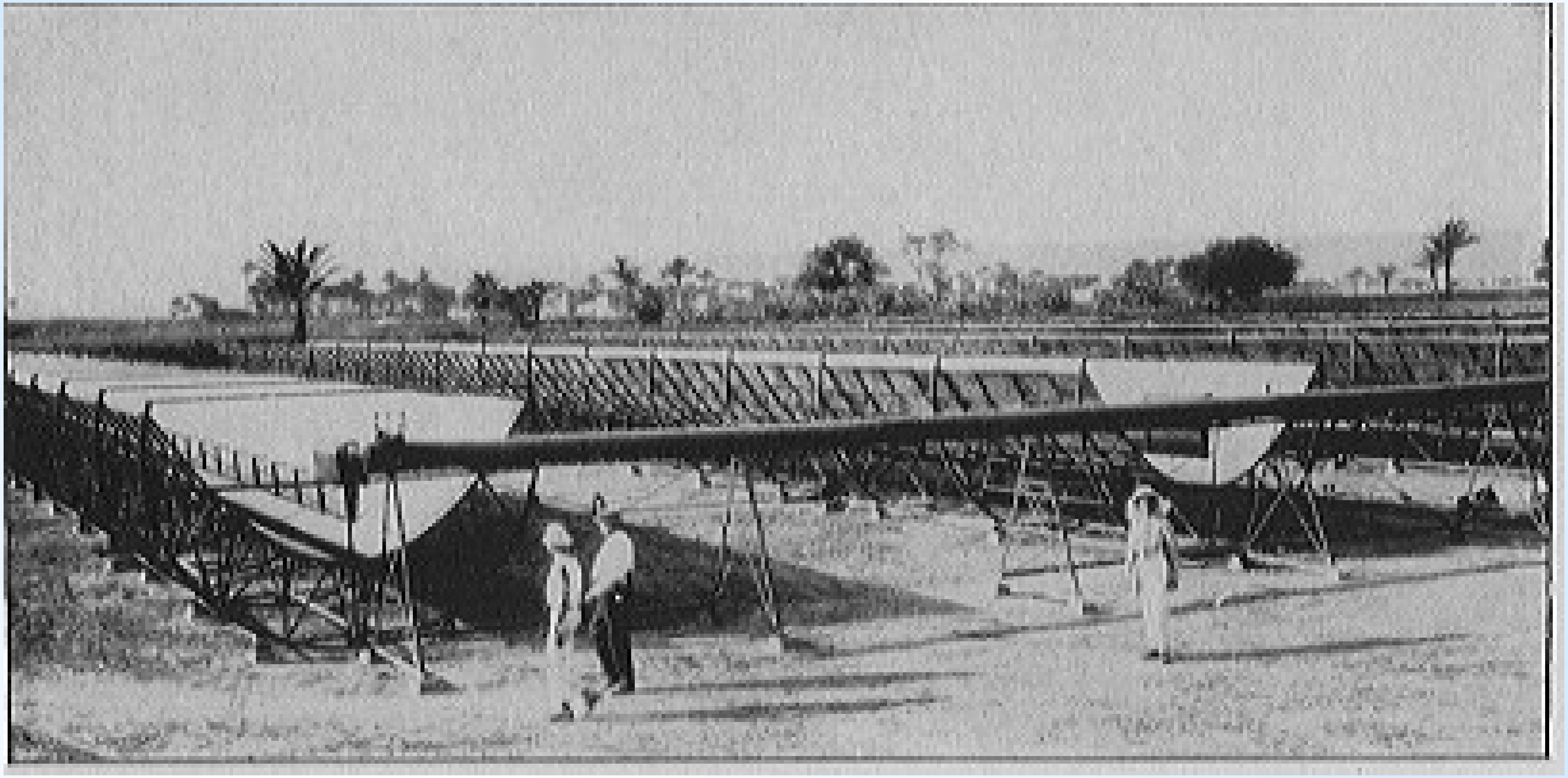
History of Solar Energy Use

- 1500 BC Egyptian ruler Amenkotep III supposedly had “sounding statues” that emitted a tone when air inside was heated by the sun
- 800 BC Plutarch noted that vestal virgins used metal cones to light ritual fires
- 212 BC Archimedes purportedly used burning mirrors to set fire to ships according to Galen in De Temperamentis (see Mythbusters)
- ~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 4.7 kW/m^2)
- ~1760 Swiss de Sanesure made a solar oven that reached 320°F
- 1837 Herschel used a solar oven to cook food at 240°F in South Africa
- ~1860 Bessemer made a solar furnace that melted copper and zinc

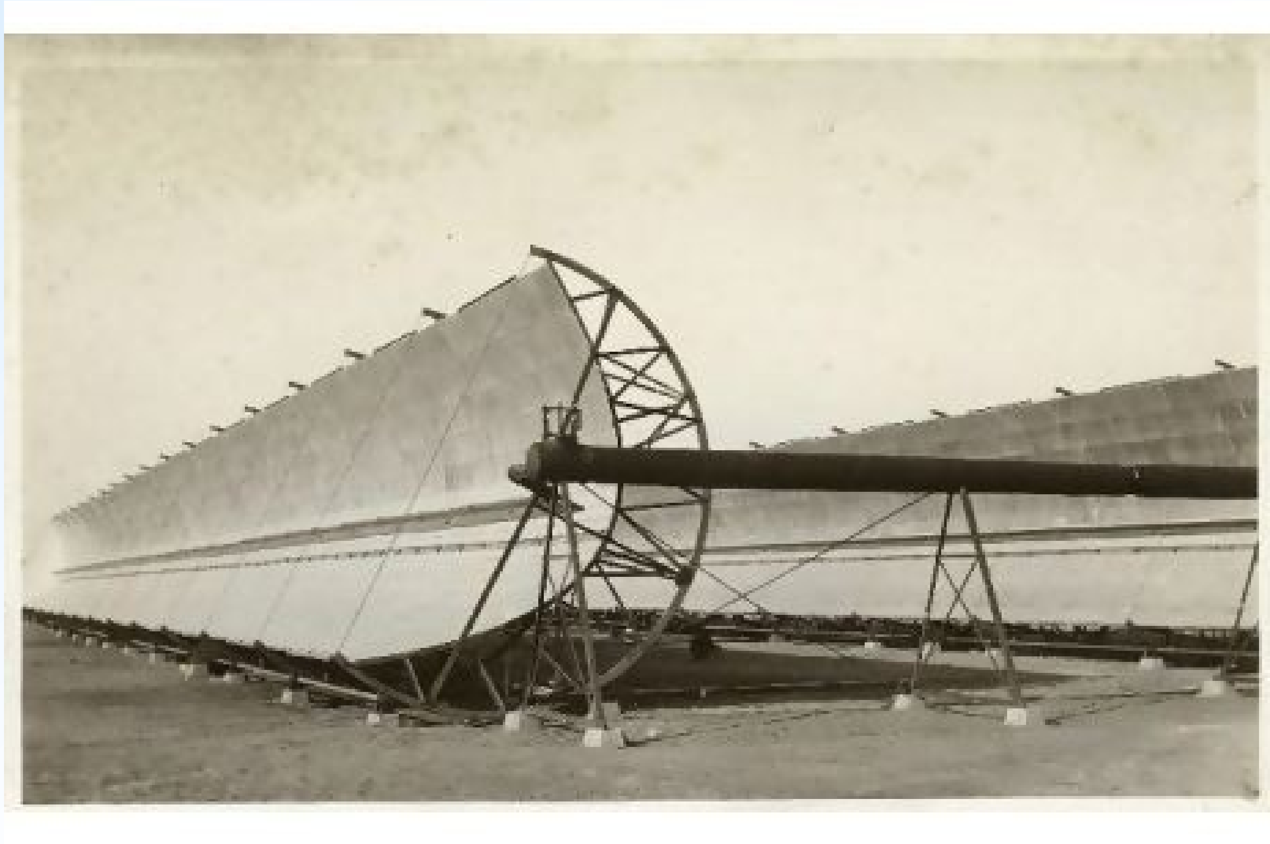
- ~1860 Augustin Mouchet built “axicons” (simple cone) to focus on a tube; built steam engines with a 40 ft^2 reflector
- 1868 John Ericsson built a solar-powered 2.5 HP engine that used a parabolic reflector
- 1878 William Adams built a 2 kW solar water pump near Bombay, India
- 1880 E. Weston suggested a thermocouple for generating electricity
- 1882 Abel Pifre & Mouchot demonstrated a steam engine at Tucleries Garden, Paris, driving a printing press to supply fair visitors with handouts
- 1896 C.G.O. Barr patented an idea to place mirrors on railroad cars, precursor of solar towers
- 1912 Prof. C.V. Boys & Frank Shuman built a 50 HP solar pumping engine at Meadi, Egypt

1913 Maadi, Egypt Solar Engine



See : https://en.wikipedia.org/wiki/Frank_Shuman

Frank Shuman's plant used parabolic **troughs** to power a 60-70 horsepower engine that pumped 6,000 gallons of water per minute from the Nile River to adjacent cotton fields.



http://www.thenational.ae/news/uae-news/technology/the-promise-of-solar-power-made-a-century-ago

2012 Andalusia, Spain
Andasol Solar Power Station

150-megaWatt (MW) solar power station; Europe's first commercial plant to use parabolic troughs with tanks of molten salt as thermal energy storage

Parabolic trough concentrators at Kramer Junction, CA. The system, called the Solar Electricity Generating System (SEGS) installed at Kramer Junction in Mojave desert, California, starting from 1984. The SEGS system is the largest solar electricity generator set on the world. The total capacity is 354 MW.

Two Main Categories:

Solar Thermal

Water heating and cooking

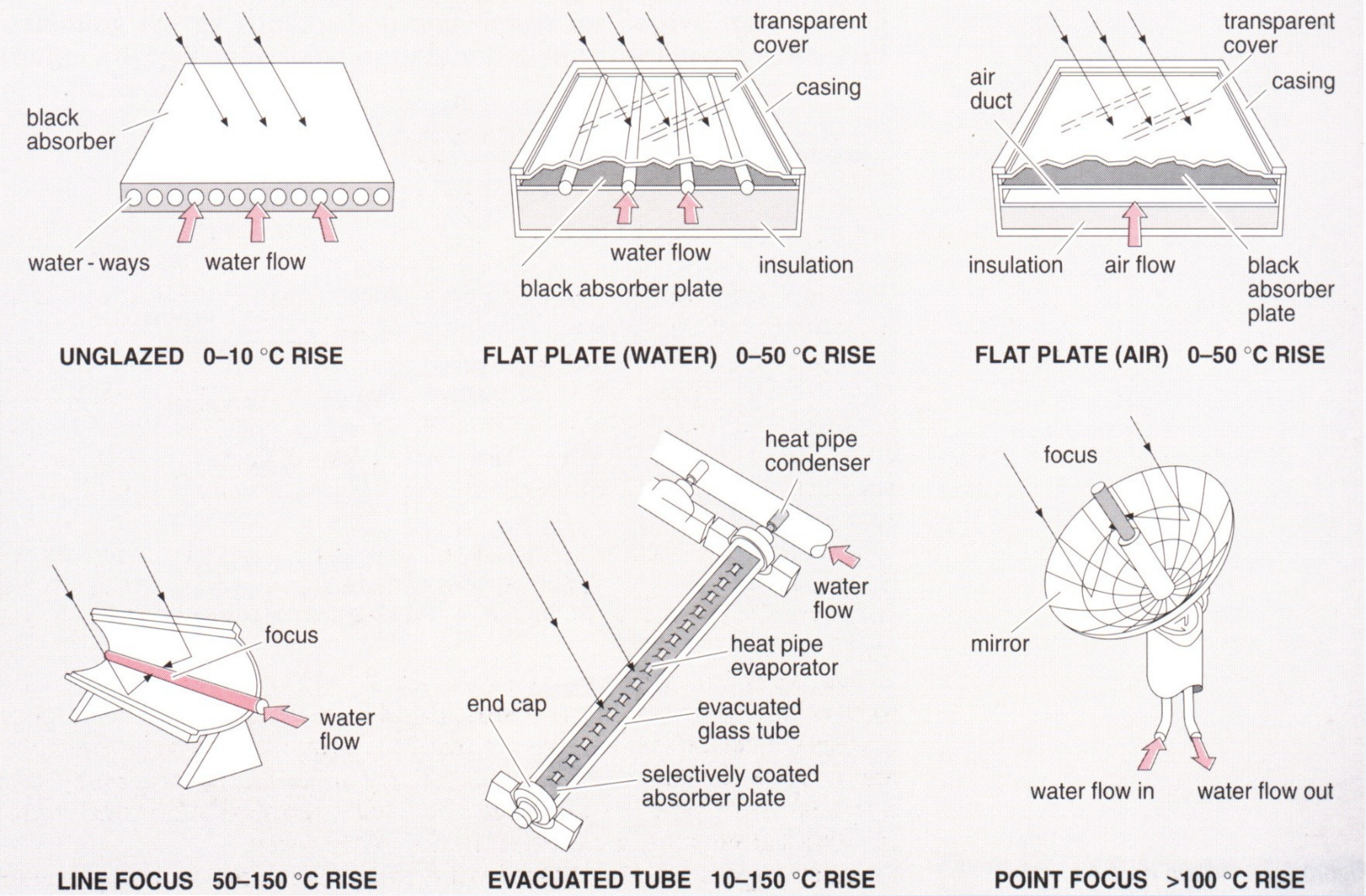
Solar Photovoltaic (PV)

