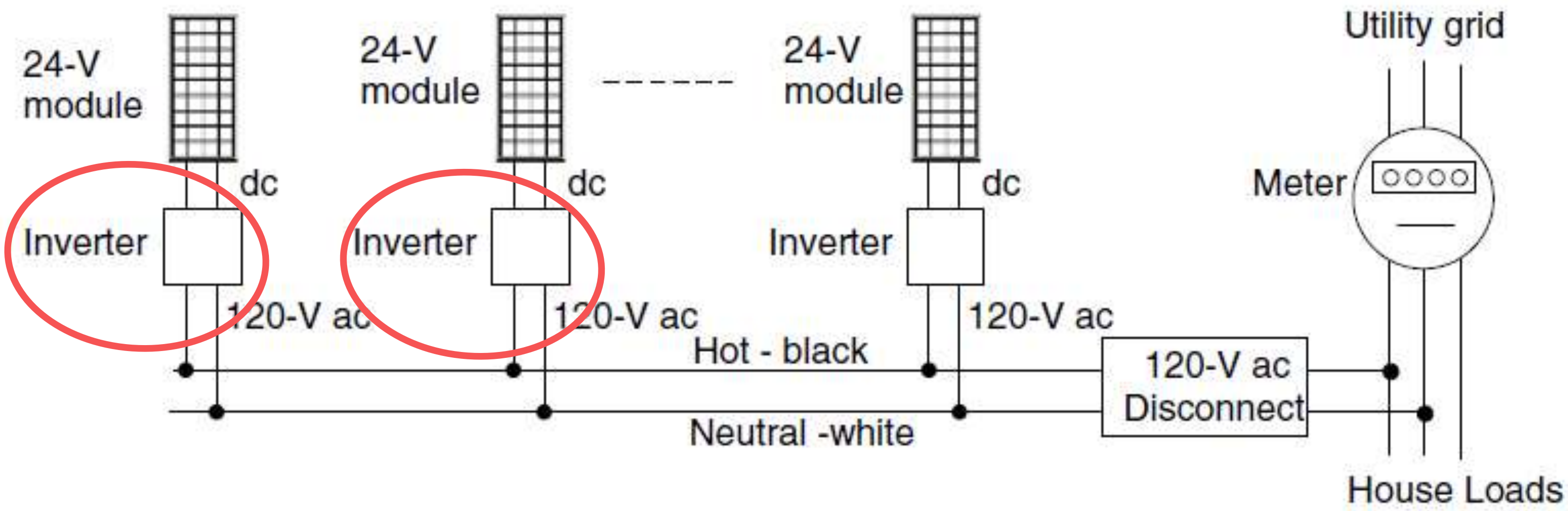


Grid-connected PV Systems

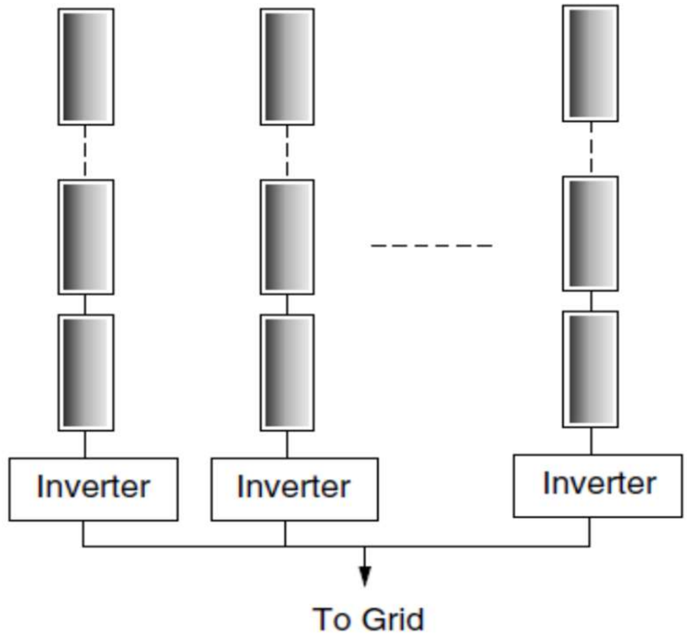
can add on modules in // easily

AC modules each with their own inverters

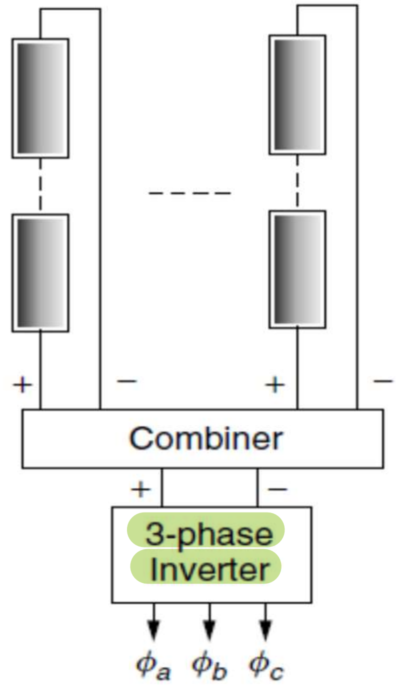
- Allows modular expansion of the system
- Uses simpler, less expensive switches, circuit breakers and wiring



- Large grid-connected systems may use an individual inverter for each string



- Or, a large central inverter system can be used to provide three-phase power

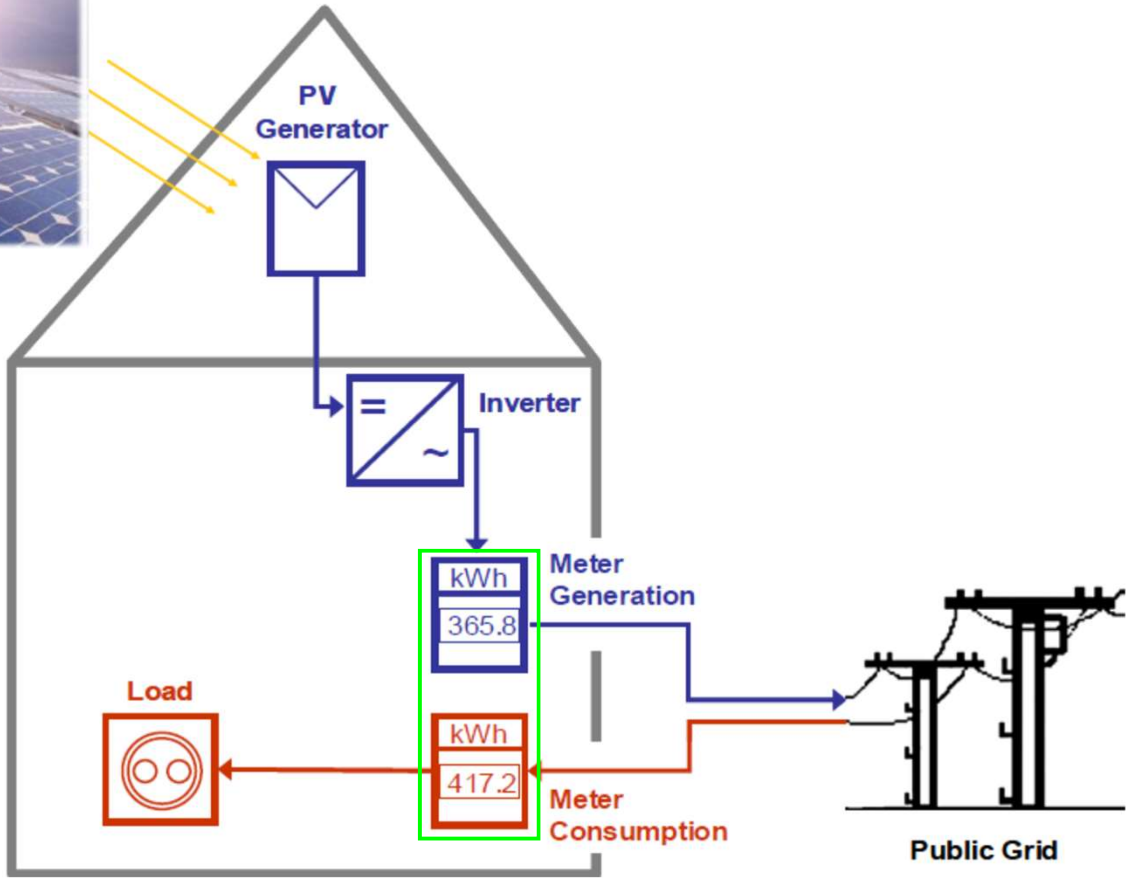


Grid-connected PV Systems

Interfacing with the utility: Net metering

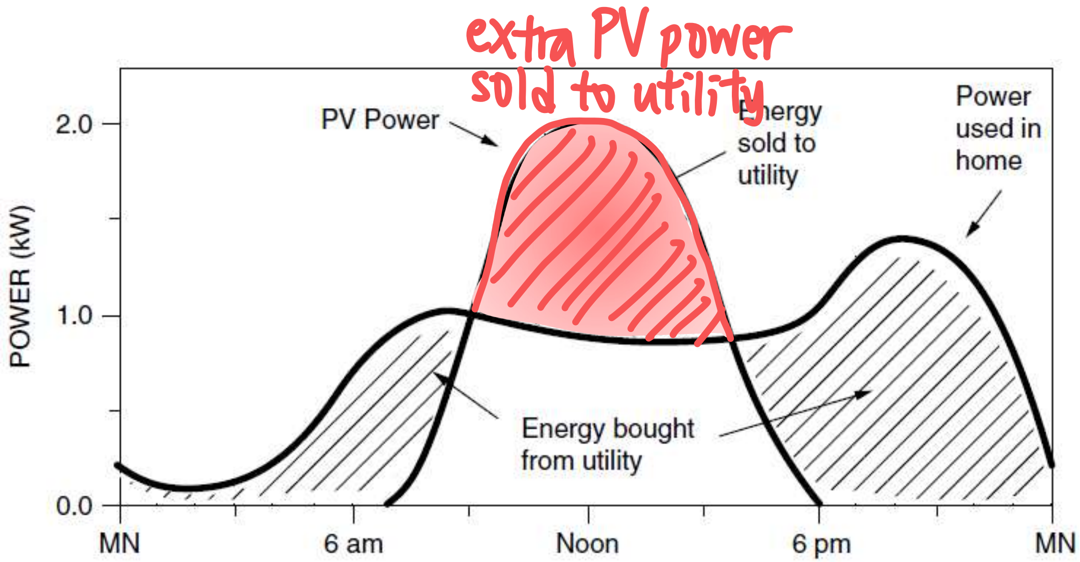
- Whenever PV system delivers more power than demanded by the home, the electric meter runs backwards
- When demand > supply from PV, the grid supplies additional power

↳ sold to utility ⇒ $$



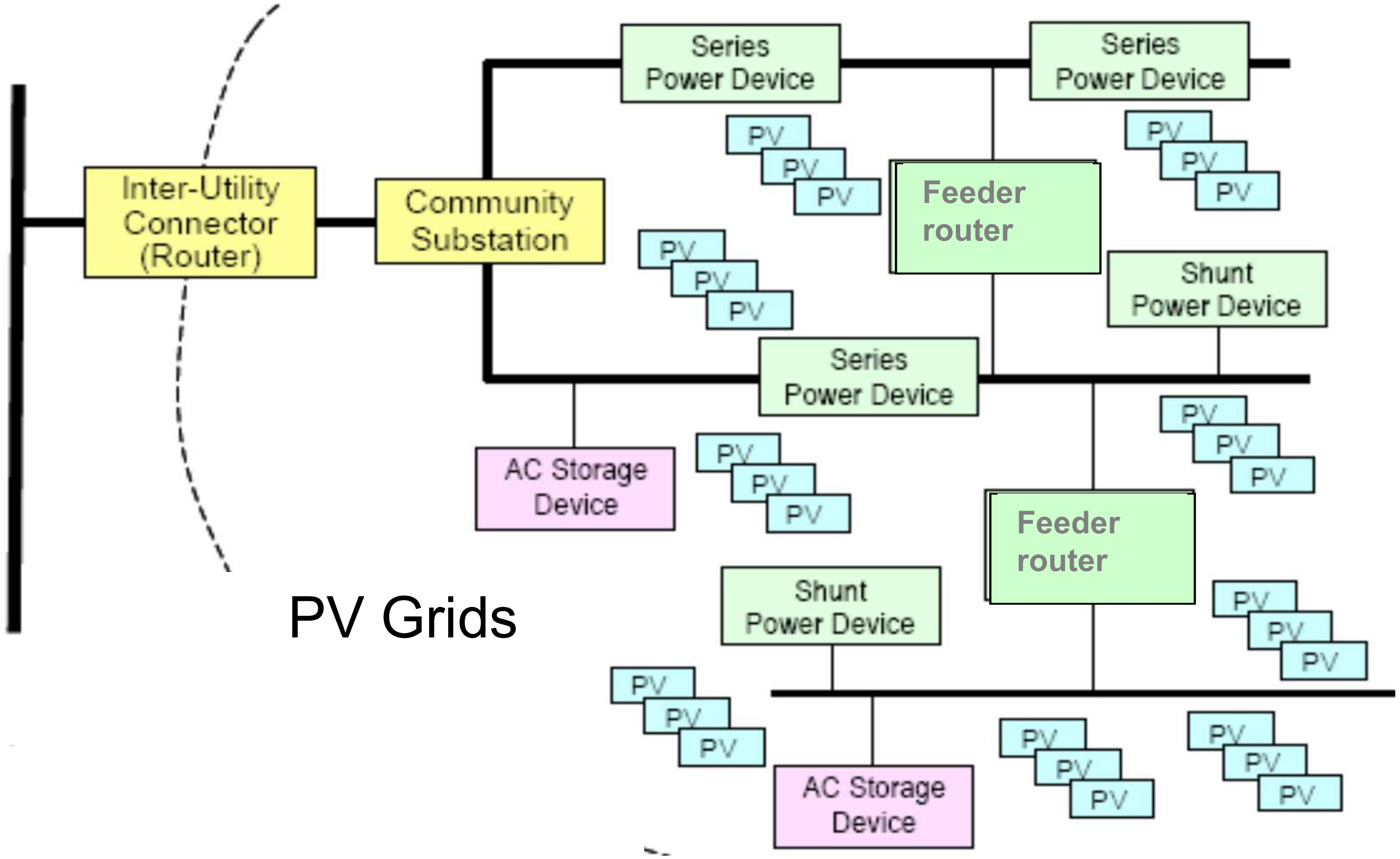
Grid-connected PV Systems

- Example: net metering



Grid Connected PV Systems: Large clusters

- Wide spread PV penetration in the future may have several PV Clusters with power electronic devices and battery storage stations

