RENEWABLE ENERGY
SOLAR PHOTOVOLTAICS

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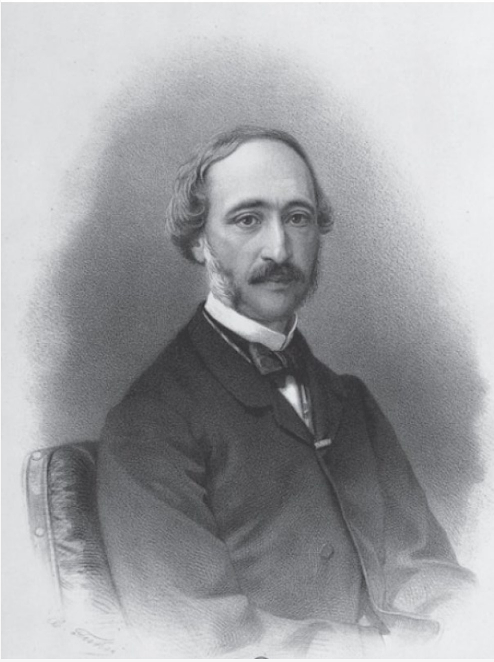
LECTURE OUTLINE

- History and basic principles
- PV Physics in Silicon
- Crystalline PV cells
- Thin film PV cells
- Other PV technologies
- Electrical characteristics of PV
- PV for remote power
- Grid-connected PV
- Discussion: Costs, Environmental impact & Integration

History & Basic Principles

History of PV

- The discovery of the **photovoltaic effect** is generally credited to the French physicist Edmond Becquerel in 1839 .
- The first report of the PV effect in a solid substance was made in 1877 by two Cambridge scientists, Adams and Day.
- In1883 Charles Edgar Fritts, a New York electrician, constructed a selenium solar cell at an efficiency of 1%.
- In 1953 the Chapin, Fuller & Pearson produced 'doped' silicon slices that were much more efficient than earlier devices in producing electricity from light. The efficiency was 6%.



Edmond Becquerel, who discovered the photovoltaic effect

Power Rating

The **power rating** of a particular cell or module is the output when illuminated by bright sunlight with an intensity of 1000 watts per square meter (1 sun).

Figure 4.5 The International Space Station is powered by large arrays of PV panels with a combined output of around 130 kW