Electricity production

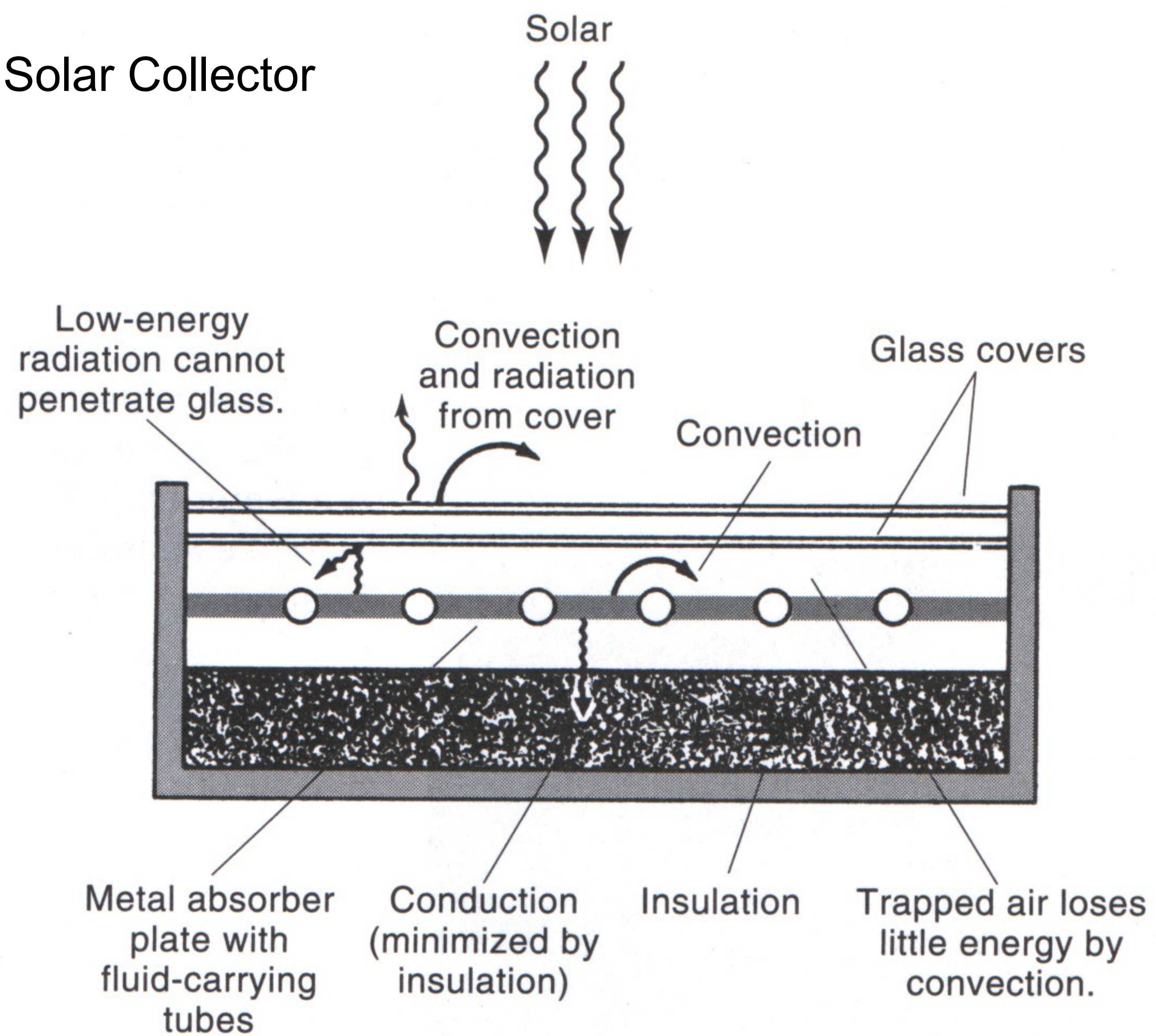
Solar Collectors

Table 3.1. Types of solar thermal collectors and their typical temperature range

Type of Collector	Concentration Ratio	Typical Working Temperature Range (°C)
Flat plate collector	1	≤70
High efficiency flat plate collector	1	60–120
Fixed concentrator	3–5	100–150
Parabolic trough collector	10–50	150–350
Parabolic dish collector	200–500	250–700
Central receiver	500–>3000	500–>1000


black absorber
water - ways
water flow
UNGLAZED 0–10 °C RISE
transparent cover
casing
water flow
insulation
black absorber plate
FLAT PLATE (WATER) 0–50 °C RISE
transparent cover
air duct
casing
insulation
air flow
black absorber plate
FLAT PLATE (AIR) 0–50 °C RISE
focus
water flow
LINE FOCUS 50–150 °C RISE
heat pipe condenser
water flow
heat pipe evaporator
end cap
evacuated glass tube
selectively coated absorber plate
EVACUATED TUBE 10–150 °C RISE
focus
mirror
water flow in
water flow out
POINT FOCUS >100 °C RISE

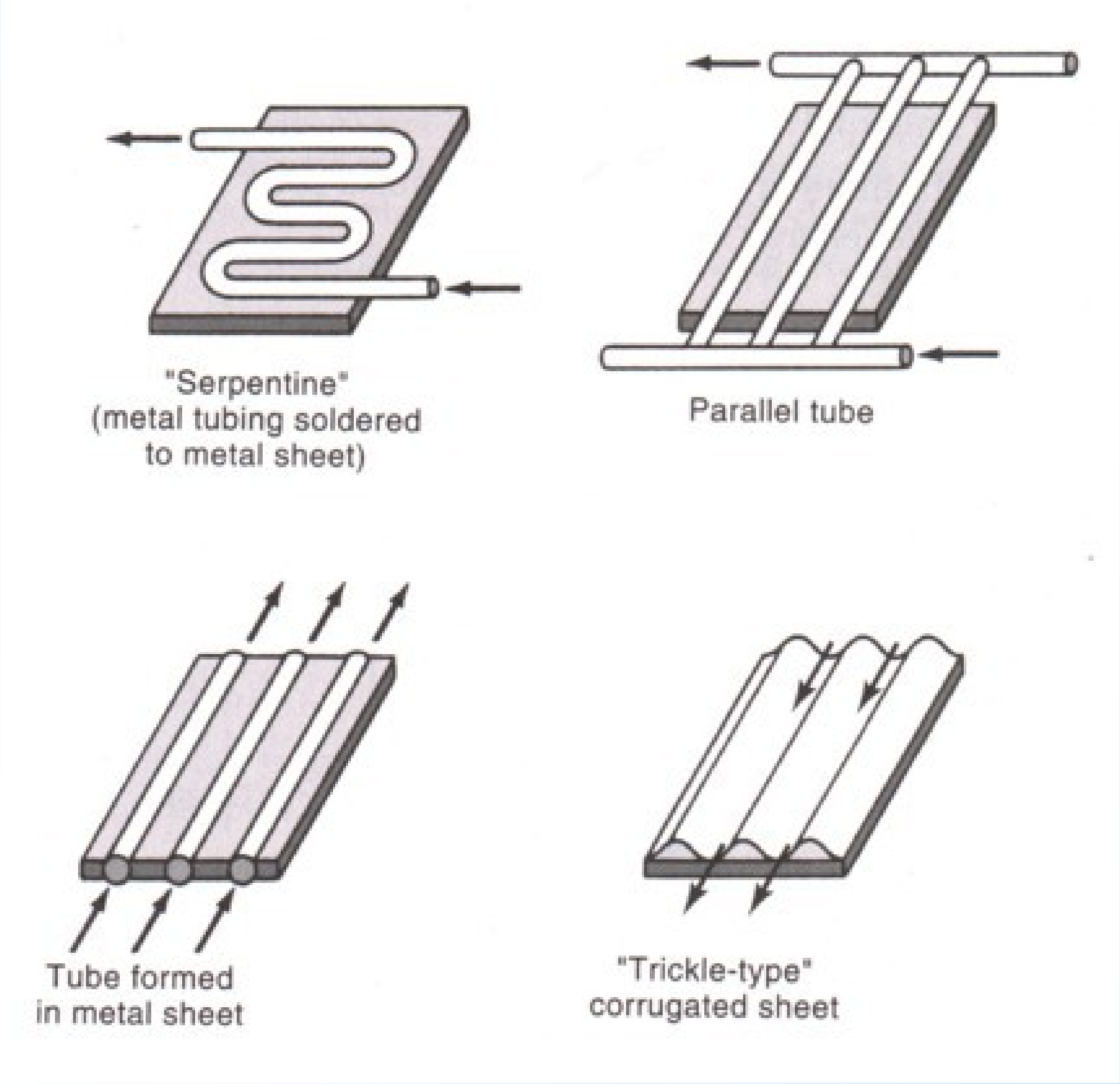
Flat-Plate Solar Collector

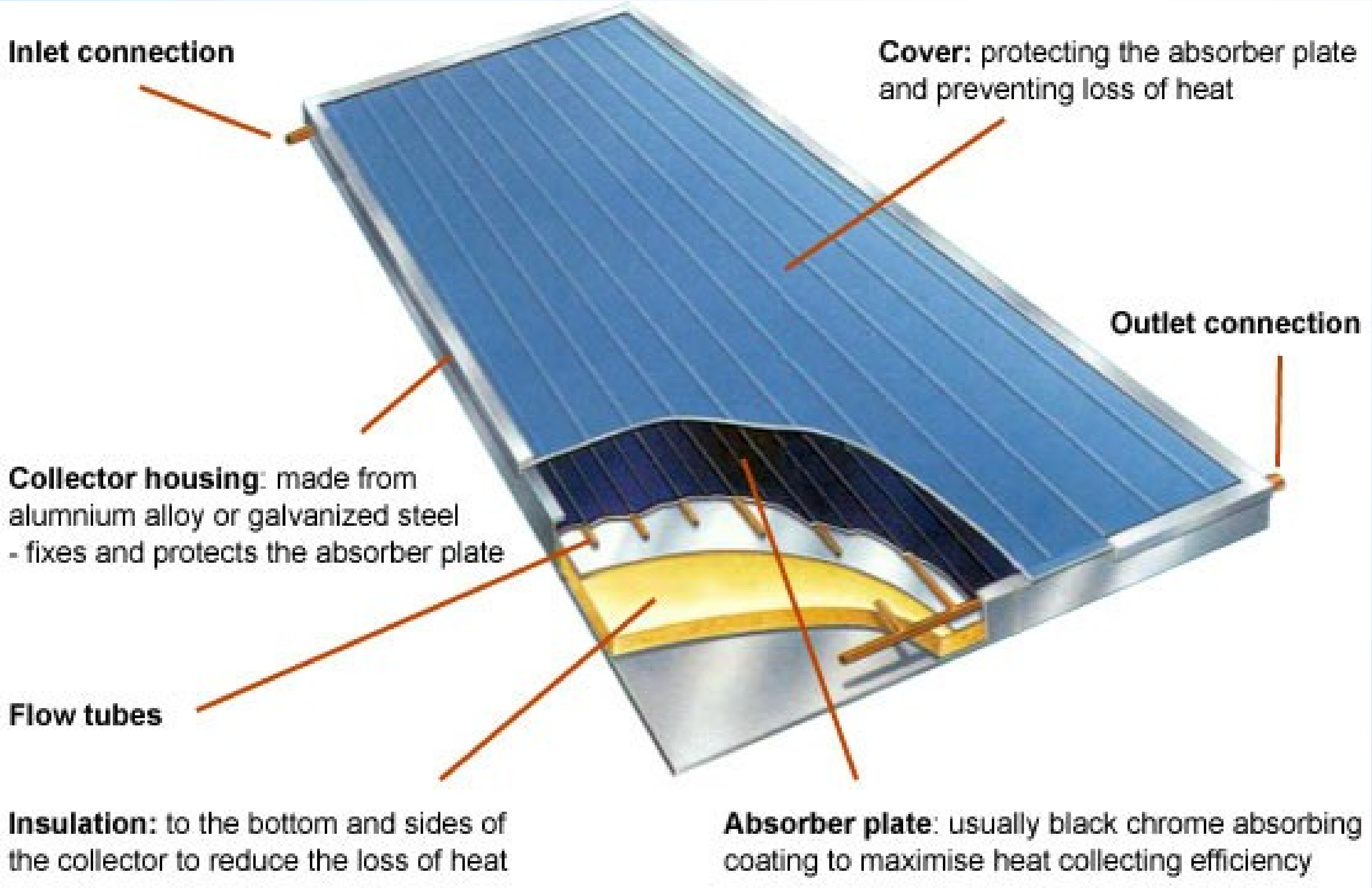


Types of

Flat Plate

Collectors




Inlet connection
Cover: protecting the absorber plate and preventing loss of heat
Outlet connection
Collector housing: made from alumnium alloy or galvanized steel - fixes and protects the absorber plate
Flow tubes
Insulation: to the bottom and sides of the collector to reduce the loss of heat
Absorber plate: usually black chrome absorbing coating to maximise heat collecting efficiency