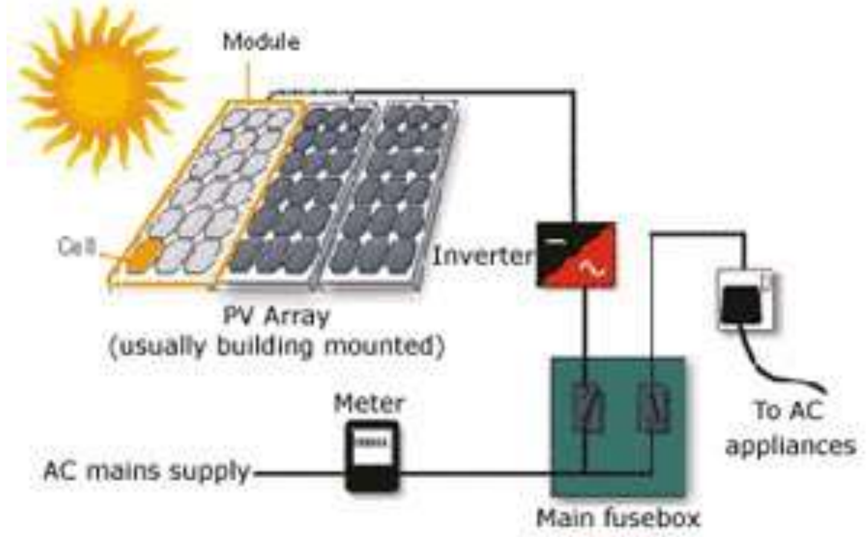


- Estimating PV system performance
- Grid-connected PV system design
- System integration issues

Estimating the system performance

- A good starting point to estimate system performance is the **rated dc power** output of an individual module under standard test conditions (STC)—that is, 1-sun, AM 1.5 and 25◦C cell temperature.
- Then we can try to estimate the **actual ac power** output under varying conditions.
- Actual ac power delivered at 1-sun,

$$P_{ac} = P_{dc,STC} \times \text{(Conversion Efficiency)}$$

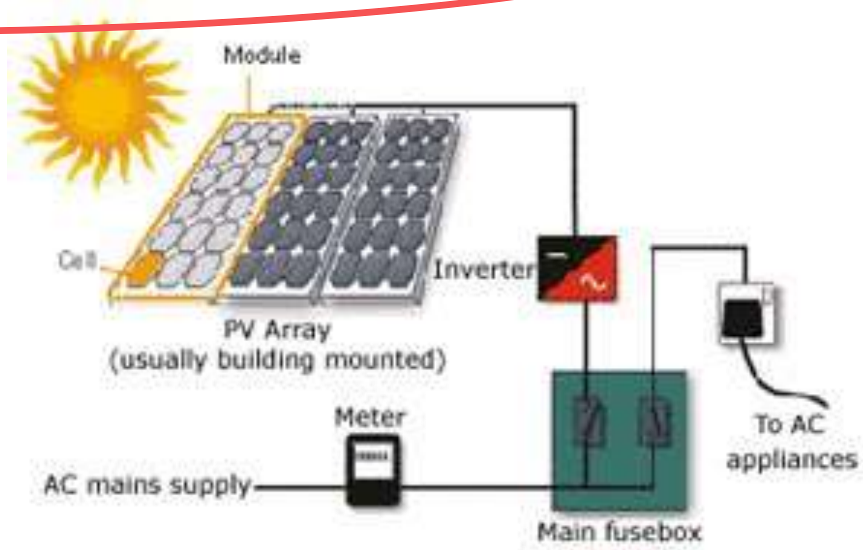


Estimating the system performance

$$P_{ac} = P_{dc,STC} \times \text{(Conversion Efficiency)}$$

The conversion efficiency accounts for

1. inverter efficiency,
2. dirty collectors,
3. mismatched modules, and
4. differences in ambient conditions.

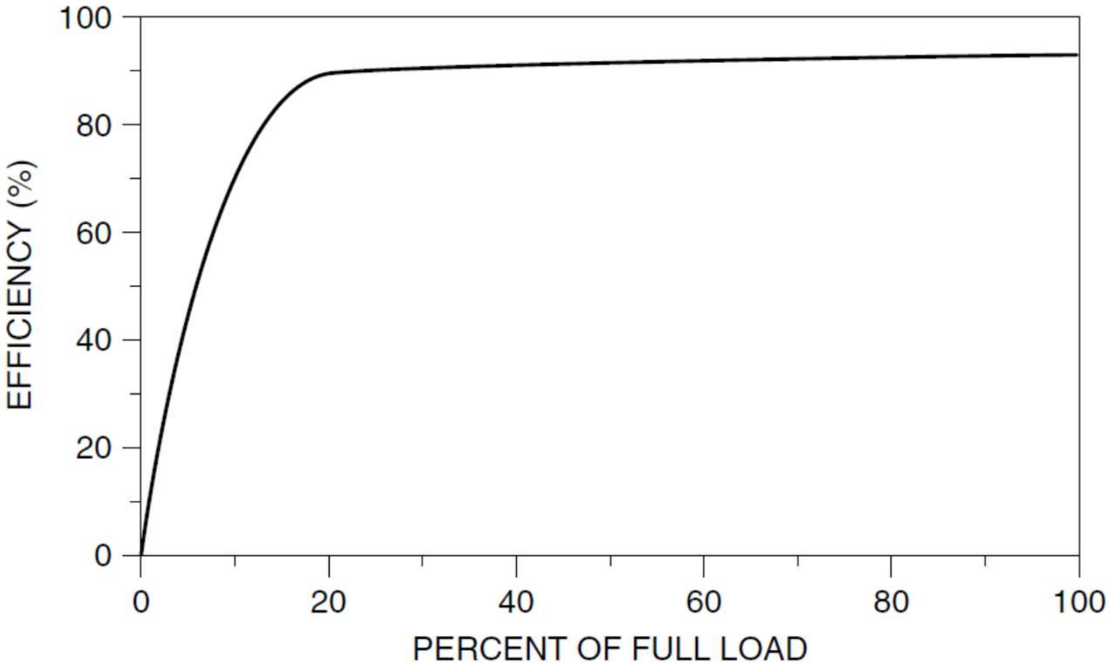


Even in full sun, the impact of these losses can easily derate the power output by 20–40%.

ö emotional damage

Efficiency of the inverter

- Efficiency of the inverter depends on the **load**
- Typical grid-connect inverters have efficiencies above 90% for upto 20% loading

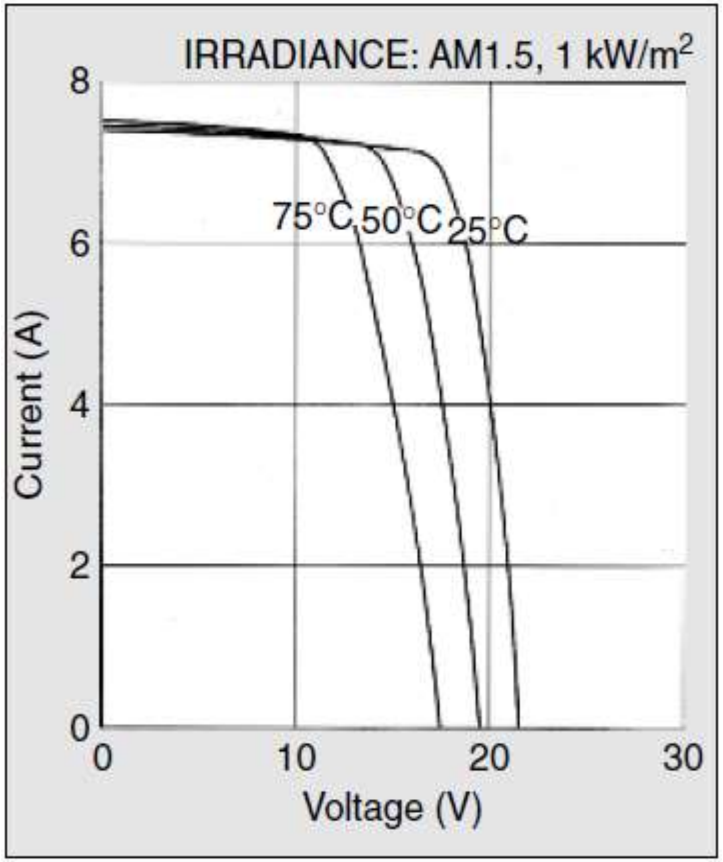


↑ loading, ↑ inverter η

Effect of temperature

- With increase in temperature, voltage reduces while current increases very slightly
- For crystalline Silicon cells, V_{OC} drops by 0.37% per degree C, and I_{SC} increases by 0.05% per degree C
- **MPP drops by approx 0.5% per deg C**

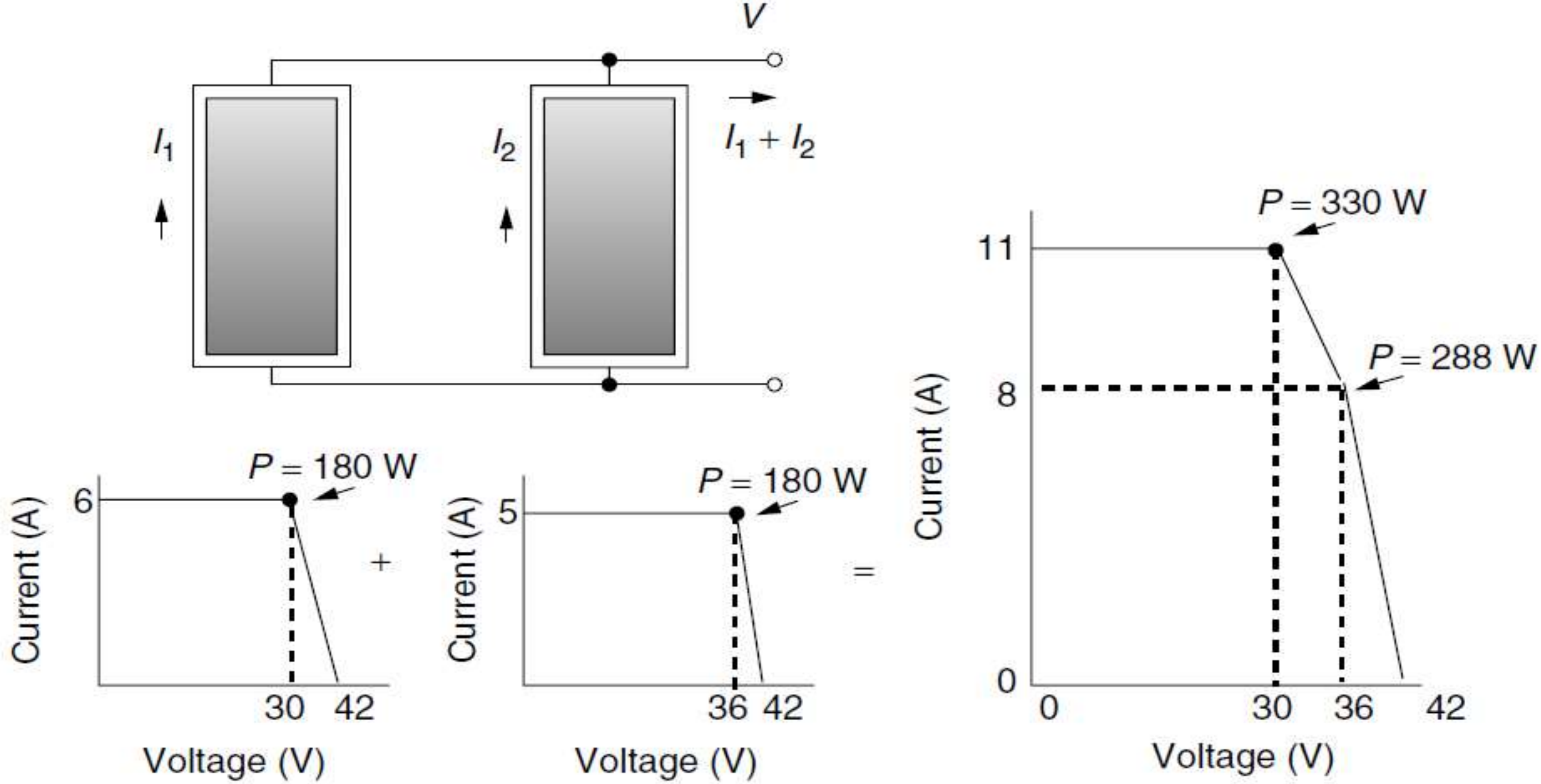
↑T, ↓η



in reality, modules don't add up perfectly...

Effect of variation in I-V curves

- Example: Each module is rated at 180 W, but the parallel combination yields only 330 W at the maximum power point



Example: Consider a PV array rated at 1 kW under standard test conditions. Module cell temperature is 53.8◦C . DC power output at the MPP drops by 0.5%/◦C above the STC temperature of 25◦C. Estimate its ac output if there is a 3% array loss due to mismatched modules, dirt loss is 4%, and the inverter has an efficiency of 90%.

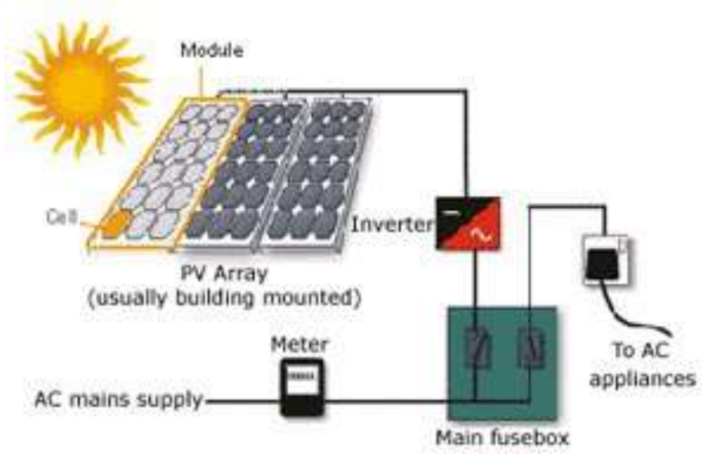
Solution:

With power loss at 0.5% per degree above 25◦C, the dc rated power of the array would be

$$P_{dc} = 1\ \text{kW}[1 - 0.005(53.8 - 25)] = 0.856\ \text{kW}$$

Including mismatch, dirt, and inverter efficiencies will result in an estimated ac rated power at PTC of

$$P_{ac} = 0.856\ \text{kW} \times \underline{0.97} \times \underline{0.96} \times \underline{0.90} = 0.72\ \text{kW}$$

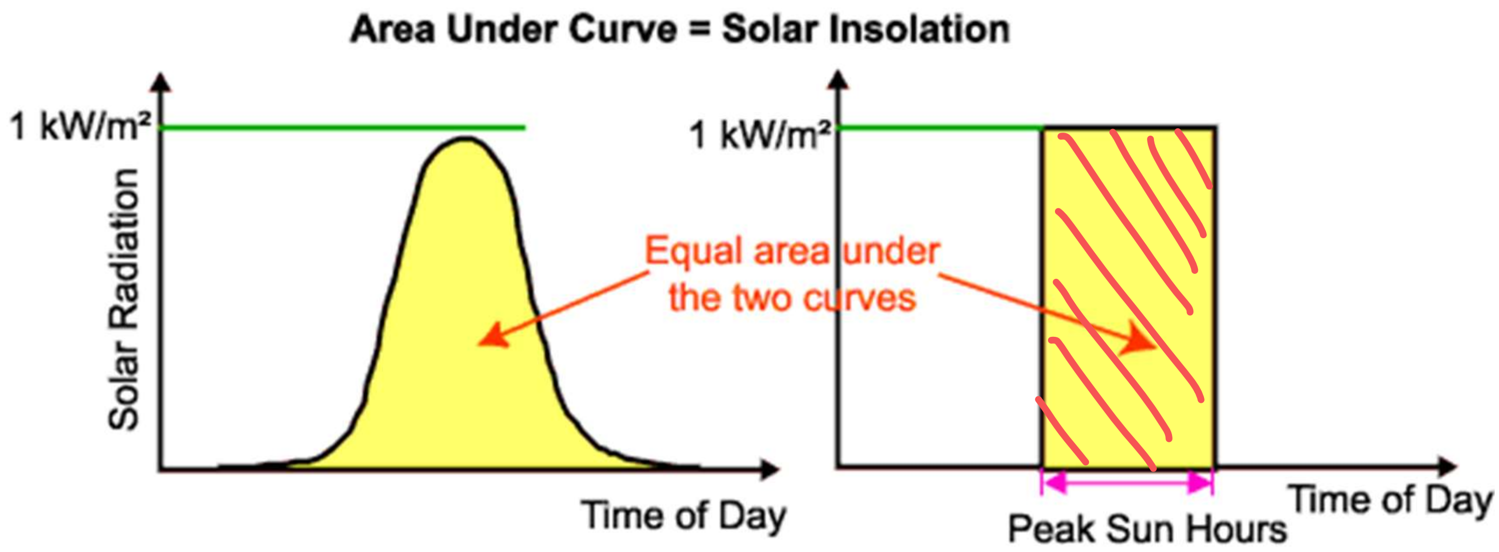


Even though the system would be sold as a "1-kW system", the array will deliver **only 72%** of that as ac power to the load under realistic conditions

Peak Sun Hours

- **The term "peak sun hours" refers to the solar insolation which a particular location would receive if the sun were shining at its maximum value for a certain number of hours.**

- For example, a location that receives 8 kWh/m^2 per day can be said to have received 8 hours of sun per day at 1 kW/m^2.