Installed Capacity of PV

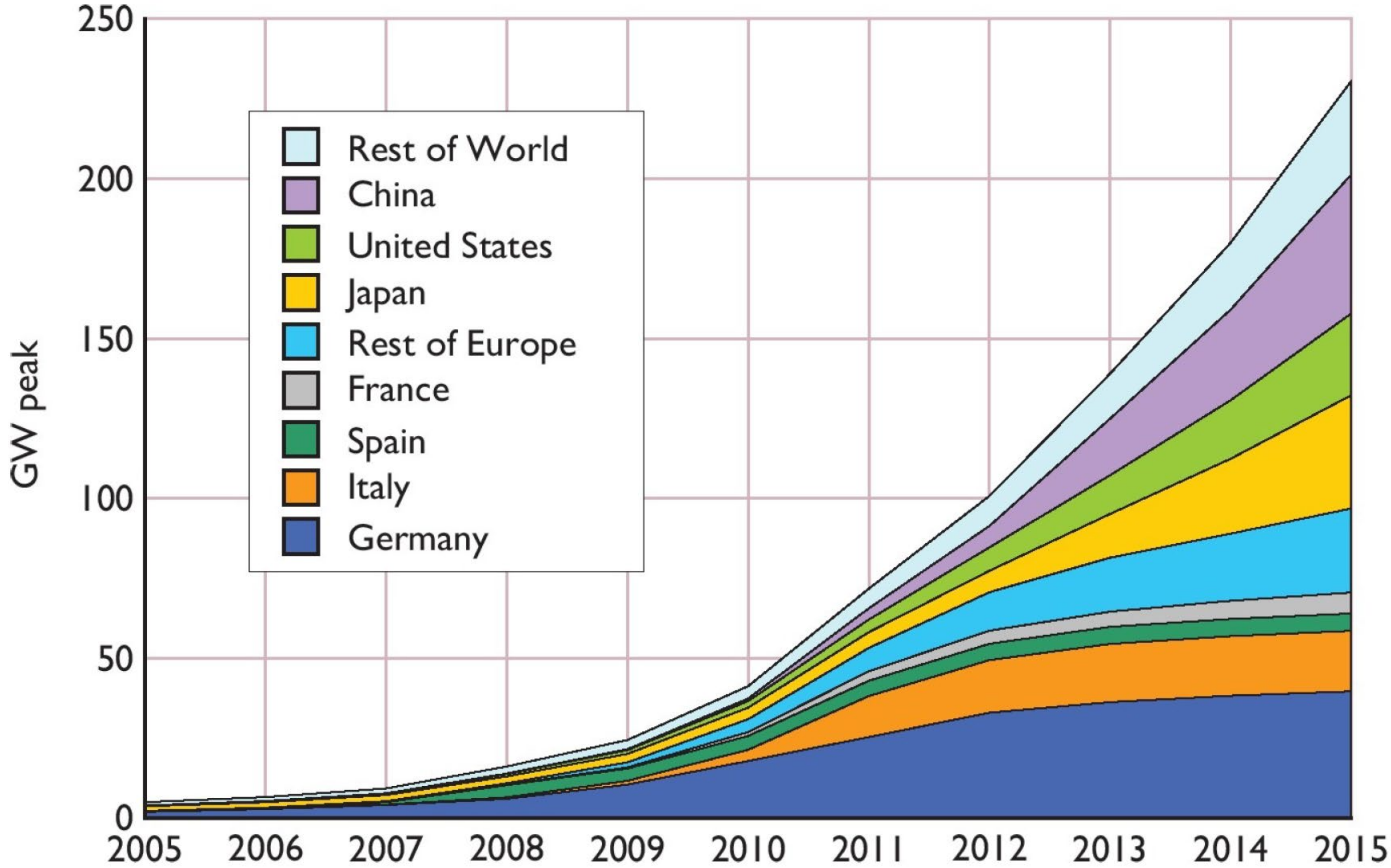


Figure 4.6 Growth of total PV installed capacity in various countries and regions of the world 2005–2015 (source BP, 2016)

PV Economics

- The best silicon PV modules have an efficiency of around 24%
- A peak kilowatt could be produced from four square meters of panels.

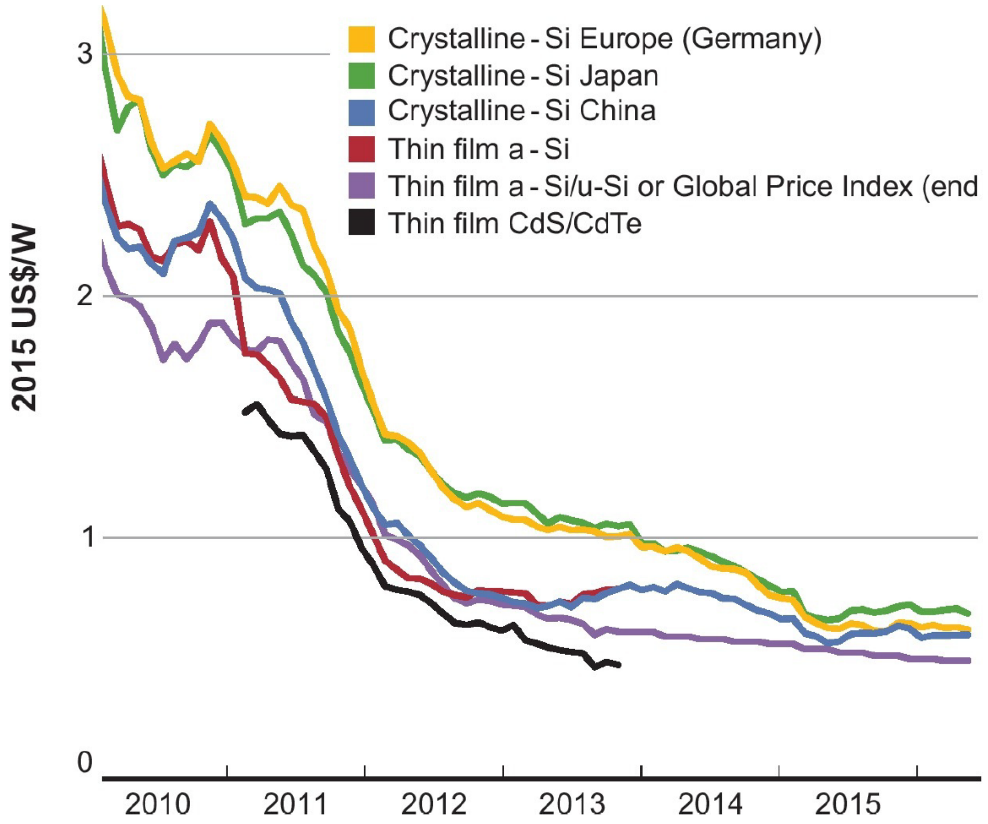


Figure 4.7 Average quarterly solar PV module prices by technology and manufacturing country sold in Europe,