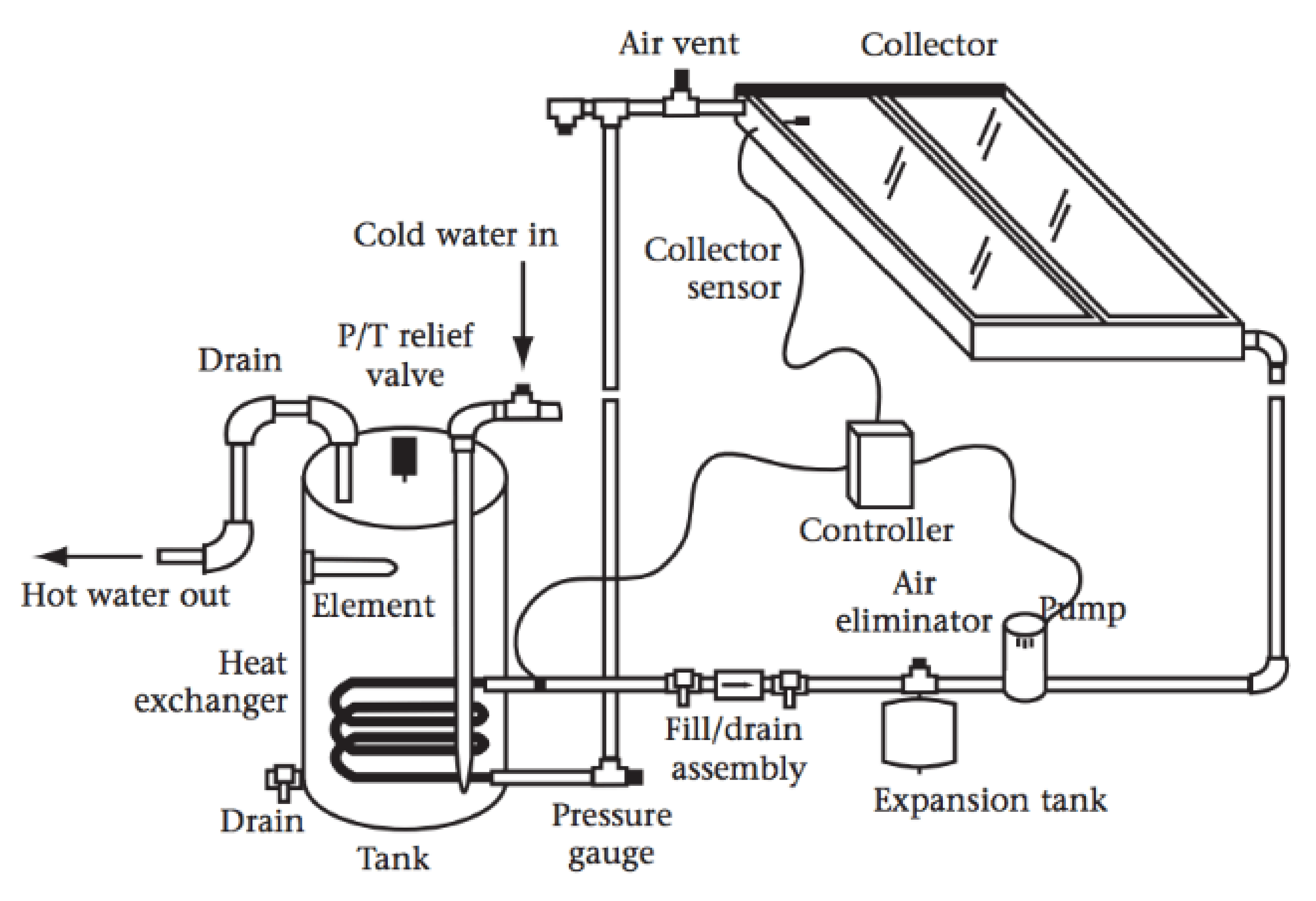
Cover or no cover

Advantages:

- High transmittance for visible light (transparent)
- Very low transmittance for thermal radiation
- Protects against convective heat loss
- Protects against adverse weather conditions (rain, etc.)

Disadvantages:

- Transmittance for visible light is angle dependent (specular)
- Absorbs and reflects part of the insolation
- Additional cost (capital and maintenance)


Air vent
Collector
Cold water in
Collector
sensor
P/T relief
valve
Drain
Controller
Hot water out
Element
Air
eliminator
Pump
Heat
exchanger
Fill/drain
assembly
Expansion tank
Drain
Pressure
gauge
Tank

Components of a solar collector include some or all of the following:

1. A surface (typically a metal sheet) that is black to absorb nearly all the incident solar energy;
2. One or more glazing sheets to transmit insolation readily to the absorber plate while intercepting and reducing thermal radiation and convection heat loss to the environment;
3. Tubes or ducts to transport a fluid through the collector to accumulate the solar heat and transport that heat out of the collector;
4. Structure (basically a box) to hold and protect the components and withstand weather; and
5. Insulation placed on the sides and behind the absorber plate to reduce parasitic heat loss.

Absorbtance, α			
,		Solar Irradiance	Infrared radiation
Non-selective		0.97	0.97
Selective	Black Nickel	0.88	0.07
	Black Chromium	0.87	0.09
	Aluminum Grid	0.7	0.07
	Tiyanium Oxide Nitrade	0.95	0.05

Energy Balance (Flat Plate Collector)

$$\dot{Q}_u = I\,A_{ap}\,\tau_c\,\alpha - U_L\,A_{ap}\,(T_{ap} - T_a) = \dot{m}\,c_p\,(T_{out} - T_{in})$$

I: Direct normal insolation, W/m^2

A_{ap}: Absorber plate area, m^2

τ_c: Effective solar transmittance of the cover

α: Absorptance of the plate

U_L: Overall heat transfer coefficient, W/m^2.K

T_{ap}: Average plate temperature, °C

T_a: Ambient air temperature, °C

T_{in}, T_{out}: Inlet and outlet temperatures of the fluid

Cover (glazing):

- Transmits shorter wavelength solar radiation, but blocks longer wavelength from absorbers
- Reduces convective heat transfer losses
- Most common material is glass

Energy Balance (Flat Plate Collector)

$$\dot{Q}_u = I\,A_{ap}\,\tau_c\,\alpha - U_L\,A_{ap}\,(T_{ap} - T_a) = \dot{m}\,c_p\,(T_{out} - T_{in})$$

$$\dot{Q}_u = F_R\left[I\,A_{ap}\,\tau_c\,\alpha - U_L\,A_{ap}\,(T_{in} - T_a)\right] = \dot{m}\,c_p\,(T_{out} - T_{in})$$

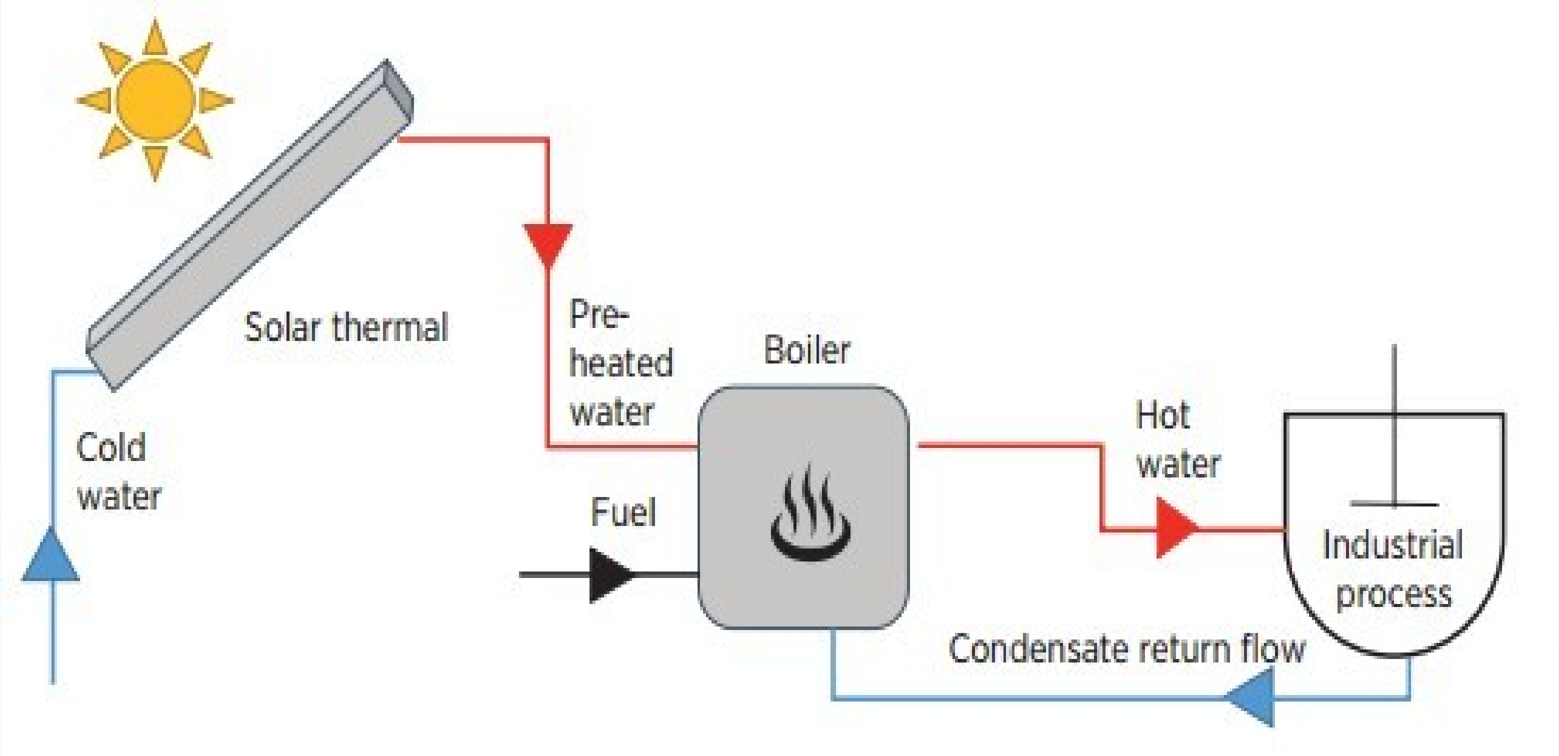
F_R: Empirical heat removal factor

Collector efficiency:

$$\eta = \frac{\text{Useful energy output}}{\text{Total insolation}} = F_R\,\tau\,\alpha - \frac{F_R\,U_L\,(T_{in} - T_a)}{I}$$

Example 5

At a location of latitude 40 °N, a process heating system employing flat plate collectors, facing south with a slope (tilt angle) of 40°, of area 50 m^2 has been installed. The collector parameters are $F_R U_L$ = 2.63 W/m^2.K and $F_R (\tau\alpha)$ = 0.72. The system is required to supply energy at a minimum temperature of 60 °C at a rate of 12 kW for 12 hours a day. Assume that the ground reflectance is 0.2. What is the necessary radiation level, I, for the month of January if daily average total insolation is H = 8.6 MJ/m^2.day, and the average ambient temperature is T_a = - 5 °C. The inlet temperature of the water circulating in the collector array is T_{in} = 10 °C.