↳ we want to know how many sun hours at max. insolation

Estimating PV Performance - The "Peak-Hours" Approach

- If we know the ac power delivered by an array under 1-sun insolation (P_{ac}), we can just multiply that rated power by the number of hours of peak sun to get daily kWh delivered
- energy delivered in a day

$$\text{Energy (kWh/day)} = \text{Insolation}\left(\frac{\text{kWh/m}^2}{\text{day}}\right) \cdot A\ (\text{m}^2) \cdot \overline{\eta}$$

Capacity Factors for PV Grid-Connected Systems

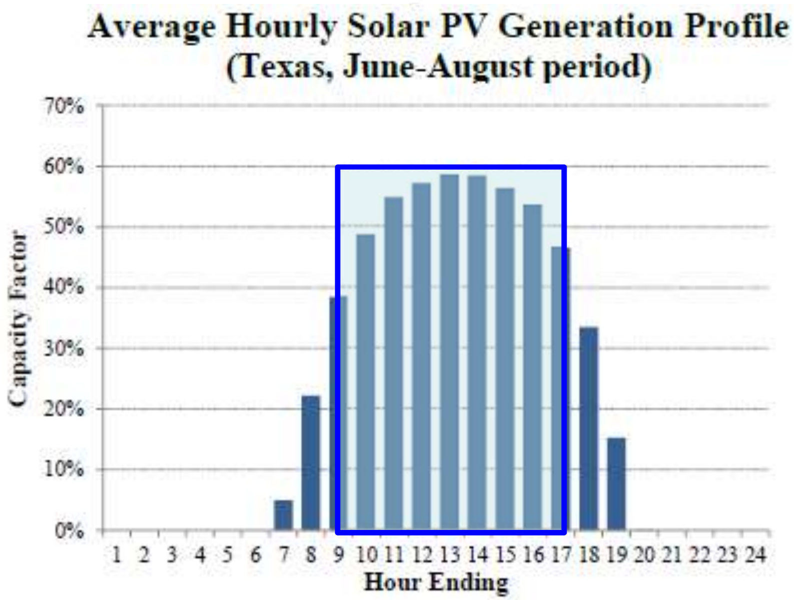
(1)

- If the system delivered full, rated power continuously, the CF would be unity.
- the energy delivered by the system in terms of its rated ac power and capacity factor (CF).

$$\text{Energy (kWh/yr)} = P_{ac}\text{(kW)} \cdot \text{CF} \cdot 8760\text{(h/yr)}$$

$$\text{Energy (kWh/day)} = P_{ac}\text{(kW)} \cdot \text{(h/day of ``peak sun'')}$$

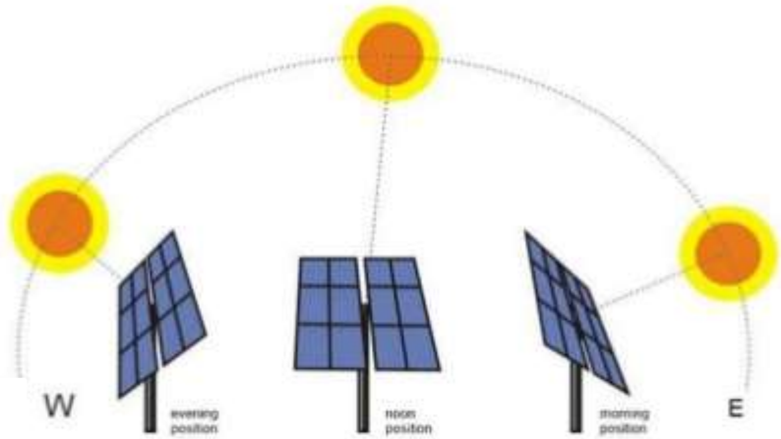
$$\text{Capacity factor (CF)} = \frac{\text{(h/day of ``peak sun'')}}{24\ \text{h/day}}$$

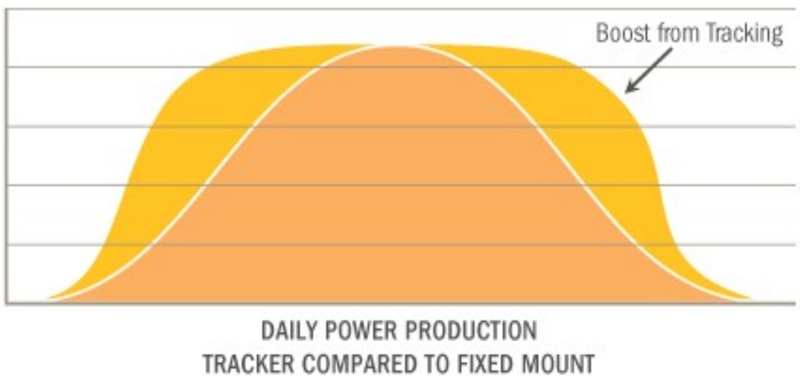


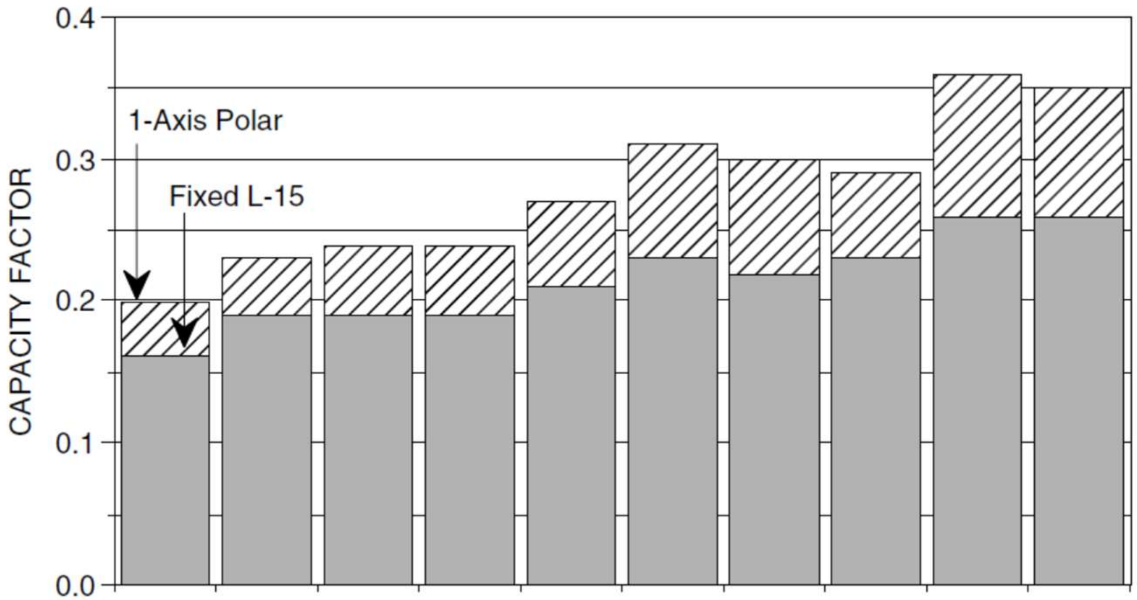
Source: Calculated based on 8,760 hourly generation data from NREL's Solar Advisor Model (SAM) version 2011.6.30.

Capacity Factors for PV Grid-Connected Systems

Single-Axis Solar Tracker







The tracker can substantially increase the power output of a solar PV system

Grid-connected PV system design

1. Estimate the rated power and area required for the PV array.

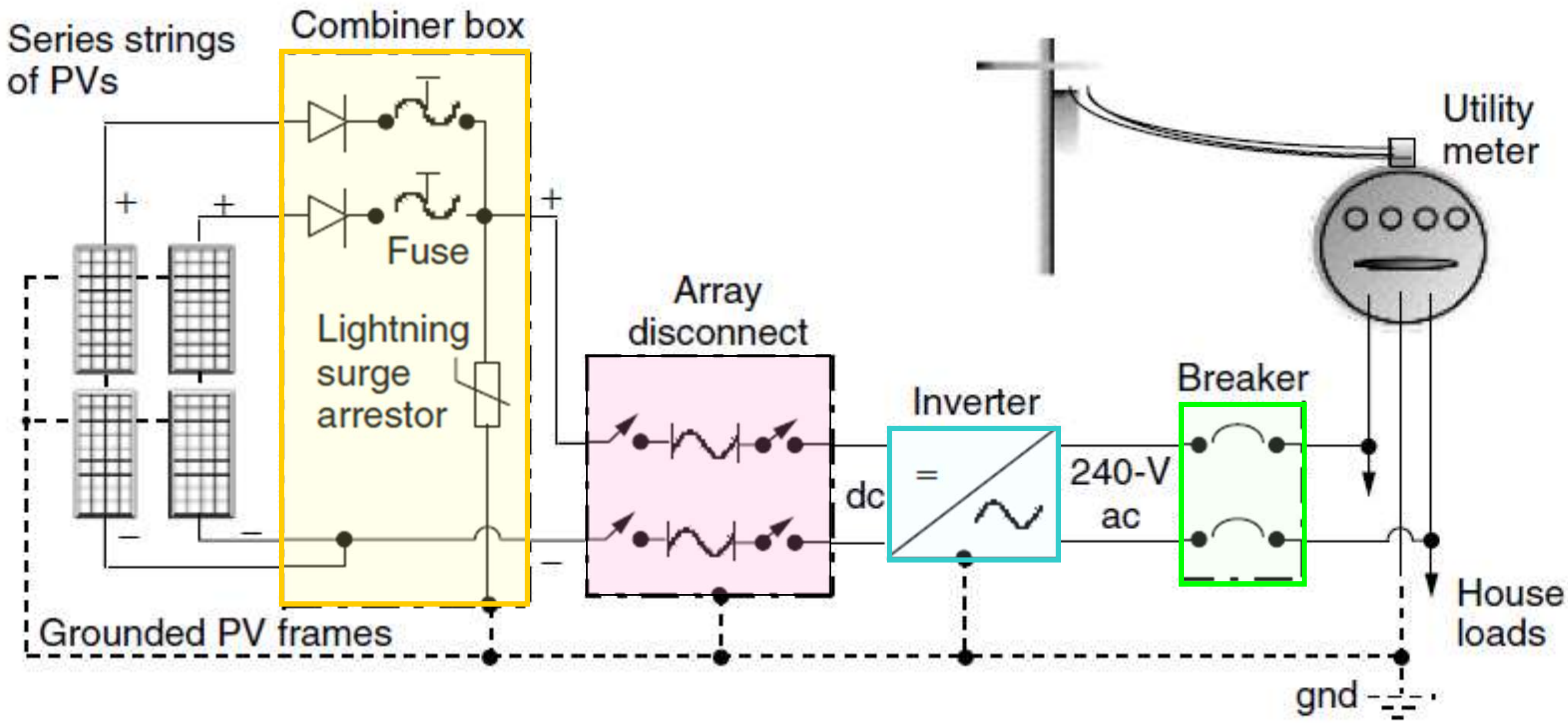
2. Explore the interactions between the choice of PV modules and inverters and how they impact the layout of the PV array.