Standard Test Conditions

- Immediately above the atmosphere, the solar power density is 1365 watts per square meter.
- This is described as the **Air Mass 0 (AM0)** distribution, and is used for testing PV cells in space.
- At the Earth's surface, the various gases of which the atmosphere is composed (particularly ozone, water vapor and carbon dioxide) attenuate the solar radiation selectively.
- When the Sun is at its zenith (i.e. directly overhead), the distance which the Sun's rays have to travel through the atmosphere to a PV module is at a minimum.
- The power distribution of solar radiation is known as the **Air Mass 1 (AM1)** distribution.

$$\text{Air Mass} \approx \frac{1}{\cos\theta}$$

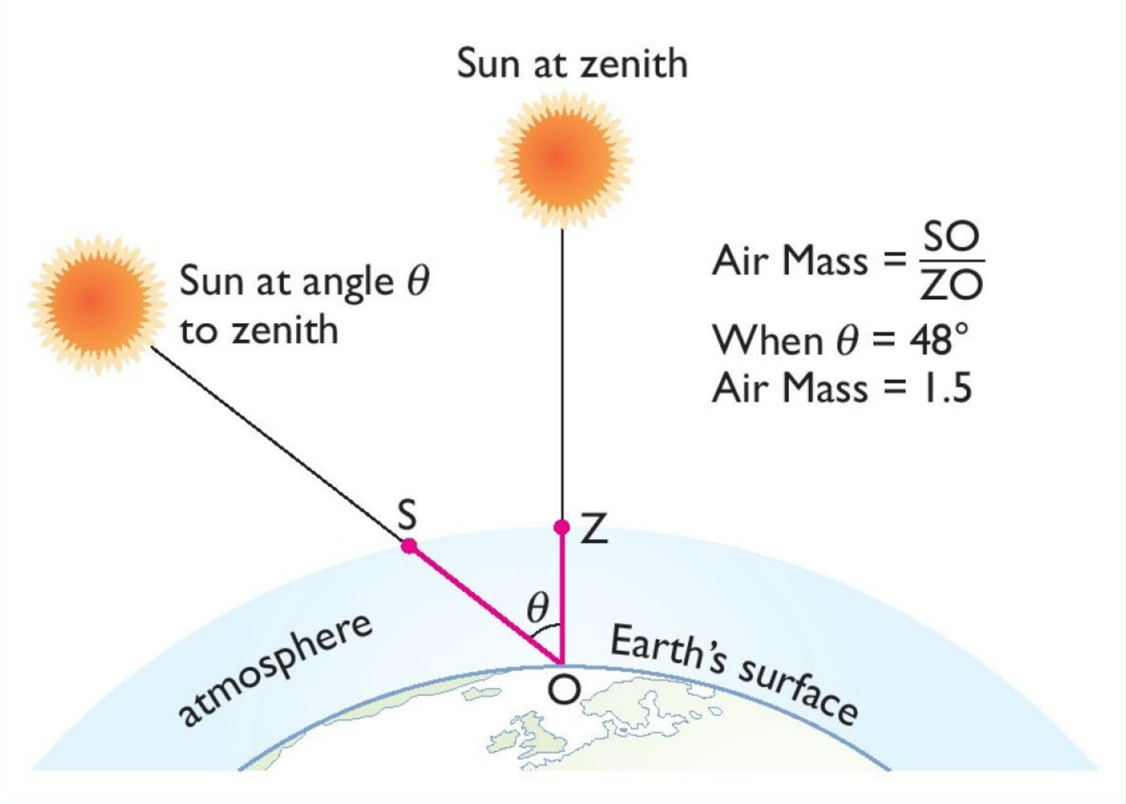


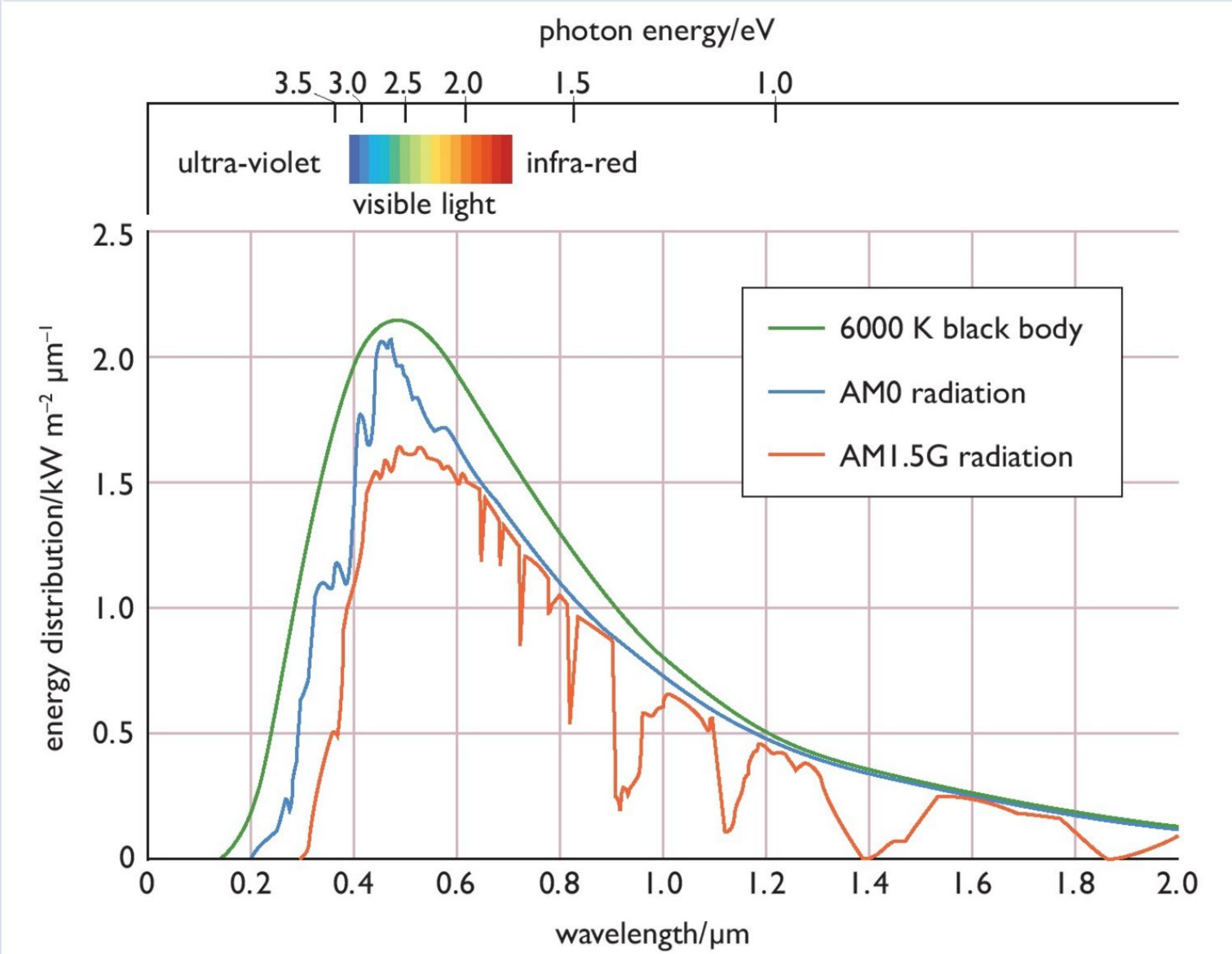
Figure 4.8 Air Mass is the ratio of the path length of the Sun's rays through the atmosphere when the Sun is at a given angle (θ) to the zenith (SO), to the path length when the Sun is at its zenith (ZO)

Standard Test Conditions

- The power rating of a PV cell or module, expressed in peak watts (Wp) of power output, is determined by measuring the maximum power it will supply at a temperature of 25 °C when exposed to radiation from lamps designed to reproduce the AM1.5 Global (AM 1.5G) spectral distribution at a total power density of 1000 W m–2 (1 'sun').

- Cells for concentrating PV applications are tested at higher intensities, up to 500 suns.

Solar Power Spectrum



PV Physics in Silicon

Semiconductors & Doping

- The difference between conductors and insulators lies in the energy levels of the electrons.

- Those electrons that normally hold the atoms of a material together, occupying a lower-energy state, are known as the **valence band**.