Given data: A_{ap} = 50 m^2 F_R (τ α) = 0.72 $F_R U_L$ = 2.63 $W/m^2.K$

T_a = - 5 °C T_{out} = 60 °C H = 8.6 $MJ/m^2.day$

c_p = 4.186 kJ/kg.K for water

There are several missing information in the given statement of the problem. We need to make few assumptions.

Thermal energy required = (12 kJ/s) (12 h/day) (3600 s/h) = 518 400 kJ/day

Solar energy available = (8600 kJ/m^2.day) (50 m^2) cos(40°) = 329 400 kJ/day

The missing energy requirement is to be supplied by burning a fuel as shown in the figure.

$$\dot{Q} = I\, A_{ap}\, F_R\, (\tau_c\, \alpha) - F_R\, U_L\, A_{ap}\, (T_{in} - T_a) \qquad I = \frac{\dot{Q} + F_R\, U_L\, A_{ap}\, (T_{in} - T_a)}{A_{ap}\, F_R\, (\tau_c\, \alpha)}$$

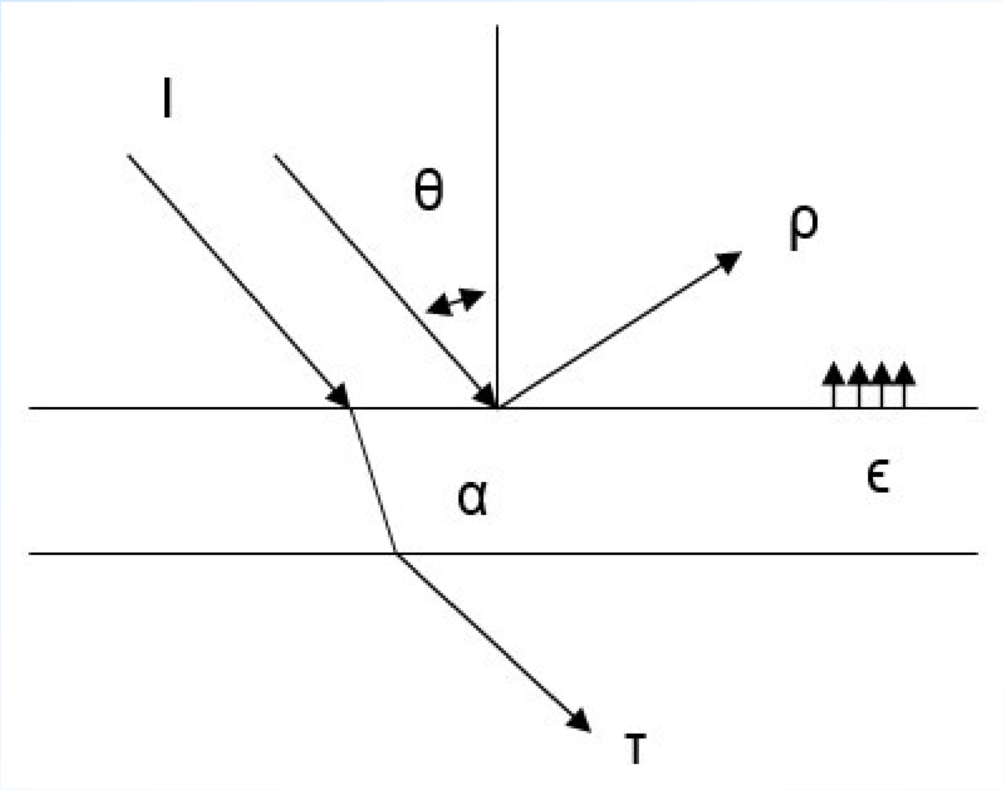
The inlet temperature of the water circulating in the solar collector array T_{in}, an Q are not given. One may calculate Q using the total insolation H, but it is not enough.

Here are few examples where solar energy is used in industrial processes:

Food Industry	Pasteurization
	Blanching
	Cleaning
Metal and Automotive Industry	Drying
	Electroplating
	Bluing
Oil & Chemical Industry	Injection Moulding
	Distillation
	Enhanced Oil Recovery
Pharmaceutical Industry	Sterilization
	Granulation
	Fermentation
Paper Industry	Bleaching
	Cooking
	Drying
Textile Industry	Dyeing
	Drying
	Washing

Read the article about use of solar energy in industrial processes.

http://www.irena.org/DocumentDownloads/Publications/IRENA_ETSAP_Tech_Brief_E21_Solar_Heat_Industrial_2015.pdf



ρ: Reflectance

τ: Transmittance

α: Absorptance

ε: Emittance

These can be all f(θ,λ)

specular and spectral

ρ can be specular (angle dependent) or diffuse

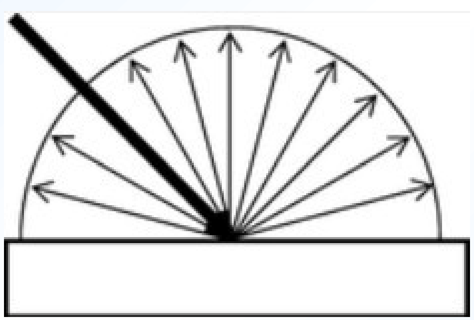
Emittance, ε, is the ratio of radiative emission to that of a black body (ideal black surface).

Distinguish between the terms that end with “*ance*” and those that end with “*ivity*”.

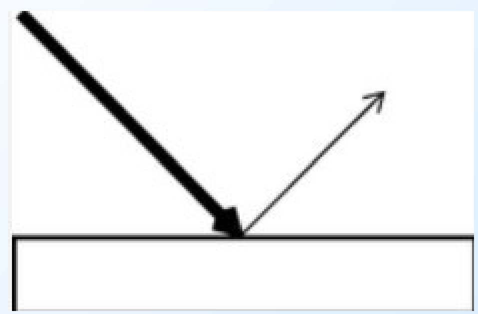
Emittance vs emissivity, Absorptance vs absorptivity, Reflectance vs reflectivity, Transmittance vs transmissivity. “Ivities” are properties of a pure substance. “Ances” are the same property for a given object, not necessarily a pure substance.

The adjective “Spectral” means wavelength dependent.

The adjective “Specular” means «like a mirrior». The opposite of “specular” is “diffuse”



Diffuse reflection



Specular reflection

Monochromatic (single wavelength) and directional emittance

$$\varepsilon_\lambda(\theta,\phi) = \frac{I_\lambda(\theta,\phi)}{I_{b,\lambda}}$$

θ: Azimuthal angle

Φ: Polar angle

$$\varepsilon = \frac{1}{\sigma T^4} \int_0^\infty \varepsilon_\lambda \, E_{b,\lambda} \, d\lambda$$

Surface properties

Monochromatic (single wavelength) and directional absorptance

$$\alpha_\lambda(\theta,\phi) = \frac{I_{\lambda,a}(\theta,\phi)}{I_{\lambda,i}(\theta,\phi)}$$

a: Absorbed radiation

i: Incident radiation

$$\alpha(\theta,\phi) = \frac{1}{I_i} \int_0^\infty \alpha_\lambda \, I_{\lambda,i} \, d\lambda$$

Not just a surface property.
Can design materials which absorbs radiation selectively