3. Finally, consider details about voltage and current ratings for fuses, switches, and conductors.

Grid-connected PV Systems

Grid-connected system using a single inverter

(MPPT, protection circuitry and battery bank are not shown)



Example: System sizing (first cut)

- **An energy efficient house in Singapore is to be fitted with a rooftop PV array that will annually displace all of the 1550 kWh/yr of electricity that the home uses. How many PV panels will be required and what area will be needed? Make assumptions as needed.**
- Using data for Singapore -- 4.1 kWh/m^2-day of annual insolation, using the peak hour approach,
- Energy (kWh/yr) = P_{ac}(kW) · (h/day @1-sun) · 365 days/yr

$$P_{ac} = \frac{1550}{4.1 \times 365} = 1.0357\ kW$$

Considering the impacts of temperature, inverter efficiency, module mismatch, and dirt to come up with conversion efficiency of 75% from dc to ac.

$$P_{dc} = \frac{1.0357}{0.75} = 1.381 kW$$

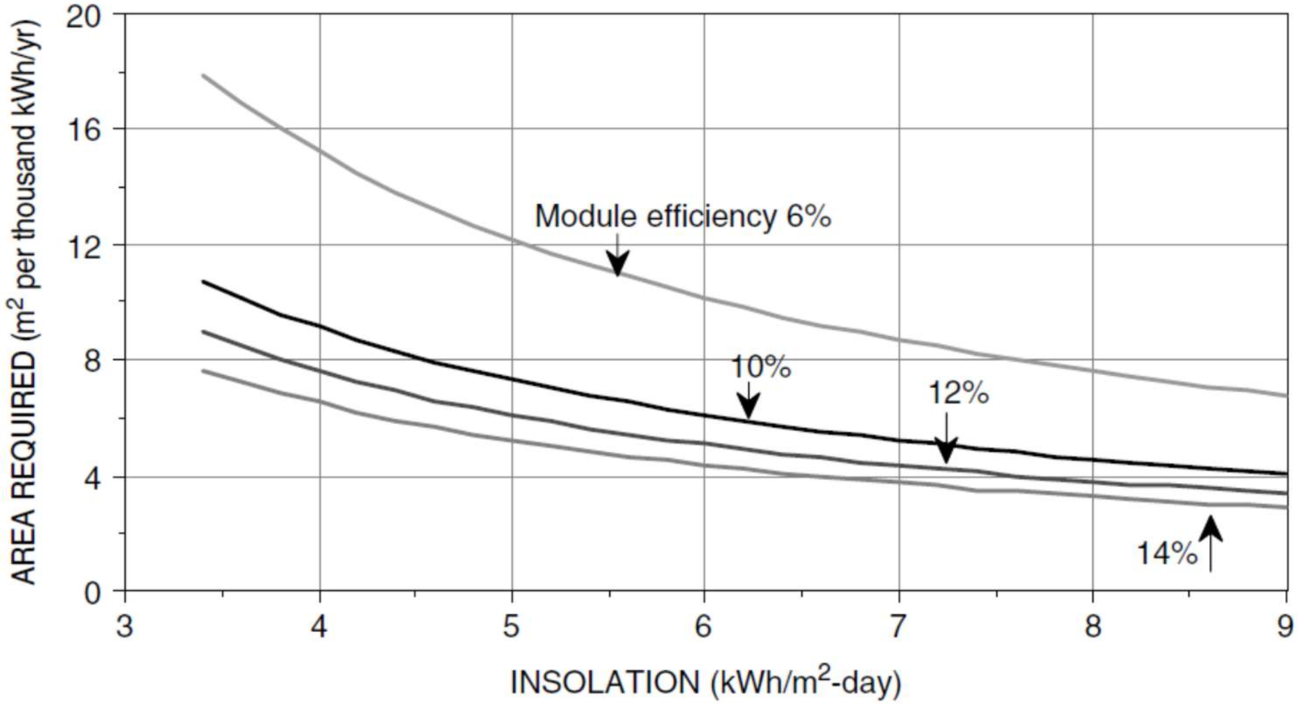
To estimate the collector efficiency, P_{dc} = 1 kW/m^2 insolation · A (m^2) · η

Assuming crystalline silicon modules which typically have an efficiency of about 12.5%, the area required

$$A = \frac{1.381 kW}{1 kW / m^2 \times 0.125} = 11.048 m^2$$

Example: System sizing

- Area required to deliver 1000 kWh/yr with module efficiency as a parameter, assuming a conversion efficiency from dc to ac of 75%.



Example: System sizing (more accurate calculation)

- Number of modules required:

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%

$$Number\ of\ modules = \frac{1381W}{158W/module} = 8.74$$

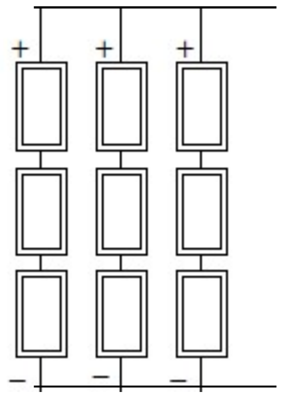
Example: System sizing (more accurate calculation)

- Inverter selection:

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%

With three modules per string, rated voltage= 3 × 23.2 = 69.6 V, which is in the MPPT range.

This suggests using an array with three strings of three modules each, for a total of 9 modules



Roof area required = 9 x 1.29 x 0.99 = 11.49 m^2 (very close to the initial estimate)

Example: System sizing

- The short-circuit current for each string of panels is 7.58 A.
- Applying the 125% factor to afford a safe oversizing margin, results in combiner fuses that must allow at least 25% safety margin

  Combiner fuses > 7.58 A × 1.25 = 9.475 A

- The array disconnect fuse must accommodate three such strings, so it must handle 3 strings!

  Array disconnect fuse > *9.475 x 3* = 28.425 A

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
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Width:	0.792 m	0.990 m	0.814 m	0.420 m
Efficiency:	13.3%	12.4%	11.4%	5.5%

Example: System sizing

- $$\text{Inverter fuse} > 1.25 \times \frac{2500\ \text{W}}{240\ \text{V}} = 13\ \text{A}$$

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
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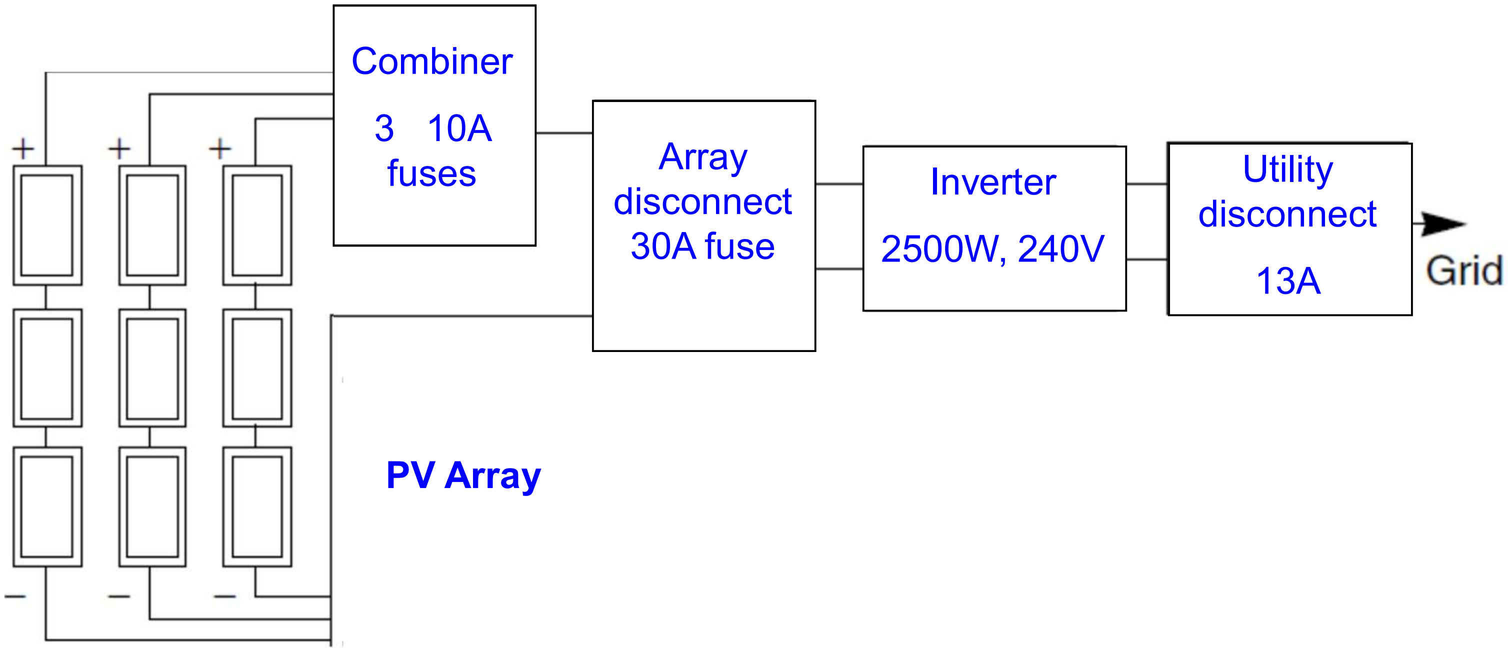
Max input current:	—	—	31.9 A	10 A	11 A
Maximum efficiency:	92%	94%	95%	96%	94%

Example: System Design

- Complete system



System Integration

PV System Integration Parameters

- Net load duration curve
- Capacity displacement
- Emissions reductions
- Fossil fuel use reductions
- Cost of electricity

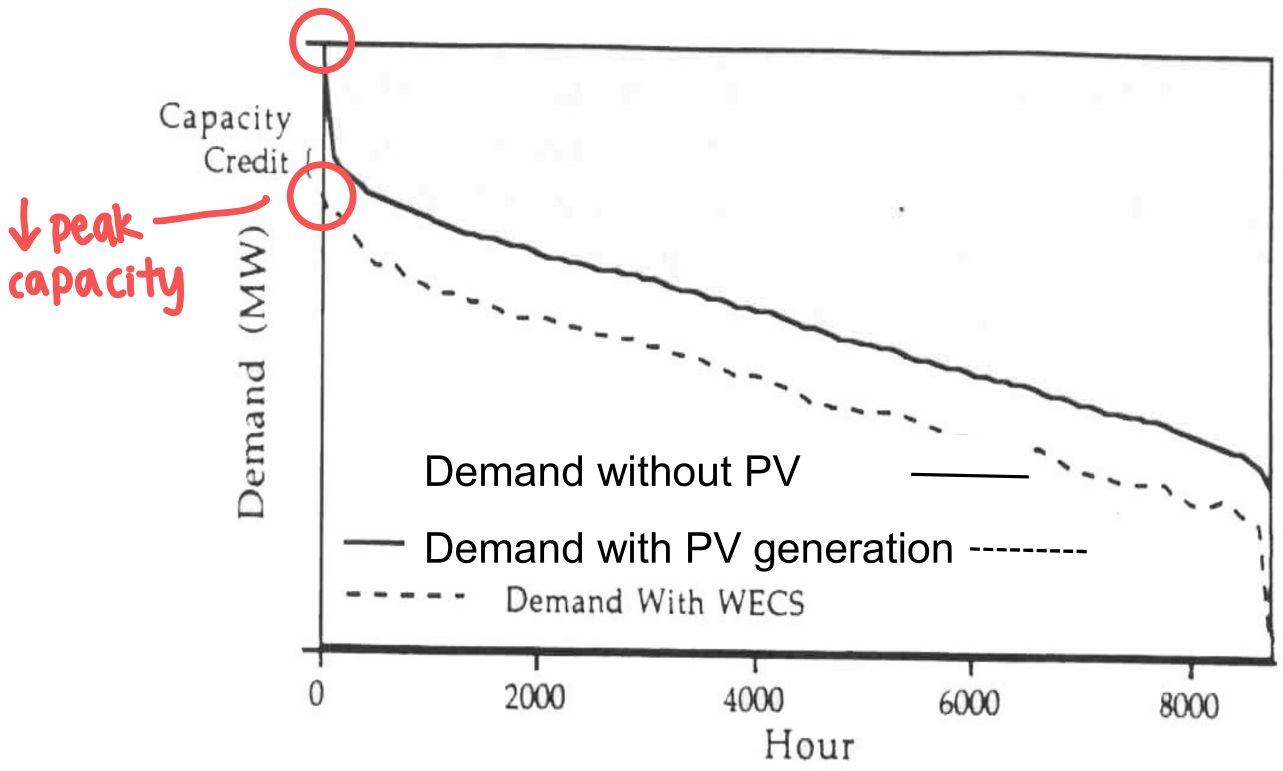
Overall reduction in the power to be generated

Capacity displacement

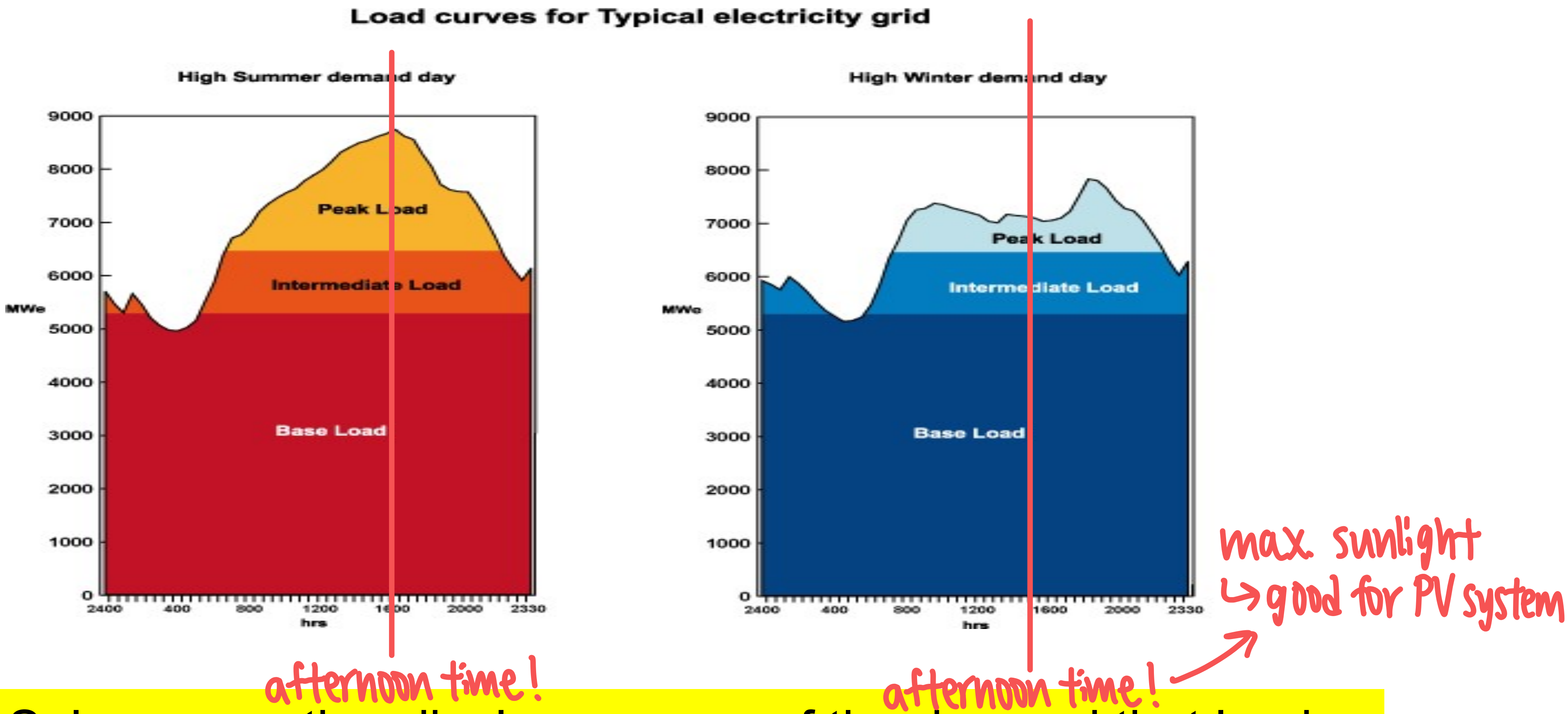
Which type of capacity does the inclusion of PVs displace