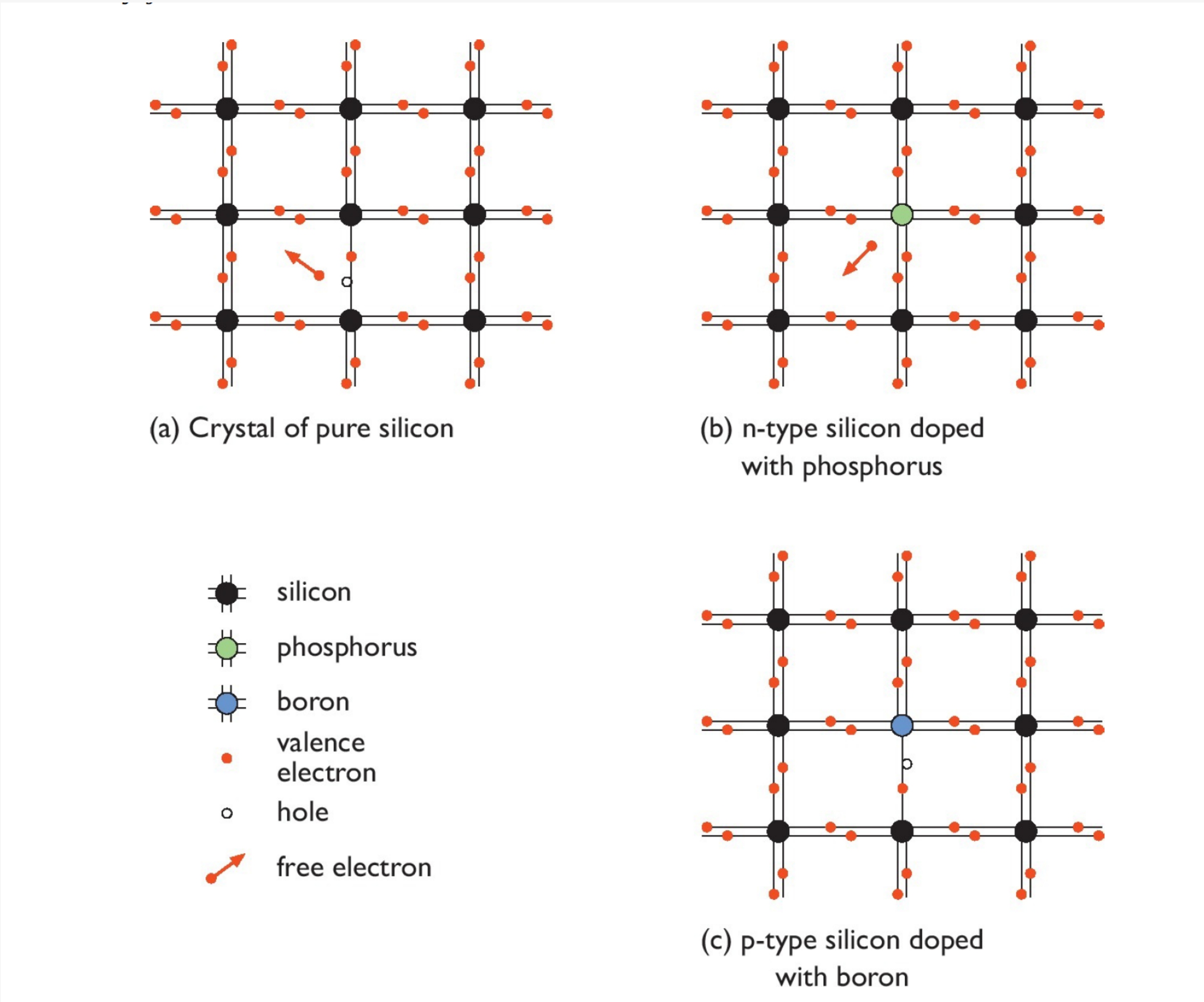
- Some electrons may acquire enough energy to move into a higher energy state, known as the **conduction band**, in which they can move around within
- the material and thus conduct electricity.

- In metals, most electrons naturally lie in a conduction band.

- In good insulators the electrons are permanently bound up in the valence bands.

- Semiconductors, such as silicon, have most of their electrons in a valence band, but it only requires a small amount of energy to ‘promote’ an electron to a higher conduction band. This energy is known as the **band gap**.

Electronic Structure with Doping

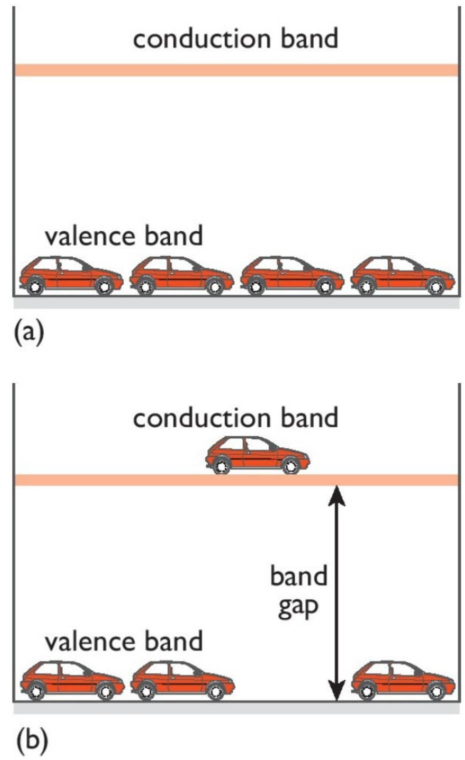


P-N Junctions

- Conventional PV cells consist of a junction between two thin layers of dissimilar semiconducting materials, known respectively as ‘p’ (positive)-type semiconductor, and ‘n’ (negative)-type semiconductor.