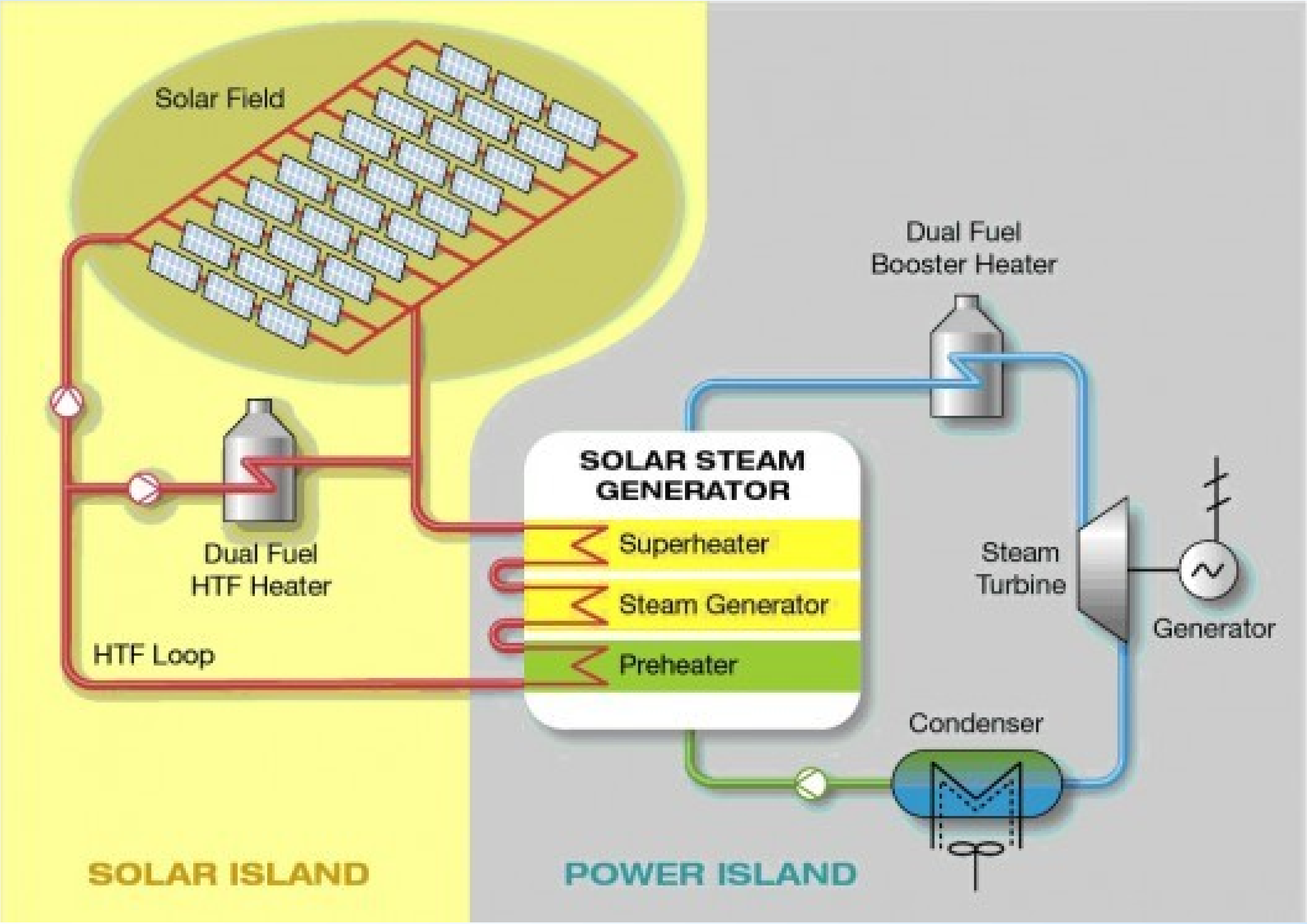
Solar – Thermal Conversion

Solar radiation converted to heat → Low temperature → flat plate → Hot water

→ High temperature → thermal reservoir for power cycle

Solar – Thermal central receiver systems

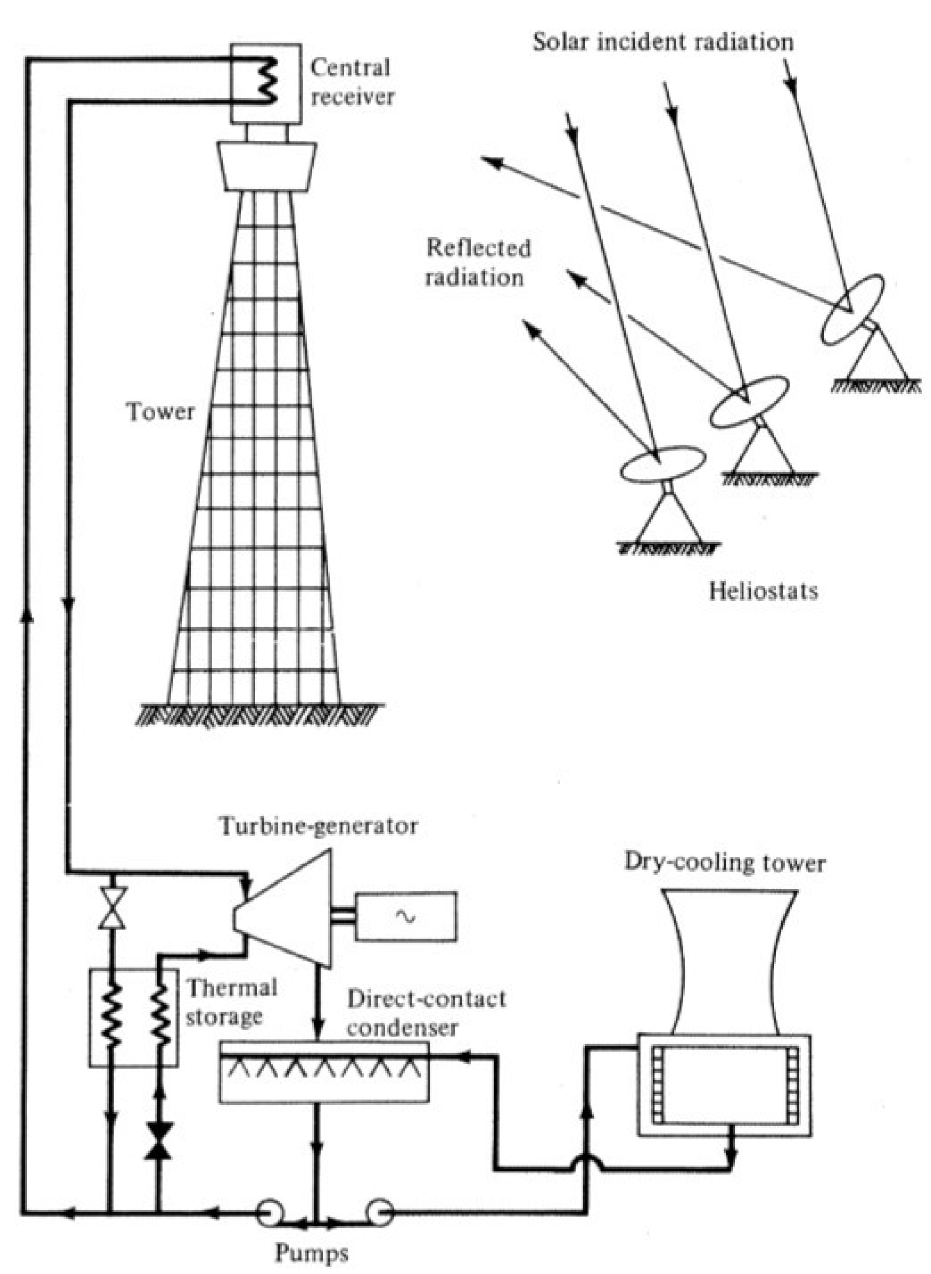
- Large field of heliostats (reflecting mirrors) → Redirect solar energy flux to a central receiver
- Heliostats individually controlled to follow the sun
- Typically has storage for night time and cloudy periods
- High peak power (excess power) bypassed to thermal storage



Solar Field
Dual Fuel
Booster Heater
SOLAR STEAM
GENERATOR
Superheater
Steam Generator
Preheater
Dual Fuel
HTF Heater
HTF Loop
Steam
Turbine
Generator
Condenser
SOLAR ISLAND
POWER ISLAND


SOLAR RECEIVER
HELIOSTATS
STORAGE
POWER BLOCK
OPTIMIZATION/CONTROL SOFTWARE


Heliostat - Solucar Solar Plant, Seville, Spain



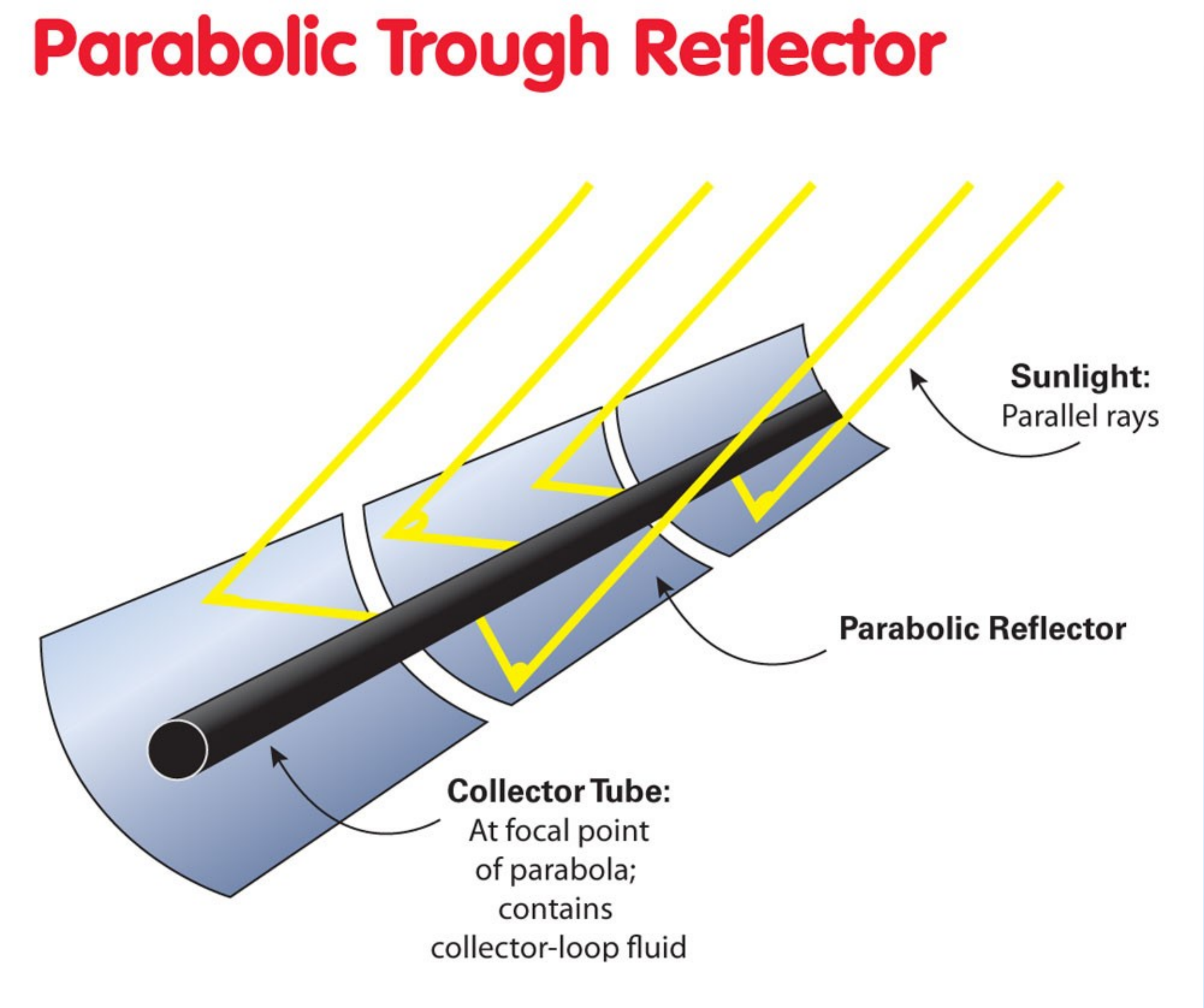
Central receiver
Solar incident radiation
Reflected radiation
Tower
Heliostats
Turbine-generator
Dry-cooling tower
Thermal storage
Direct-contact condenser
Pumps

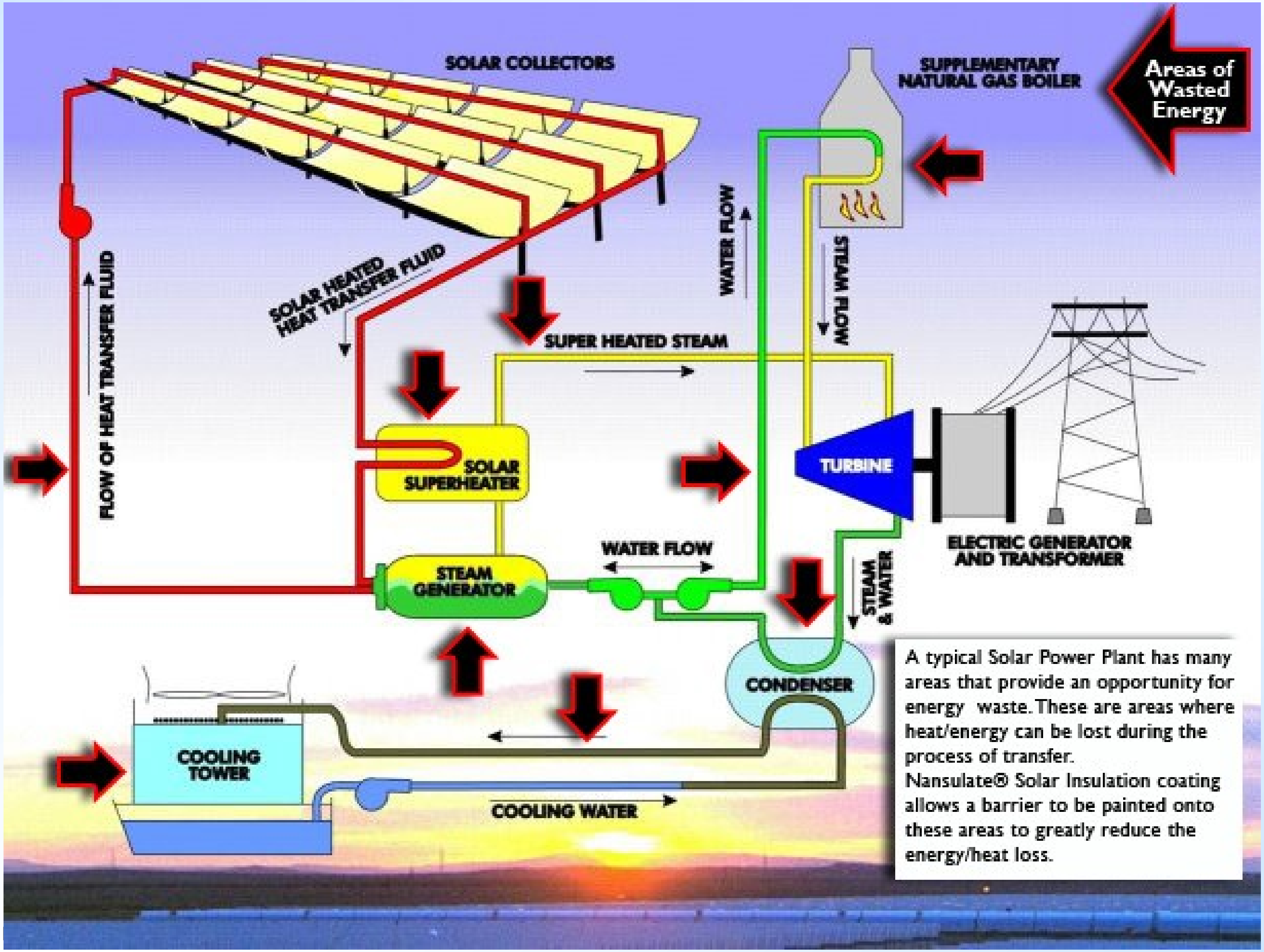
Read about **Ivanpah Solar Electric Generating System**

It is located in the USA between Nevada and California, and with more than 300,000 installed heliostats .This plant, that began operating in 2014, has 3 towers and a nominal capacity of 400 MW (enough power to supply around 140,000 homes).

Read about **Odeillo Solar Furnace**

It is situated in Font-Romeu-Odeillo-Via, in the department of Pyrénées-Orientales, in the south of France. It is 54 meters high and 48 meters wide, and includes 63 heliostats. It was built between 1962 and 1968, started operating in 1969, and has a power of one megawatt.