- in terms of short run operation, and
- long run construction needs

- Net load duration curve



Overall reduction in the power to be generated



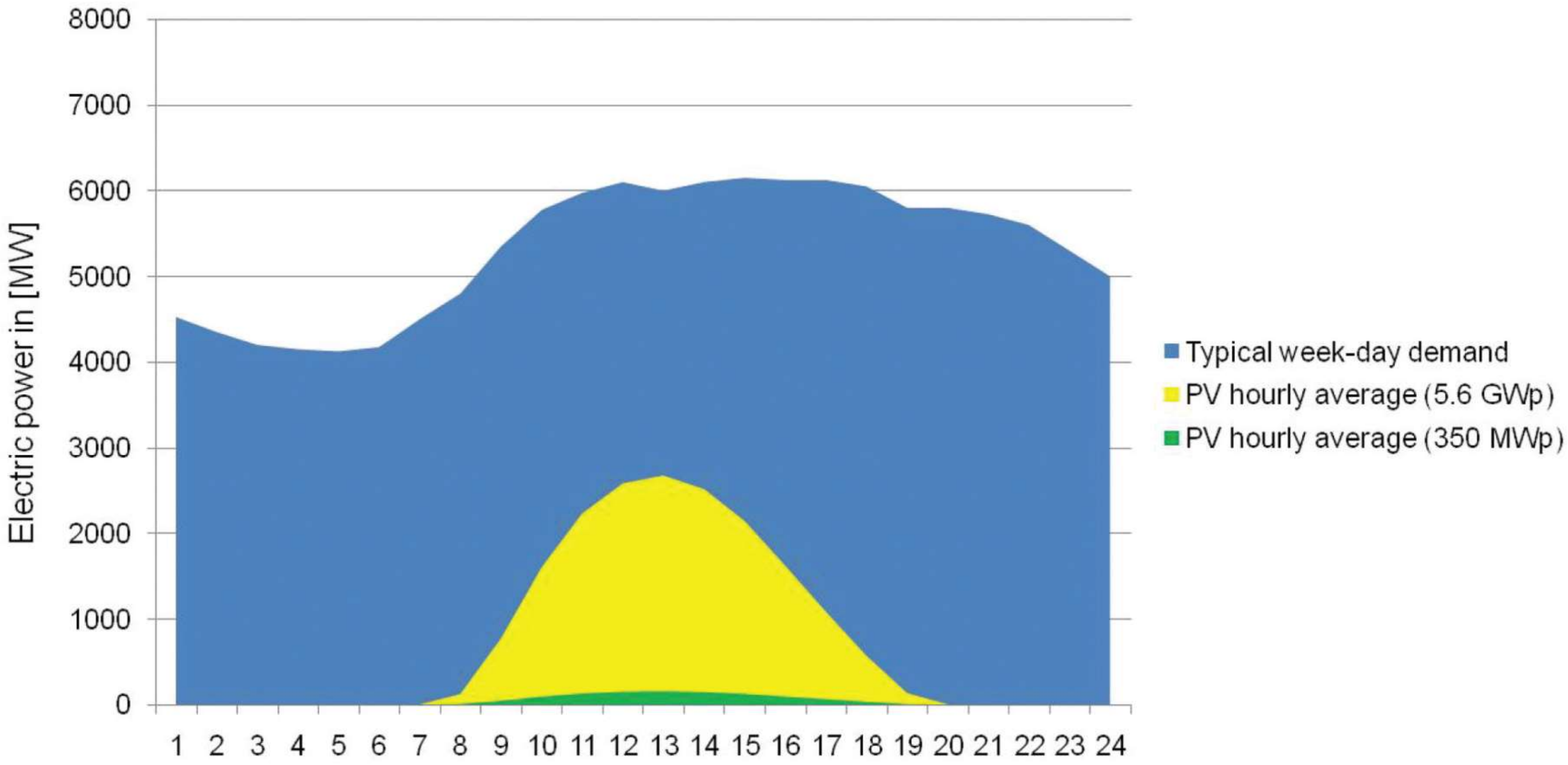
Solar generation displaces some of the demand that leads to peaking plants being activated.

Capacity displacement

- PV generation has huge potential to reduce peak load
- Capital expenditure on installation of utility generators is therefore reduced

↓peak load

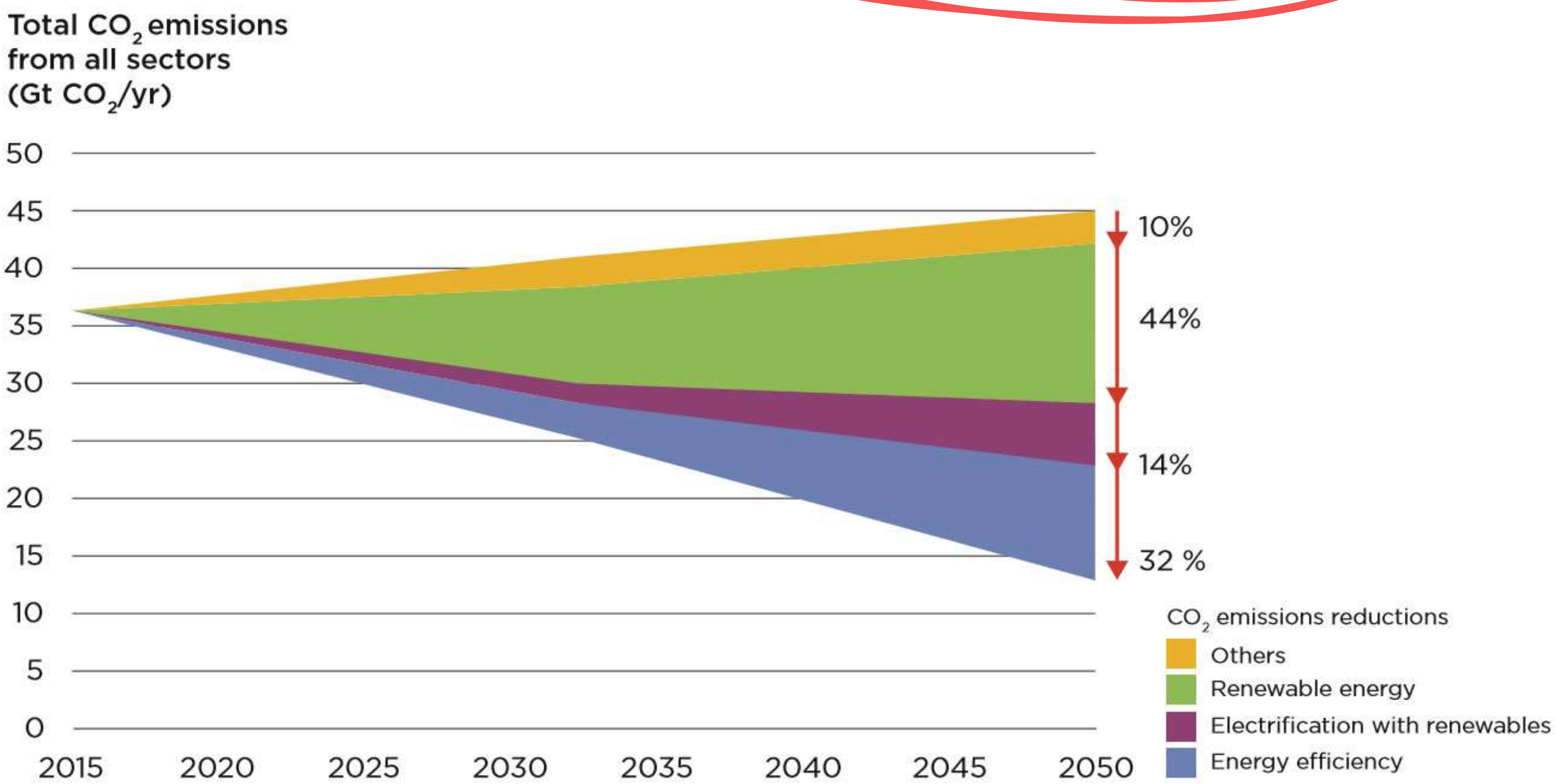
Case study in Singapore:



(Source: Phoenix Solar)

System Integration: Emission Reductions

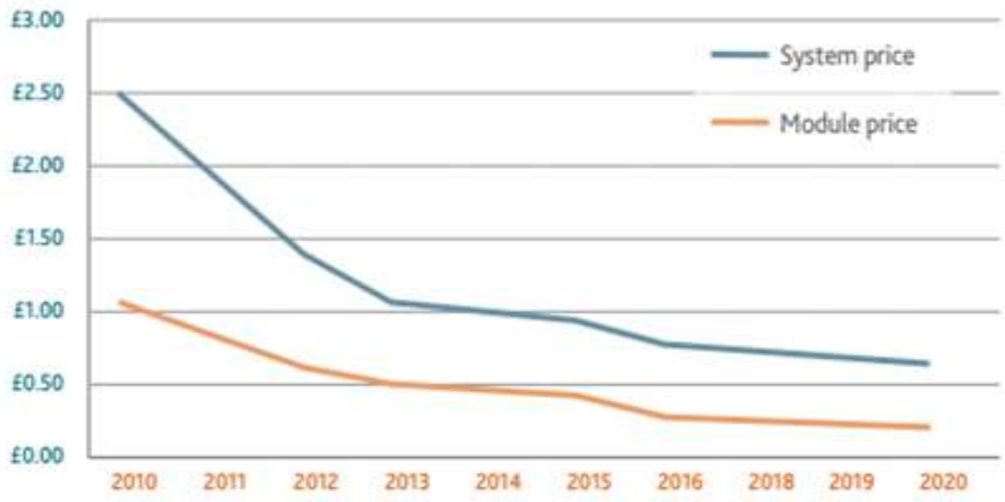
- Overall emissions decrease both from demand management/conservation and from new supply options
- **Energy Emissions Can Be Reduced 70% By 2050**



Source: IEA & IRENA Report

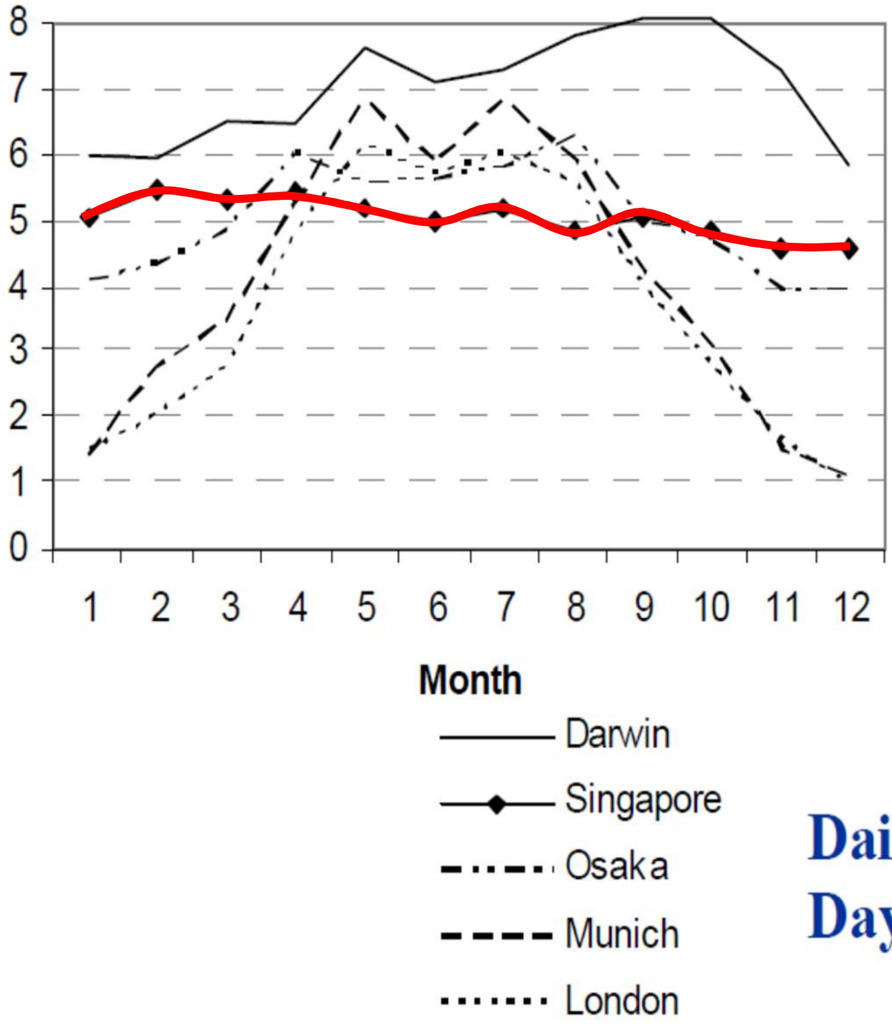
Cost of electricity

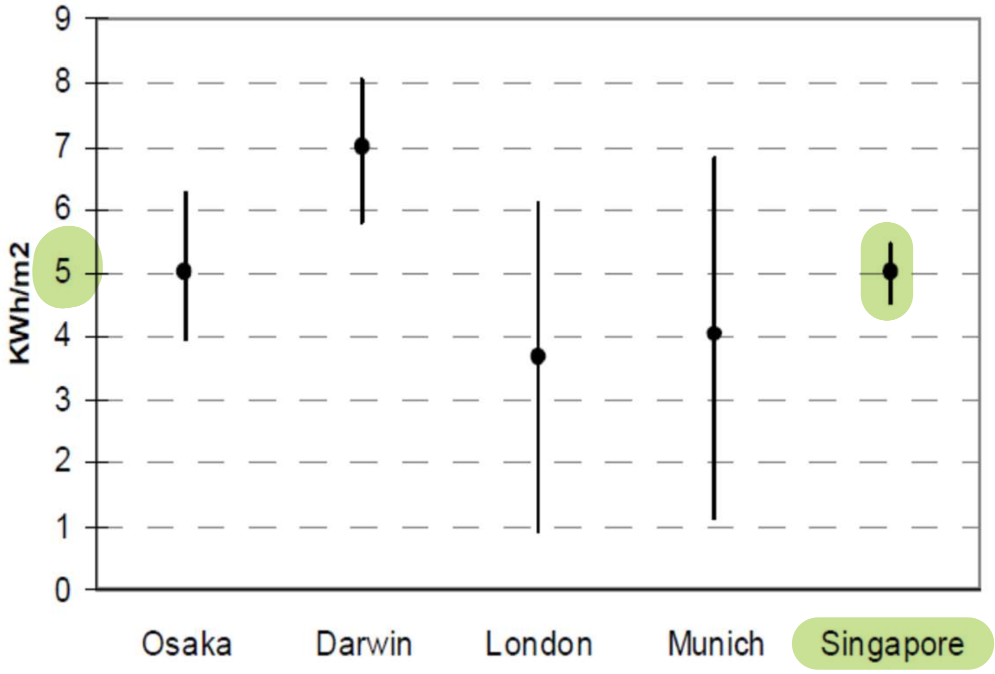
- The energy output of such PV plants reaches it's peak at midday, meeting the daily energy consumption peak, when the spot prices on energy are highest
- **Grid parity: the point at which the costs are equal to grid power**
- PV-generated electricity is usually more expensive than conventional utility-supplied electricity.
- PV power requires a high initial investment but very low running costs



Cost of electricity from PVs

Daily global solar radiation





Daily Global Solar Radiation Charts

Daylight = Sunlight + Skylight

SG: ~5 kWh/m²

Renewable Energy potential in Singapore

Source NEA

Non-existent

Non-existent

Local sources fully-utilized

Low wind speeds

Low tidal range

High and even irradiation - Greatest potential

Solar energy has the greatest potential!