- n-type semiconductors are made from crystalline silicon that has been ‘doped’ with tiny quantities of an impurity such as phosphorus

- Each phosphorus atom (shown in green) has five valence electrons, so that not all of them are taken up in the crystal lattice. **Electrons** are sub-atomic particles with a negative electrical charge, so silicon doped in this way has a *surplus of free electrons*.



P-N Junctions

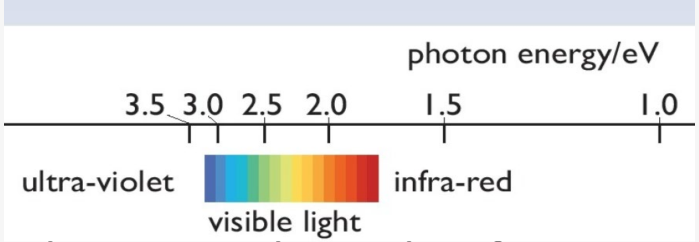
- p-type semiconductors are also made from crystalline silicon, but are doped with very small amounts of a different impurity such as boron. Each boron atom has only three valence electrons, so that it shares two electrons with three of its silicon neighbors and only one electron with the fourth.
- This causes the material to have a *deficit of free electrons*.
- This is a "positive" **p (positive)-type** semiconductor.
- We can create what is known as a **p–n junction** by joining these dissimilar semiconductors.
- The doping level changes from 'p' to 'n' gradually across the junction.
- This sets up an **electric field** in the region of the junction, which
- promotes the flow of electrons and holes, i.e. an electric current.

Photon Physics

- The energy of a photon of light (E) is dependent on its wavelength λ: $E = hc / \lambda$
- where h = Planck's constant and c = velocity of light

- At this atomic level, energy is normally described in terms of electron-volts (eV), the energy required to raise the charge on a single electron through one volt. This is 1.6×10^{-19} joules.

- $E\ (\text{eV}) = 1240 / \lambda\ (\text{nm})$



- A photon of blue light with a wavelength of 410 nm will have twice as much energy, 3 eV, as one of infrared radiation with a wavelength of 820 nm, which only has an energy
- of 1.5 eV.

Photon Physics

(1) In order to promote an electron from the valence band to the conduction band, an incoming photon *must have an energy greater than the band gap of the particular semiconductor*.

(2) For pure crystalline silicon this band gap is 1.1 eV. This corresponds to the energy of a photon of infra-red radiation with a wavelength of about 1130 nm. *Only light with a shorter wavelength than this will have any effect on a silicon PV cell*. The energy of the remaining low frequency infra-red radiation is effectively wasted.

(3) Even though a photon promoting an electron to the conduction band may have an energy considerably *greater* than the band gap, the useful electrical energy that it contributes to the cell is only *equal* to the band gap. Any surplus energy will be dissipated as heat and again wasted.

(4) These two mechanisms of energy loss have led to the development of cells with different band gaps and multijunction cells capable of absorbing light over a range of light frequencies.