Parabolic Trough Reflector
Sunlight:
Parallel rays
Parabolic Reflector
Collector Tube:
At focal point
of parabola;
contains
collector-loop fluid


SOLAR COLLECTORS
SUPPLEMENTARY NATURAL GAS BOILER
Areas of Wasted Energy
SOLAR HEATED HEAT TRANSFER FLUID
FLOW OF HEAT TRANSFER FLUID
WATER FLOW
STEAM FLOW
SUPER HEATED STEAM
SOLAR SUPERHEATER
TURBINE
ELECTRIC GENERATOR AND TRANSFORMER
STEAM GENERATOR
WATER FLOW
STEAM & WATER
CONDENSER
COOLING TOWER
COOLING WATER
A typical Solar Power Plant has many areas that provide an opportunity for energy waste. These are areas where heat/energy can be lost during the process of transfer.
Nansulate® Solar Insulation coating allows a barrier to be painted onto these areas to greatly reduce the energy/heat loss.

Direct conversion of solar energy to electricity – Photovoltaic Effect

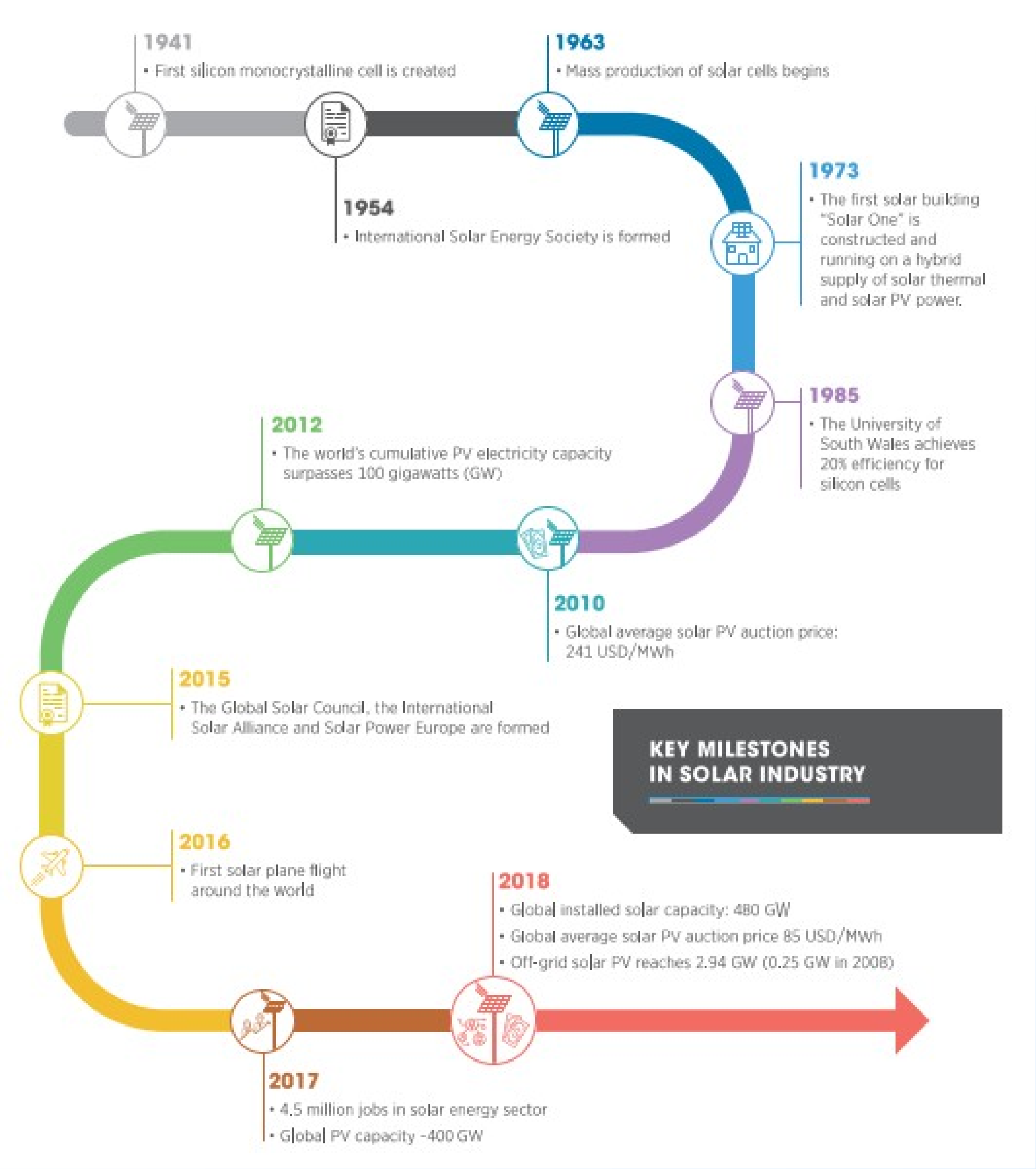
Albert Einstein, regarded as the most important physicist of the 20th century, was awarded the Nobel Prize in Physics precisely for his explanation of the photoelectric effect (and not for his most well-known contribution, his theory of relativity.)

History of PV (Photovoltaic) Cells

- 1839: Becquerel discovers photovoltaic effect in electrochemical cells
- 1904: Albert Einstein published his first paper on the photoelectric effect
- 1954: Chapin, Fuller & Pearson develop first efficient solar cell
- Late 1950s: first non-laboratory use of PV cells
  - Telephone relay station in rural Georgia
  - Power for NASA’s Vanguard I satellite

Vanguard-I was the 4th satellite ever launched. This was the very first time that PV technology was used for a real application. 6 solar panels (0.5 W each), allowed the satellite to send data about the composition of the atmosphere back to Earth during 6 years.

See OdtuClass: “Solar_Energy_v1.1_Udelft.pdf” for PV technology.


1941
• First silicon monocrystalline cell is created
1963
• Mass production of solar cells begins
1954
• International Solar Energy Society is formed
1973
• The first solar building "Solar One" is constructed and running on a hybrid supply of solar thermal and solar PV power.
1985
• The University of South Wales achieves 20% efficiency for silicon cells
2012
• The world's cumulative PV electricity capacity surpasses 100 gigawatts (GW)
2010
• Global average solar PV auction price: 241 USD/MWh
2015
• The Global Solar Council, the International Solar Alliance and Solar Power Europe are formed
KEY MILESTONES IN SOLAR INDUSTRY
2016
• First solar plane flight around the world
2018
• Global installed solar capacity: 480 GW
• Global average solar PV auction price 85 USD/MWh
• Off-grid solar PV reaches 2.94 GW (0.25 GW in 2008)
2017
• 4.5 million jobs in solar energy sector
• Global PV capacity ~400 GW

Overview of PV Function

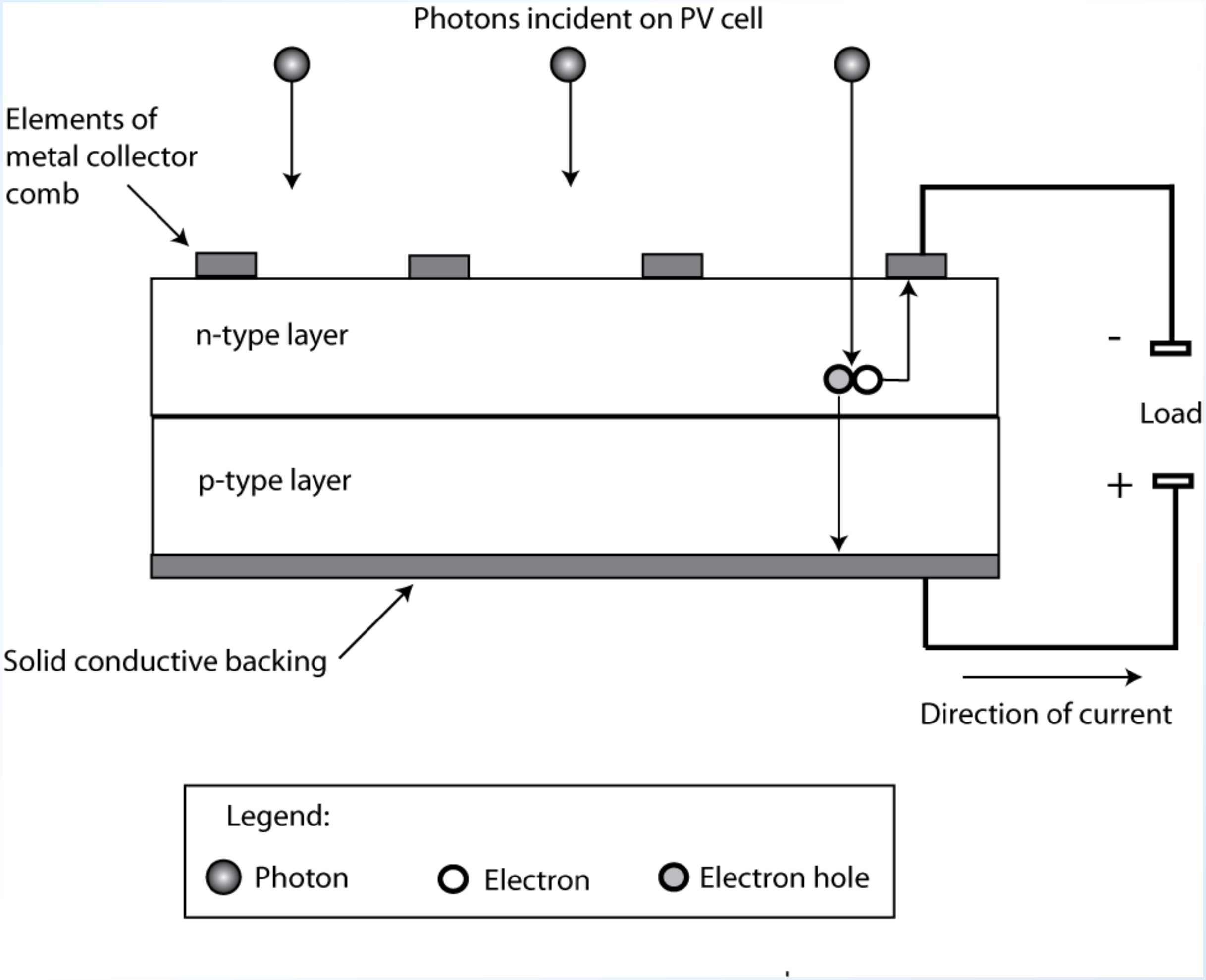
How PV cells work:

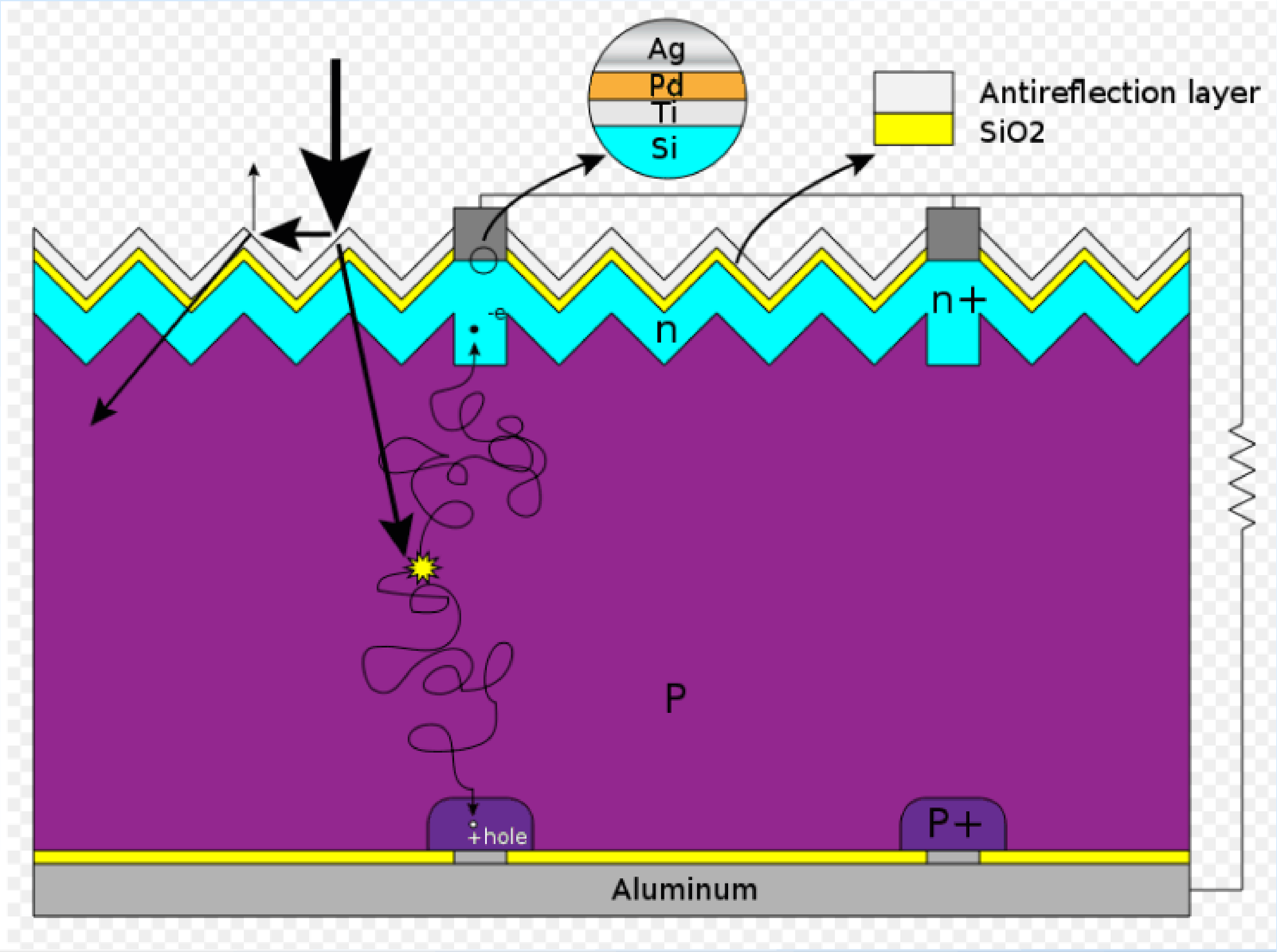
- incoming photon breaks bond
- electron is free to roam lattice
- vacancy left by electron is also able to move in lattice
- Structure of PV cell controls movement of electrons & vacancies so as to create useful current in an external circuit