Singapore rooftops could generate 20% of electricity*

Singapore has 100km^2 of “free” real estate for PV

– Built-up land exceeds 260km^2

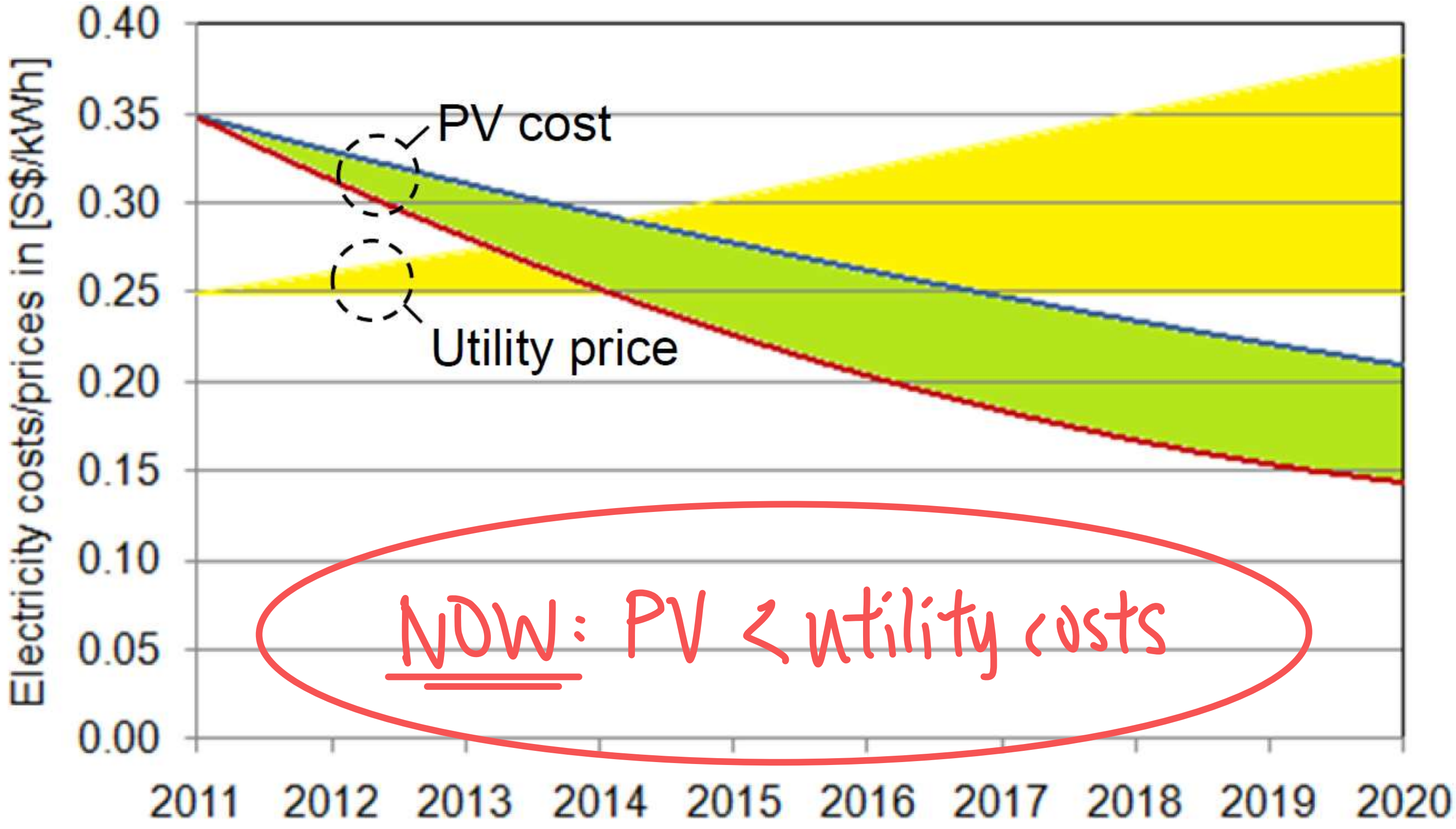
– Conservative estimate = 100km^2 of roof + useful facade space)

– $\boxed{\text{10GW of PV capacity can generate 20\%}}$ of Singapore’s electricity!

* 2016 electricity consumption = 48 TWh (source: EMA)

(Source: Phoenix Solar)

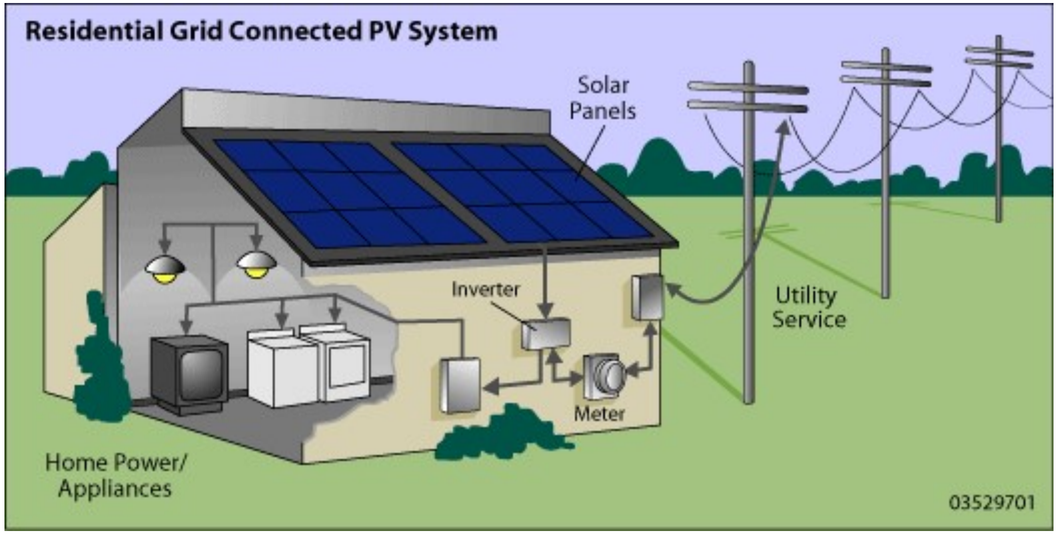
Cost of PV electricity in Singapore (Source: SERIS)



Singapore achieved grid parity in 2012 — when the cost of installing and maintaining solar photovoltaic (PV) panels became the same as that from the grid (conventional sources)

Integration of PV: Issues

- Why does industry resist inclusion of small-scale generation?
  - First problem – local instability in the distribution system
  - Second problem – schedule mismatches and decentralized control in the transmission system
- How would an owner get paid for the benefits provided by installing PV power system? utility company benefits from this ↓demand, NOT owners ⇒ why would owners spend $ to benefit others???
- Can PV power systems be part of the competitive markets?



Source: GE Energy

Technical issues for system integration of PV

Long term planning

- Pros: modular, low emissions, small footprint
- Cons: non-dispatchable, requires different planning frameworks

Short term operations

- Do not fit into the existing or emerging institutional structures (system operation, market rules)

Cost-Effectiveness of Installation

- Tracking arrays of modules gather more energy (perhaps 35%) but add to the cost; one could just increase array area in a fixed mount
- Reduce load demand by $\boxed{\text{conserving energy and efficiency}}$ – the rule is that **saving a watt in conservation is worth saving three watts in conversion**
- Compare installation & utility line extension costs
- Consider adding wind turbine for hybrid energy
- Use fueled generator occasionally to decrease cost of PV
- Modules can be placed vertically on the side of a building at high latitudes or flat on the roof at low latitudes

ugly tho...

Flat Roof and Wall Installations

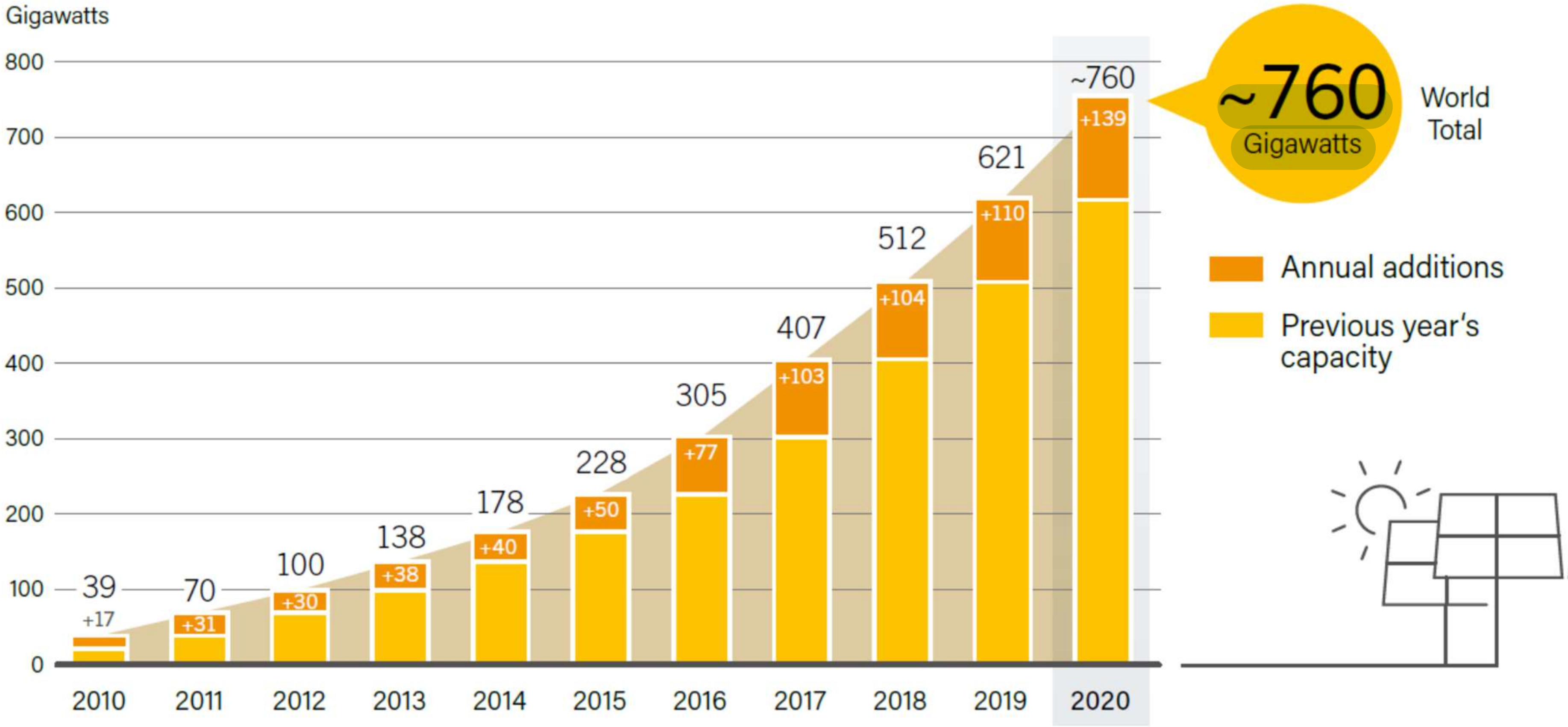
- Integrated PV may be more acceptable

Building Integrated PV in Tampines Grande project (Phoenix Solar)

Net Zero Energy Building in NUS

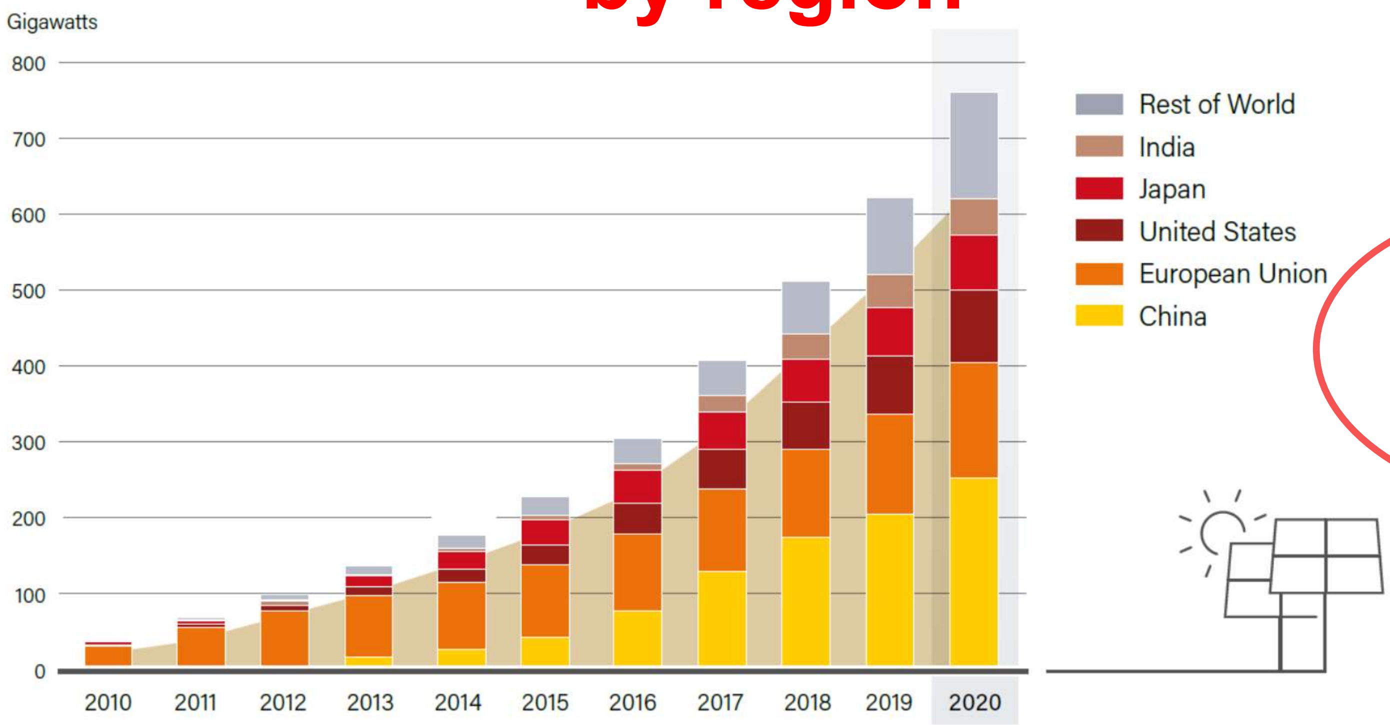
Solar PV: Current Status

Solar PV Global Capacity and Annual Additions (2010-2020)

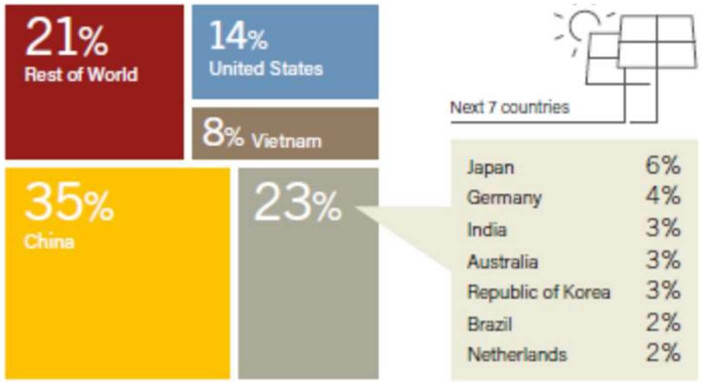


- Solar PV saw a rapid growth in 2020, driven by favourable economics and policy changes.
- About 140 GW was added in 2020 (large scale PV systems and distributed rooftop installations)