Basic PV Cell

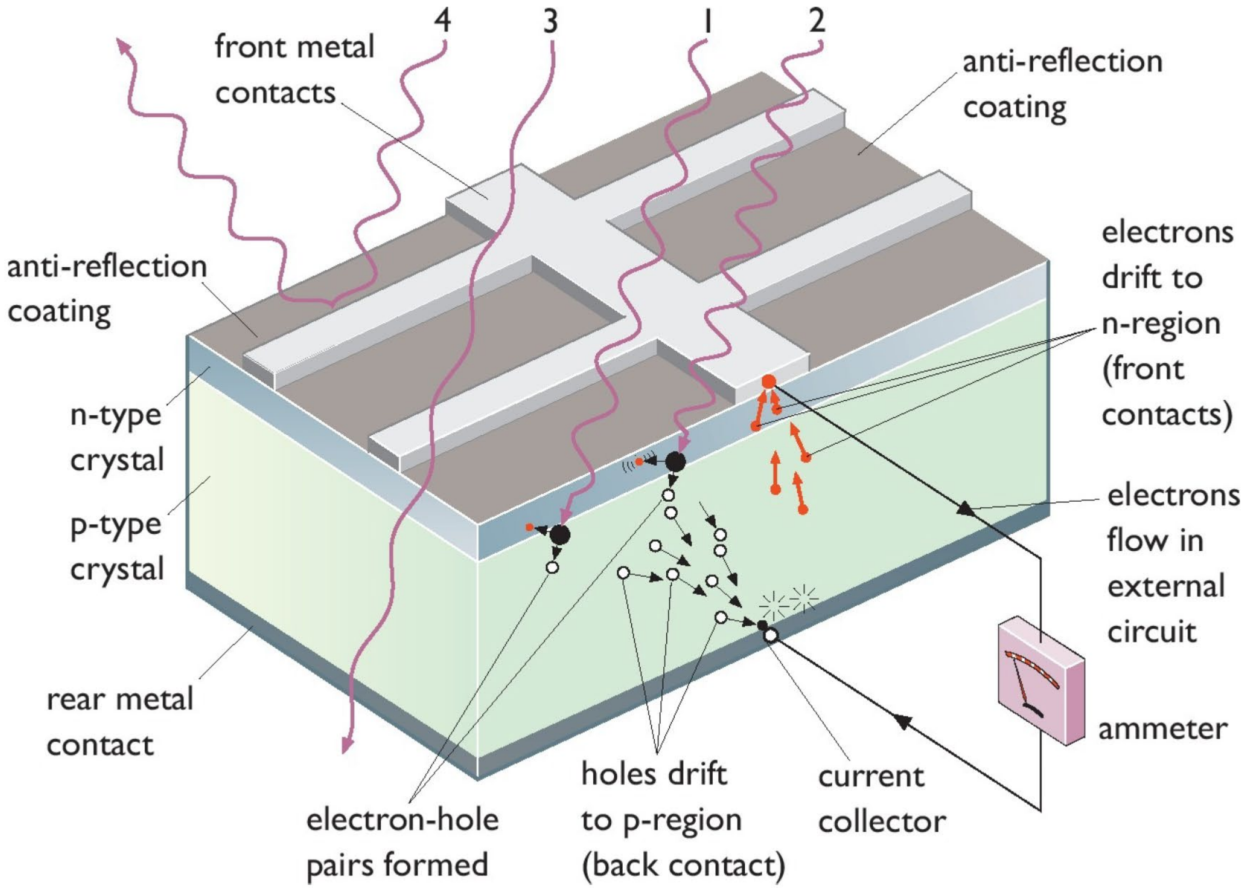
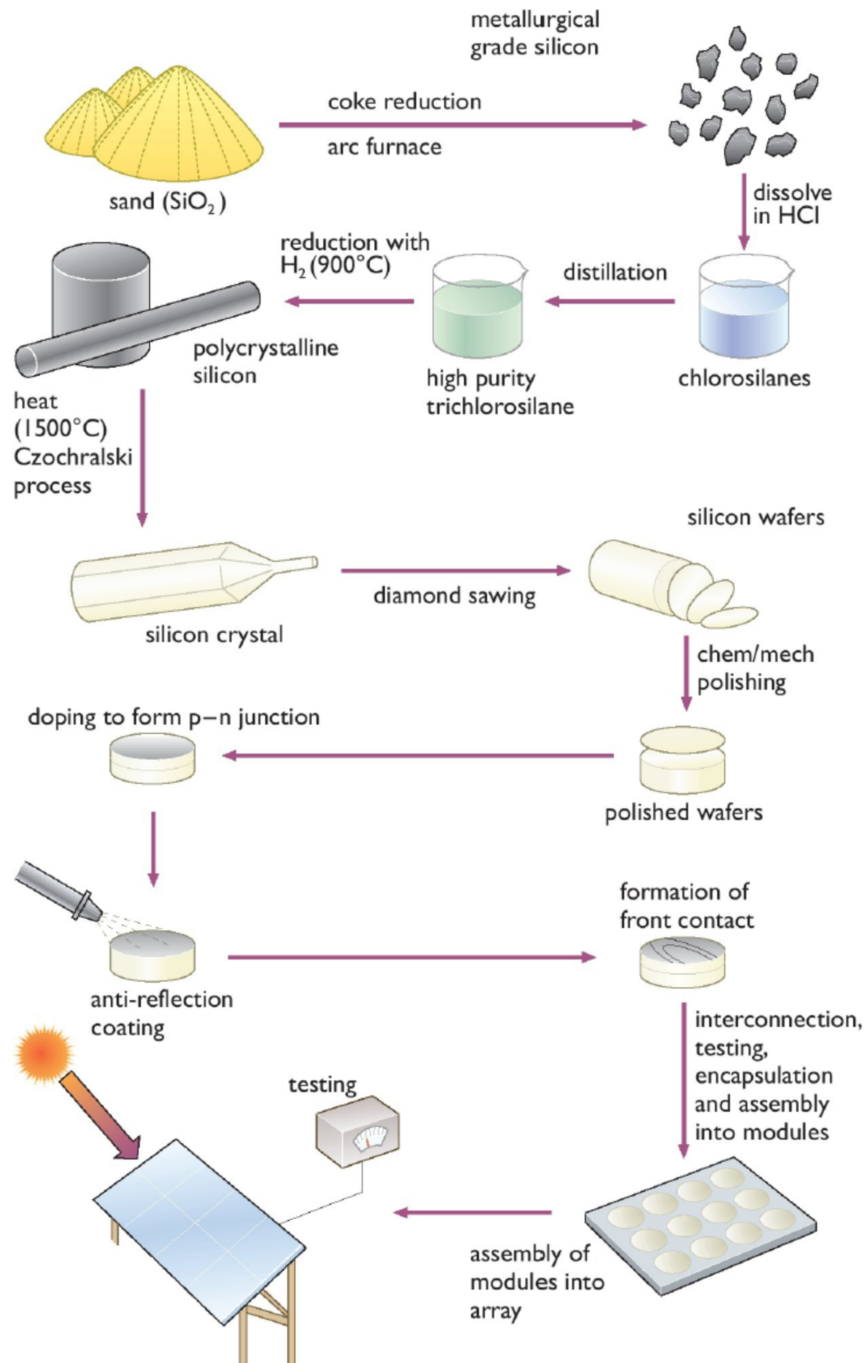