Practical PV cells: case of silicon semiconductor

- n-type region doped with Phosphorus (5 valence electrons)
- p-type region doped with Boron (3 valence electrons)
- Difference in concentration across “p-n junction” causes permanent electric field from n to p

Cross section of PV cell



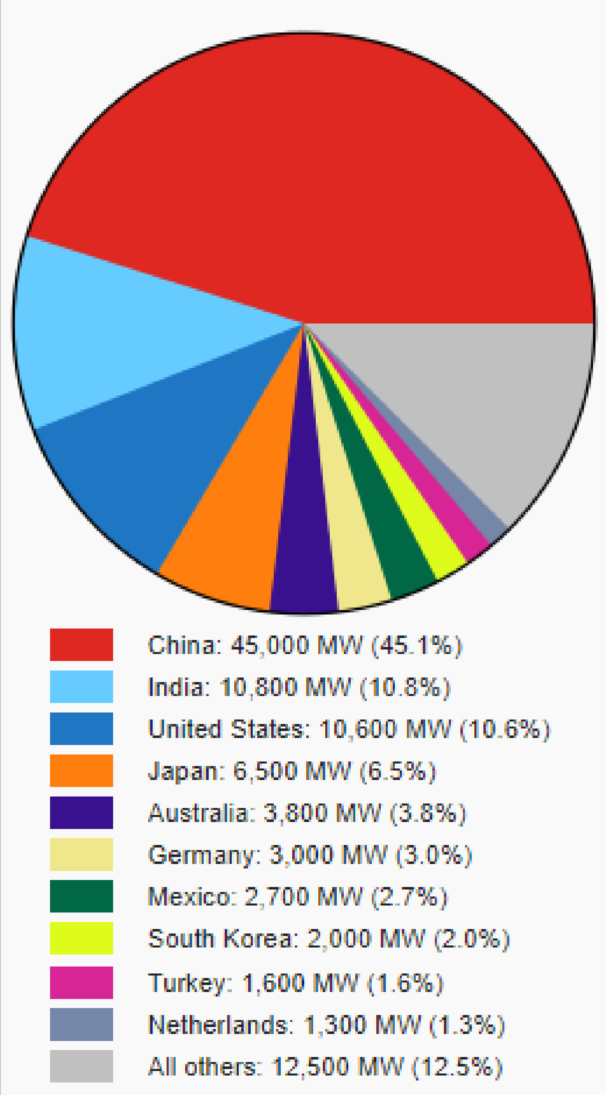

Ag
Pd
Ti
Si
Antireflection layer
SiO2
n
n+
-e
P
+hole
P+
Aluminum

PV Power Plant at METU North Cyprus Campus

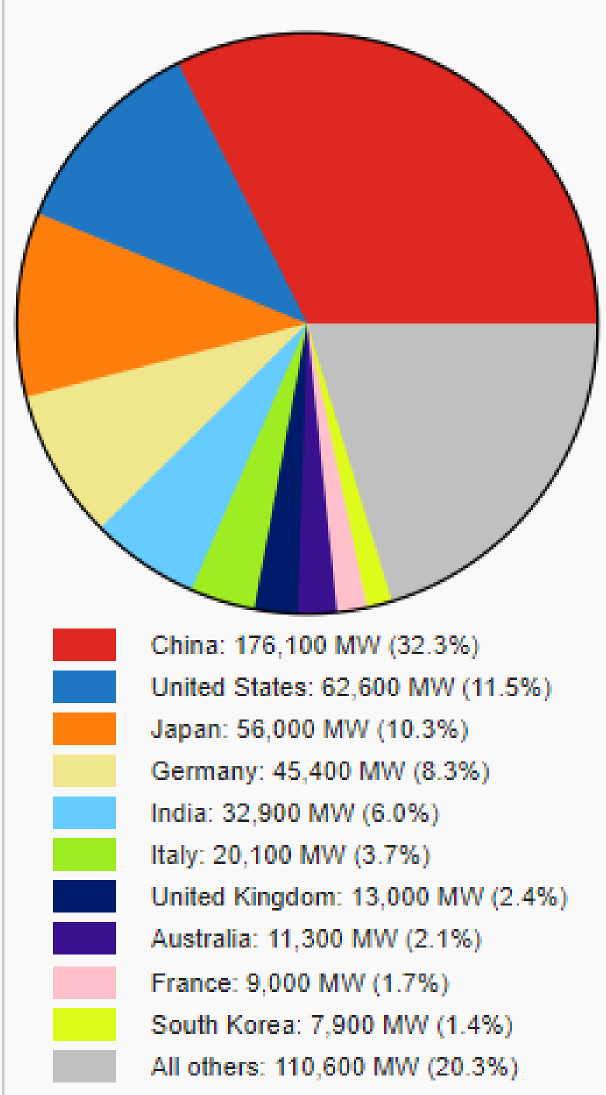
- 1000 kW: Total installed capacity (average electrical energy requirement of 540 houses with 4-person occupancy)
- 16,500 m^2: Total land area (About 2 football fields)
- 1,640,000 kWh: Estimated annual energy production
- 85%: Estimated annual performance ratio
- 20%: Fraction of the annual energy requirement of the campus met by the plant
- 40%: Fraction of the annual average energy requirement of the campus during sunshine hours met by the plant
- 4000: Number of PV modules (capacity 250 W, reference efficiency 15.37 %)
- 40: Number of inverters (capacity 25 kW)
- 30 degrees: Tilt angle of the modules with respect to the ground
- 70 tons: Mass of the galvanized steel mounting system
- 6.5 - 7 years: Estimated payback period

Example of Large-Scale PV Application: Muehlhausen, Germany, 10 MW

Top 10 countries by added solar PV capacity in 2018[7]



Top 10 countries by cumulative solar PV capacity in 2018[8]



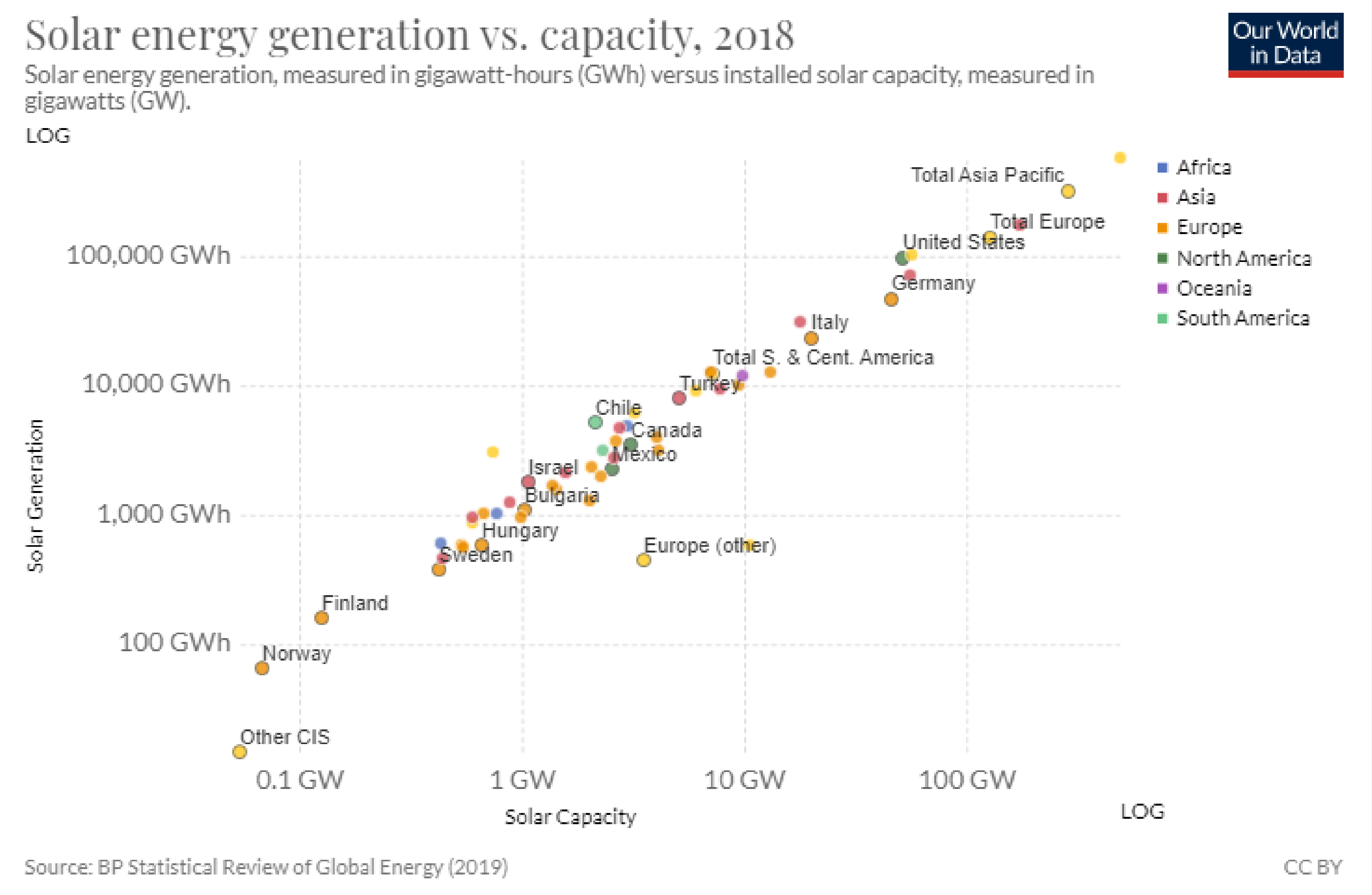
See https://en.wikipedia.org/wiki/List_of_solar_thermal_power_stations for a list of solar thermal power stations.