Annual Installed PV capacity (2010-2020) by region



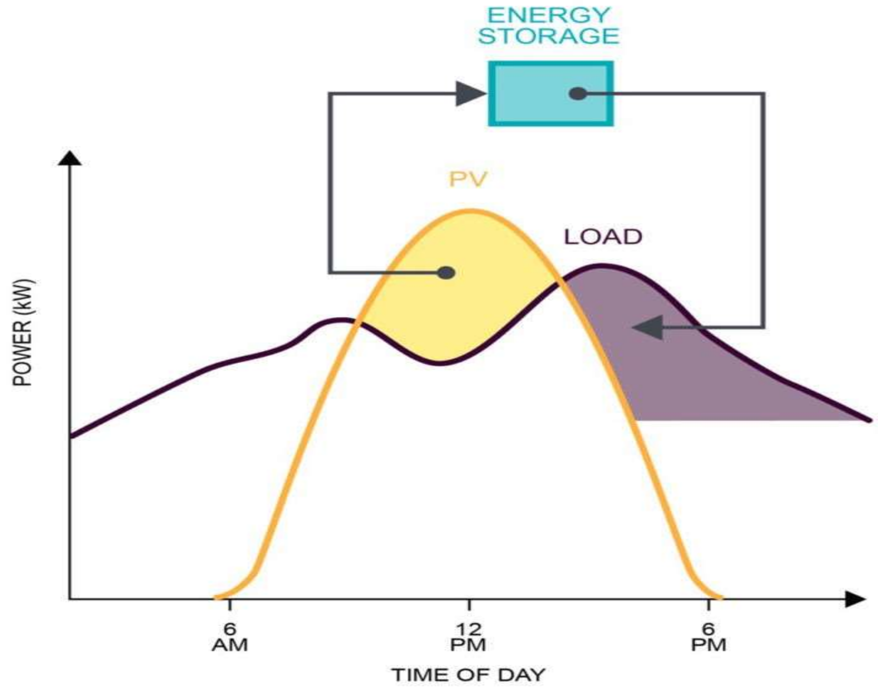
CHINA



- China is the global leader.
- Asia accounted for nearly 60% of new PV installations
- Increased interest in home improvements during the pandemic helped drive demand for residential systems around the world

Source: REN21 Renewables 2021 Global Status Report

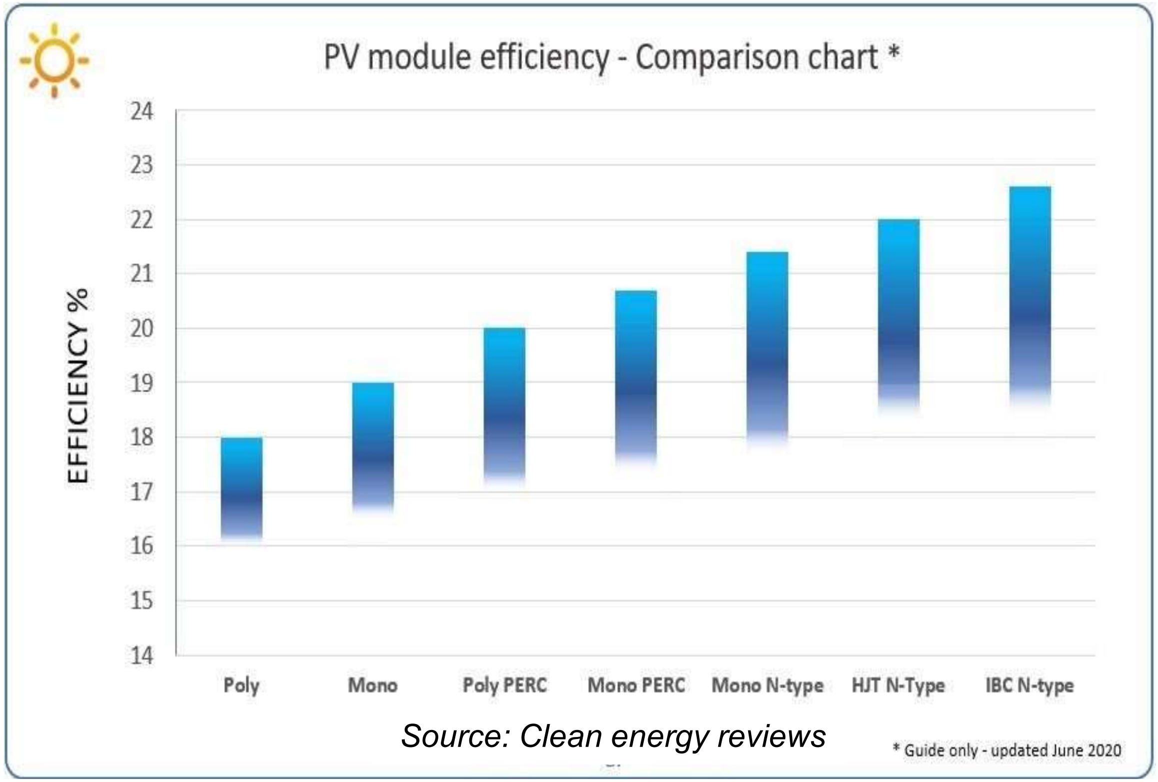
Integrated PV-Storage Systems Provide Several Benefits



Integrating PV with properly designed energy storage systems can provide a combination of financial, operational, and environmental benefits through peak shaving and reliability applications.

Efficiency of Commercial PV Modules

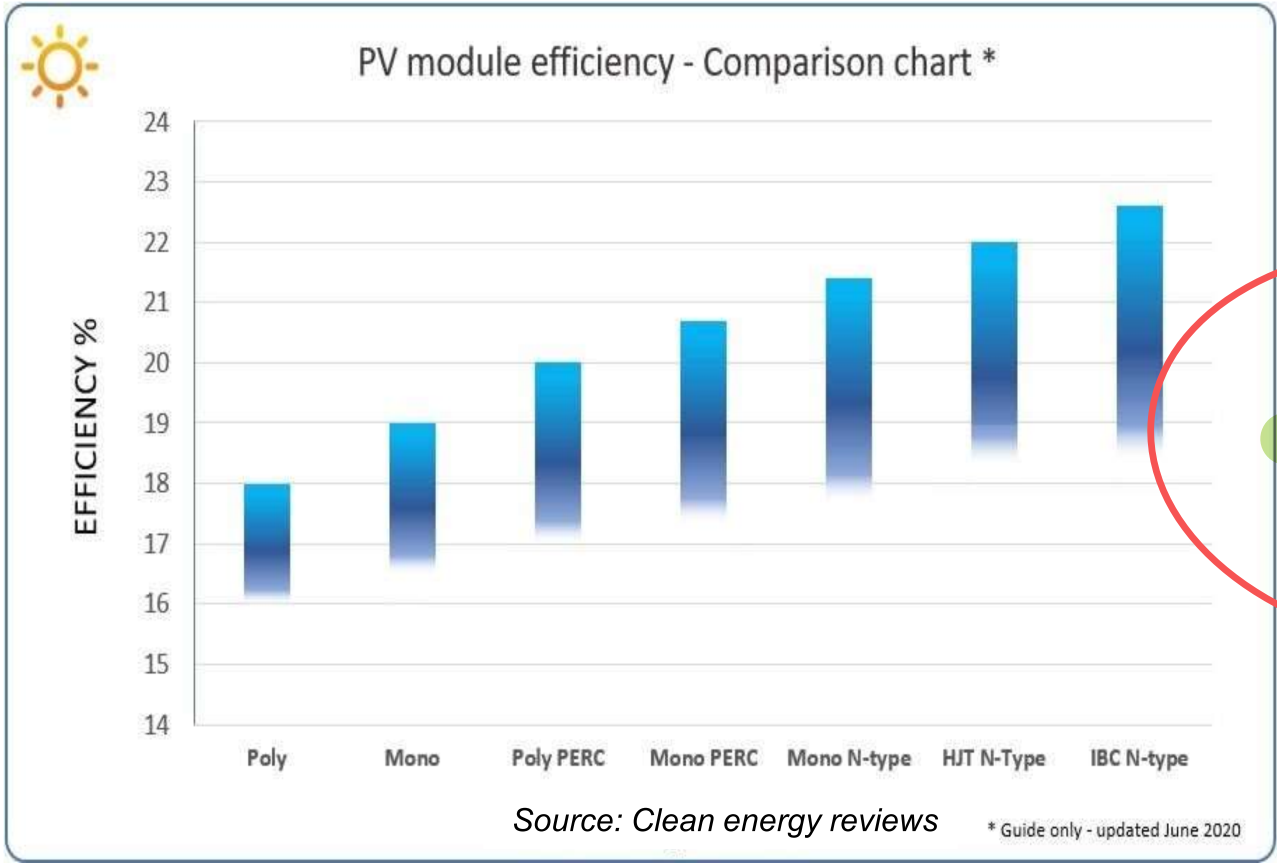
- The average panel conversion efficiency has increased from 15% ten years ago to well over 22%
- Thin Film technology (e.g. from First Solar) shows promise
- Spectrolab, a subsidiary of Boeing, has developed multi-junction solar cells with an efficiency > 40%, a new world record for solar photovoltaic cells!



Source: Clean energy reviews

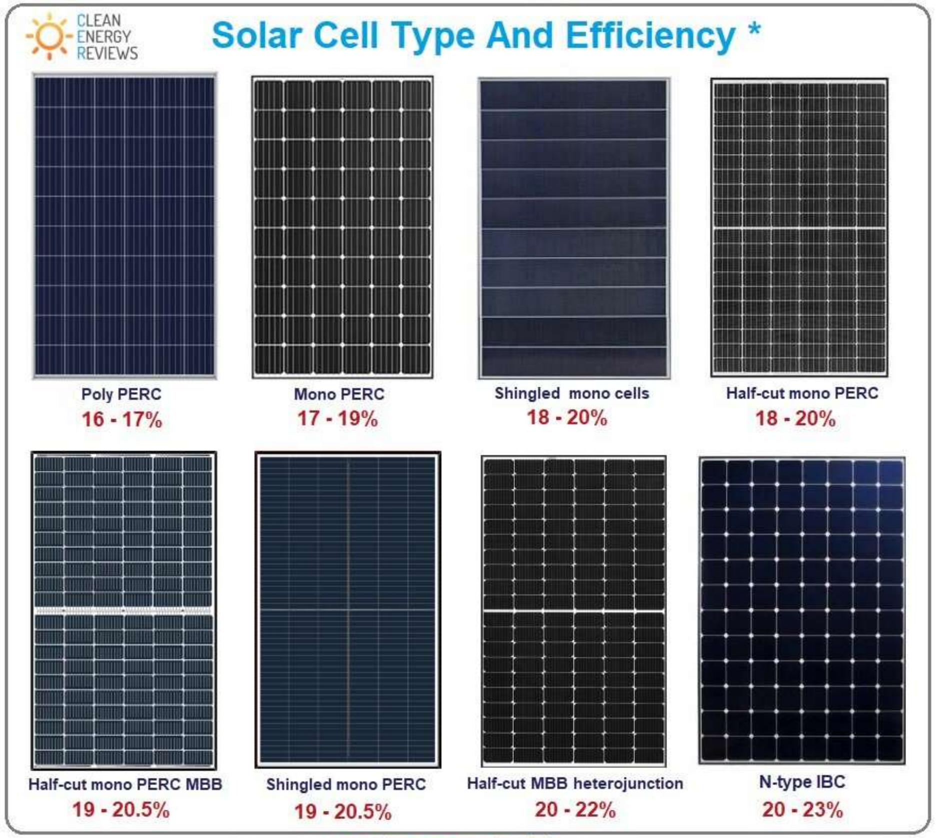
Efficiency of Commercial PV Modules

- Currently, the best achieved solar module efficiency is around 22.5%
- The average panel conversion efficiency has increased from 15% ten years ago to well over 22%



Efficiency of Commercial PV Modules

- Cell efficiency is determined by the cell structure and base silicon material used which is generally either P-type or N-type.
- Cell efficiency is calculated by the fill factor (FF), which is the maximum conversion efficiency of a PV cell at the optimum operating voltage and current.



Source: Clean energy reviews

- Panels built using advanced 'Interdigitated back contact' (IBC cells) are the most efficient, but also very costly
- Recent heterojunction (HJT) cells have achieved efficiency levels well above 20%.

- Thin Film technology (e.g. from First Solar) shows promise
- Spectrolab, a subsidiary of Boeing, has developed multi-junction solar cells with an efficiency > 40%, a new world record for solar photovoltaic cells!

Largest solar PV projects in recent years

Project Name	Country	Year	Capacity (MW)
Bhadla Solar Park	India	2018	2250
Huanghe Hainan Solar Park	China	2020	2200
Pavagada Solar Park	India	2020	2050
Benban Solar Park	Egypt	2019	1650
Tengger Desert Solar Park	China	2016	1547
Noor Abu Dhabi	UAE	2019	1200
Mohammed bin Rashid Al Maktoum Solar Park	UAE	2020	1013
Kurnool Ultra Mega Solar Park	India	2017	1000
Datong Solar Power Top Runner* Base	China	2016	1000
NP Kunta	India	2018	978
Villanueva Solar Park	Mexico	2018	828

- These Utility-scale solar plants generate reliable, clean electricity with a stable fuel price.
- Many utility-scale solar designs can also include energy storage capacity that provides power when the sun is not shining, and increases grid reliability and resiliency.
- In some places, solar plants are grouped together in solar parks or clusters, leading to even higher capacities.