Global renewable energy consumption: See

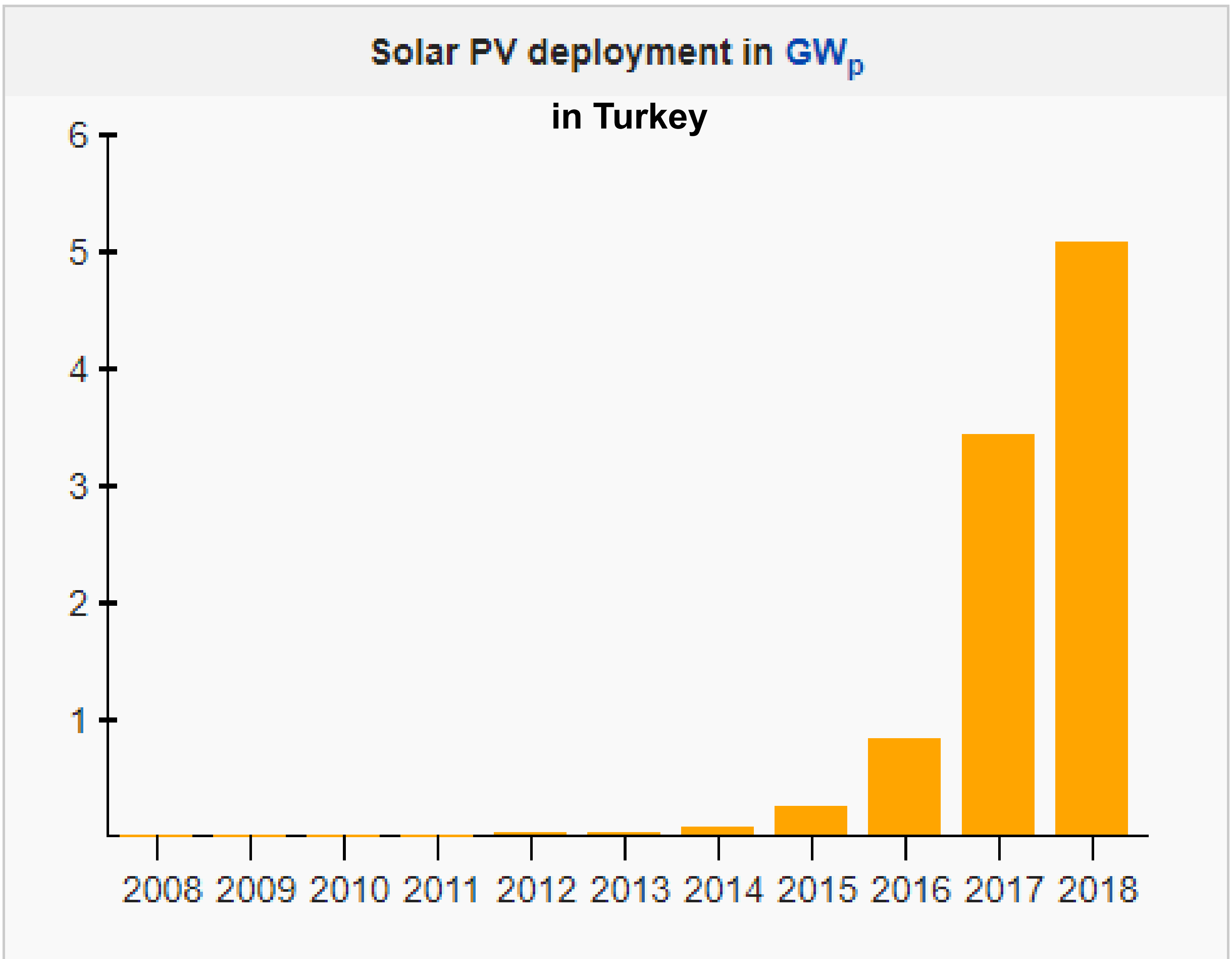
https://ourworldindata.org/renewable-energy

Top 10 Solar Companies in the World:

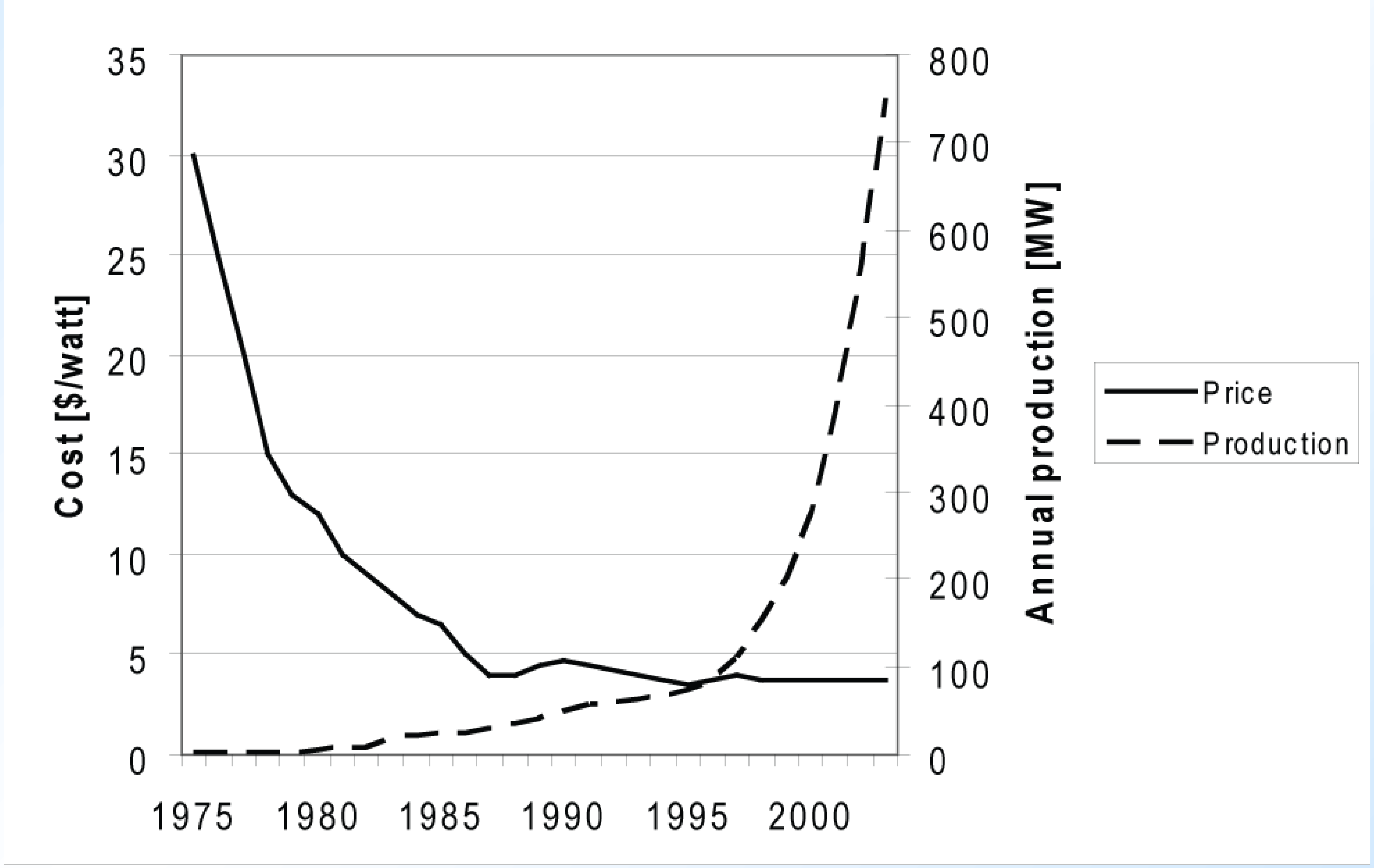
https://blog.technavio.com/blog/top-10-solar-energy-companies

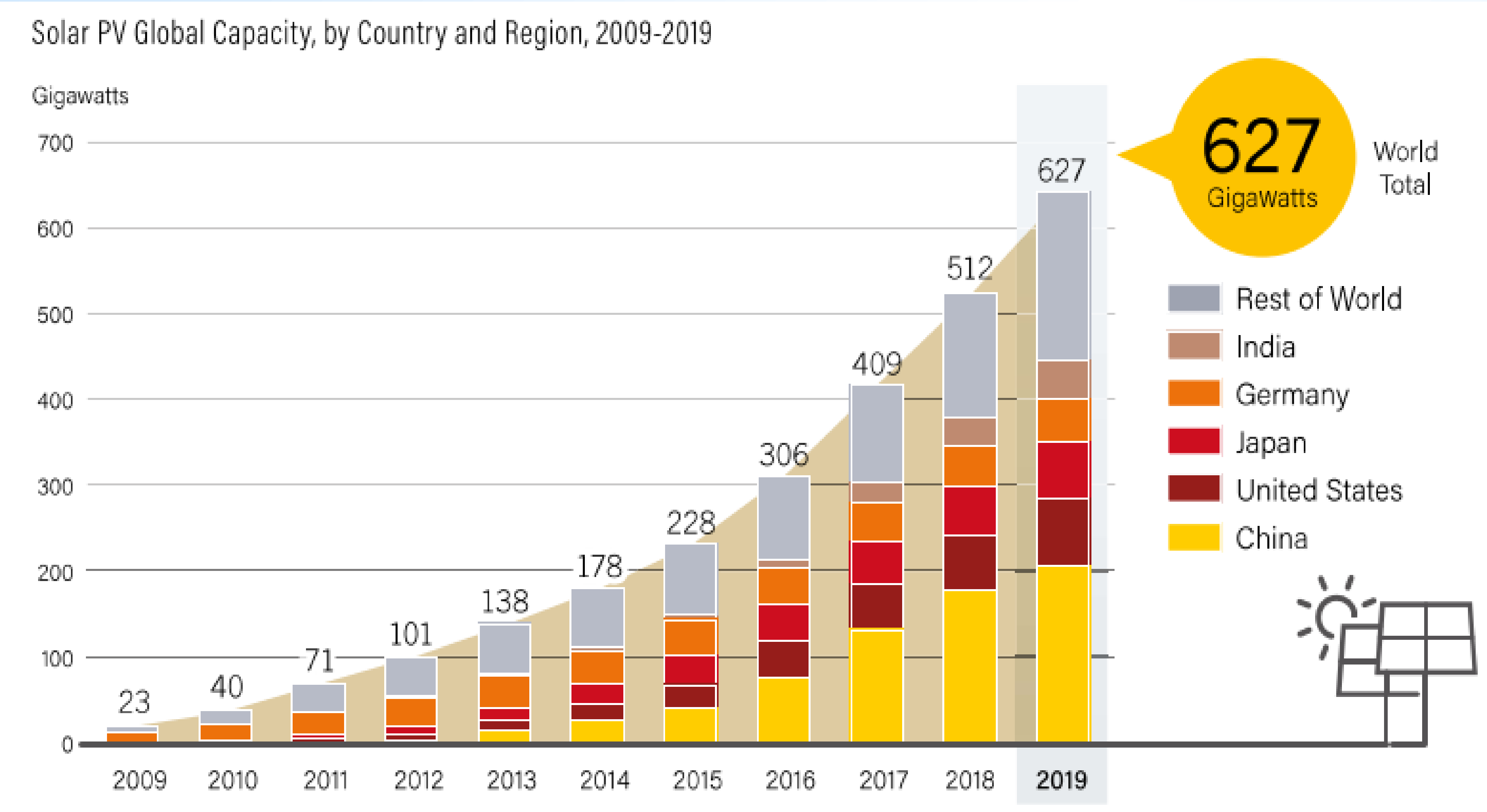


Solar energy generation vs. capacity, 2018
Solar energy generation, measured in gigawatt-hours (GWh) versus installed solar capacity, measured in gigawatts (GW).
Our World in Data
LOG
Total Asia Pacific
Total Europe
United States
Germany
Italy
Total S. & Cent. America
Turkey
Chile
Canada
Mexico
Israel
Bulgaria
Hungary
Sweden
Europe (other)
Finland
Norway
Other CIS
100,000 GWh
10,000 GWh
1,000 GWh
100 GWh
Solar Generation
0.1 GW
1 GW
10 GW
100 GW
Solar Capacity
LOG
Africa
Asia
Europe
North America
Oceania
South America
Source: BP Statistical Review of Global Energy (2019)
CC BY


Solar PV deployment in GW_p
in Turkey
6
5
4
3
2
1
2008 2009 2010 2011 2012 2013 2014 2015 2016 2017 2018

Annual output of world PV manufacturing and average cost per rated watt of panels, 1975 to 2003.




Solar PV Global Capacity, by Country and Region, 2009-2019
Gigawatts
700
600
500
400
300
200
100
0
23
40
71
101
138
178
228
306
409
512
627
2009
2010
2011
2012
2013
2014
2015
2016
2017
2018
2019
627
Gigawatts
World Total
Rest of World
India
Germany
Japan
United States
China

Figures can be very illustrative, but some data may help us to understand the real magnitude of this growth: 98 GW of solar PV capacity was added worldwide in 2017, increasing total capacity by nearly one-third, for a cumulative total of approximately 402 GW.

In 2017 China has surpassed all expectations, adding more solar capacity (51.3 GW) than was added worldwide in 2015 (51 GW). This is equivalent to the installation of nearly 40.000 solar PV panels every hour!