Bhadla Solar Park, India

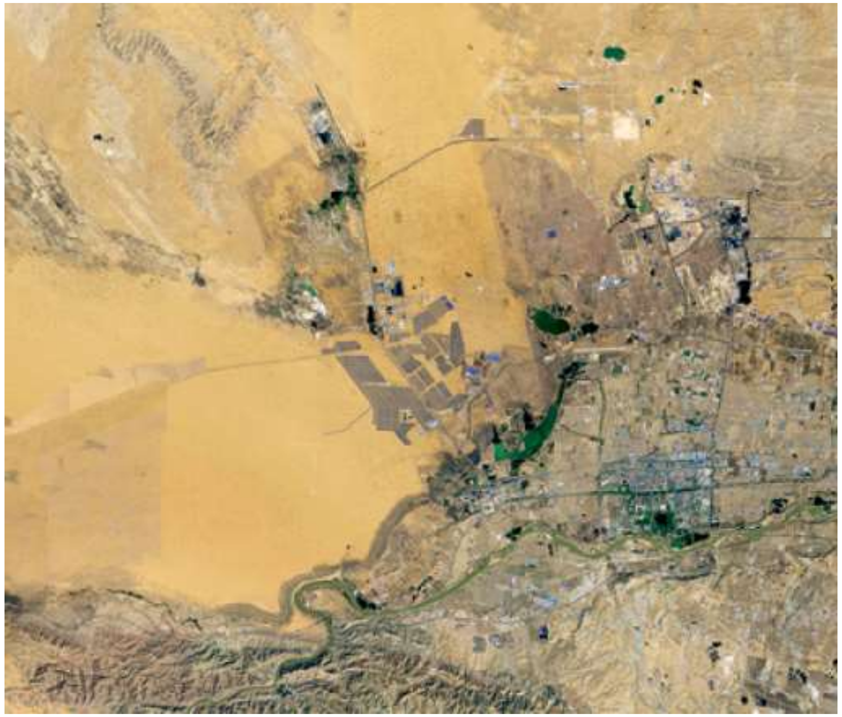
- Total capacity: 2250 MW
- World's biggest solar power plant
- Located in Jodhpur district, Rajasthan
- Comprises of 10 million solar panels, which are cleaned using robots
- Produces electricity at approx \$0.05/kWh (₹2.44/kWh), which is much lower than the utility's tariff of \$0.065/kWh

Huanghe Hydropower Hainan Solar Park, China

- World's second largest solar PV plant
- Total capacity: 2200 MW
- Located in Qinghai
- Includes an energy storage system of 202.9 MW supplied by domestic company Sungrow.
- It is part of a giant renewables project, which is planned to reach 16 GW (with 10 GW Solar PV and 1 GW Concentrated Solar Power)

Tengger Desert Solar Park, China

- Total capacity: 1547 MW
- Fully operating since: 2016
- Located in Ningxia, in the Inner Mongolia Autonomous Region in China
- Dubbed the 'Great Wall of Solar', it covers 1,200km of the 36,700km Tengger desert, occupying 3.2% of the arid region.



Kurnool Ultra Mega Solar Park, India

- PV capacity: 1000 MW
- In operation since 2017
- Located in Andhra Pradesh
- Over four million solar panels were installed in the park, each with a capacity of 315W or 320W.
- Produces electricity at approx $0.074/kWh

Villanueva solar park, Mexico

- Total capacity: 828MW
- In operation since 2018
- Located in the Mexican state of Coahuila, just south of the Texas border
- The facility comprises over 2.3 million solar panels across 2,400 hectares
- Largest solar PV park in the Americas

Lonyangxia Dam Solar Park, China

- Total PV capacity: 850 MW
- Fully operating since: 2015
- Integrated with the hydroelectric power station with a capacity of 1280 MW (4 hydroelectric generators, 320 MW each)
- The site sits on the Tibetan Plateau in northwestern China's Qinghai province
- Hybrid operation - automatically regulates the output to balance the variable generation from solar before dispatching power to the grid.

Solar PV current status

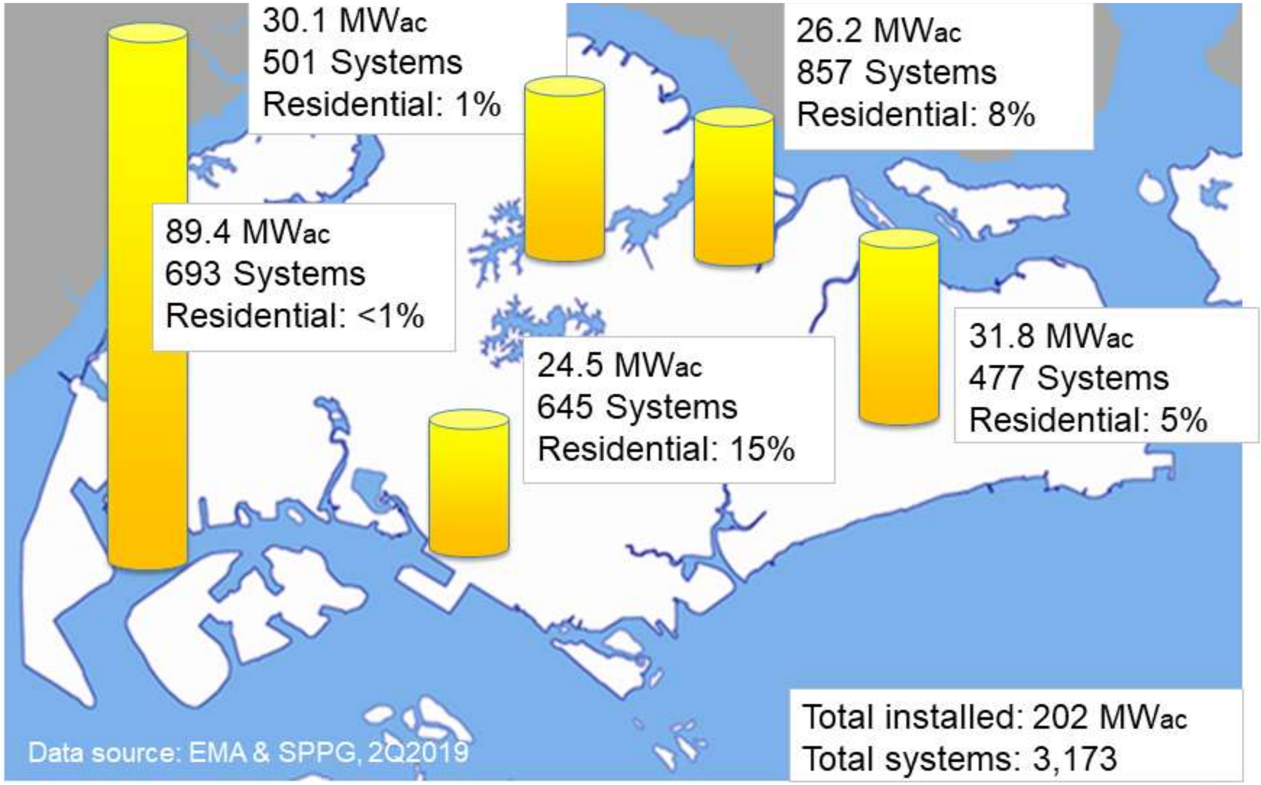
- Record efficiencies for solar cells of various materials are produced every year. Many research institutions are still exploring new materials and also tandem solar cells (multiple layers of solar cells absorbing different portions of the spectrum). Nevertheless, crystalline Silicon solar cells still dominate the market.

- China is leading the way in terms of manufacturing of components (solar cells, modules, inverters) as well as installation thanks to the government investment, but the domestic Chinese market is getting saturated with as much as 30% of the solar energy gets curtailed at some hours in the year

- Bifacial solar modules (solar modules that can capture light on both sides are gaining popularity, and so are building integrated PV (the solar modules are replacing building materials such as glass or roof)

- Solar PV, combined with batteries, can be the most economical solution to power remote areas with no grid access.

Solar PV current status
- PV Installation in Singapore



- Solar energy is the most promising renewable energy source for Singapore
- Singapore has an average annual solar irradiance of 1,580 kWh/m2/year
- Installations by end of 2020: 350 MWp
- **Singapore could be 25% solar-powered by 2025 (hoping to keep its** climate change pledge to reduce emissions intensity by 36 percent from 2005 levels by 2030)

Source: EMA and SERIS

Solar PV current status

Main challenges:

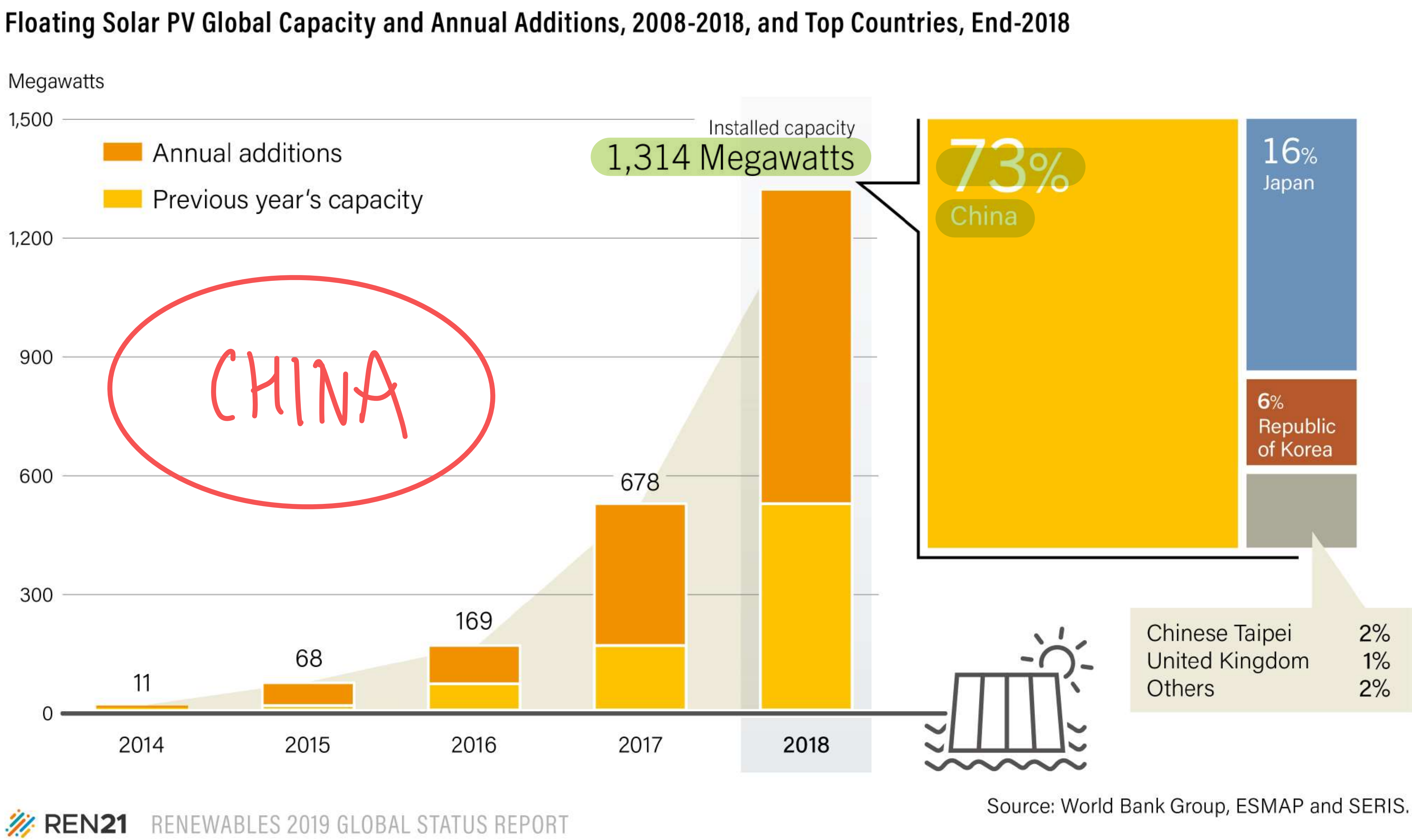
- Efficiency of single layer/material solar cells are getting closer to theoretical efficiency of 30%
- May still not be competitive in developing countries with low electricity prices (artificially low or otherwise)
- Most utilities are still wary of solar intermittency
- Batteries are still very expensive, both for remote communities, and for grid operators

Rise of Floating PV (Floatovoltaics)

Advantages:
- cooling effect from the water body → higher efficiency
- doesn't occupy land
- No fixed structure (installation is reversible)
- Reduced water evaporation

Disadvantages:
- Higher operational and maintenance cost
- Complicated anchor and mooring for changing water level

Rise of Floating PV: Current status



Rise of Floating PV : Current status

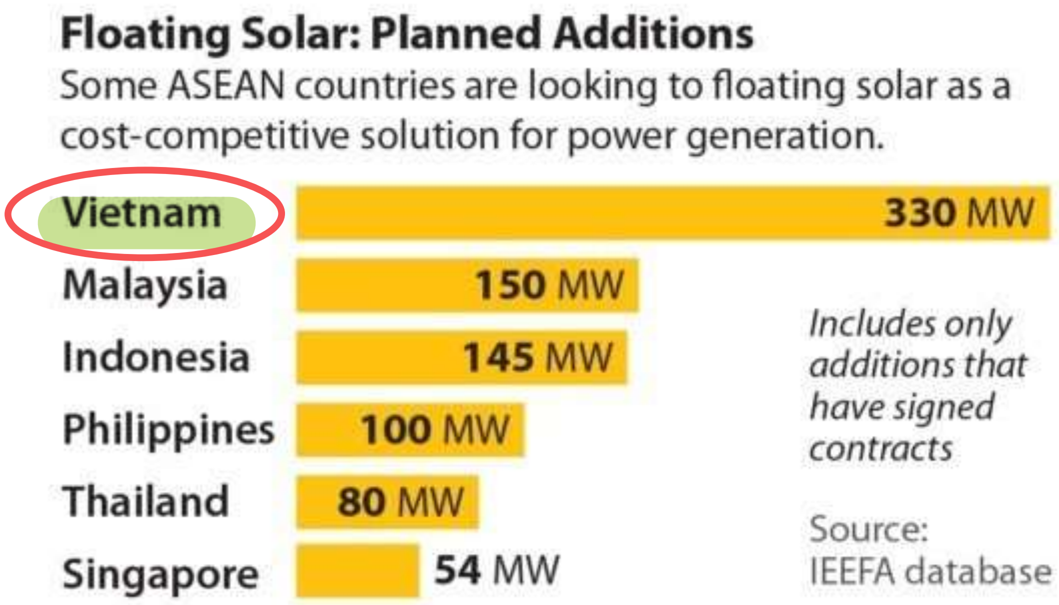
Global:

- Installed capacity now > 1 GWp
- Largest markets: China, Japan, Korea
- Largest system sizes: up to 150 MWp
- Prices from auctions <0.8 $/Wp

Singapore:

- Tengeh testbed still largest worldwide
- A new plant of 100 MWp in Kranji in the pipeline
- First Off-shore Floating PV system (5 MWp) started in 2019

Floating solar farms in Southeast Asia



- More ASEAN countries are building floating solar farms to produce electricity at prices that can compete with coal-fired power
- Floating Solar PV can help insulate coal-importing ASEAN countries from the risk of volatile fuel prices and the expensive supply logistics of the global fossil fuels market

Source: Institute for Energy Economics and Financial Analysis (IEEFA)

Advantages of solar PV

- PV generation coincides with periods of peak demand (cooling in the summer)
- No moving parts --> Very low maintenance cost
- Moderate net energy

- Moderate environmental impact
- No emissions
  (note: there are emissions during the process of manufacturing of solar PV modules)

Disadvantages of solar PV

- Unavailable at periods of high heating demand (for heating in countries with winter)
- Highly variable and intermittent
  ↳ dependent on weather etc.
- High upfront investment cost
- Require large area

Conclusion

- Solar PV cells tend to lose capacity due to darkening of the cover glass; use more area than needed at first
- While PV is expensive at $2.0/W to $16/W, the low maintenance costs reduce the overall cost
  - Lasts perhaps 30 years and usually warranted for 20 years
- Research similar installations to gain understanding
- Evaluate intended loads closely
- Use spreadsheets to change system parameters readily
- Isolated sites have no alternative power and some assumptions are warranted