Figure 4.12 A basic silicon PV cell and four possible interactions with photons of light

Crystalline PV Cells

Manufacturing Steps of Mono-crystalline Silicon Cells. About 20% of world production.



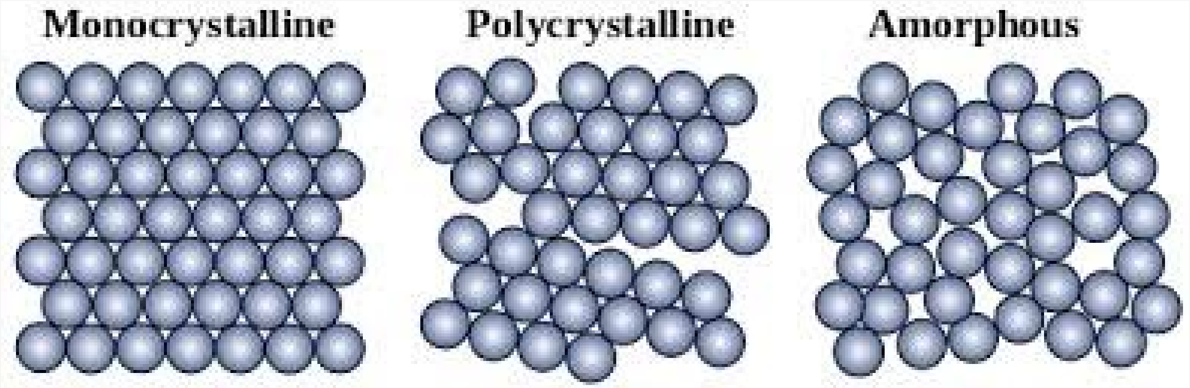
Approaches for Cost Reduction

- The first approach involves improving the energy efficiency of pure silicon production. For example, the Fluidized Bed Reactor, produces silicon granules at a ‘solar grade’ purity but uses less energy and as a continuous flow process

- The second approach is to use polycrystalline rather than single-crystal material, thus eliminating the slow Czochralski process.

- The third is to minimize the amount of silicon needed by growing silicon wafers in ribbon form, or using it in extremely thin films.

Polycrystalline Silicon



- Conventional silicon solar cells need to be around 150–200 µm thick to ensure that photons can be absorbed.
- Light trapping techniques involving giving the front surface of the cell a fine rough texture can maximize the interaction of photons with the material allowing much thinner 'films'.
- A cell using a polycrystalline film of silicon only 35 µm thick has demonstrated an efficiency of 21%

Solar cell wafers can be made directly from polycrystalline silicon in various ways. These include the controlled casting of molten polycrystalline silicon into cube-shaped ingots that are then cut, using fine wire saws, into thin square wafers and fabricated into complete cells in the same way as monocrystalline cells.

Other Semiconductors

Table 4.1 Elements in the Periodic Table used in PV semiconductors

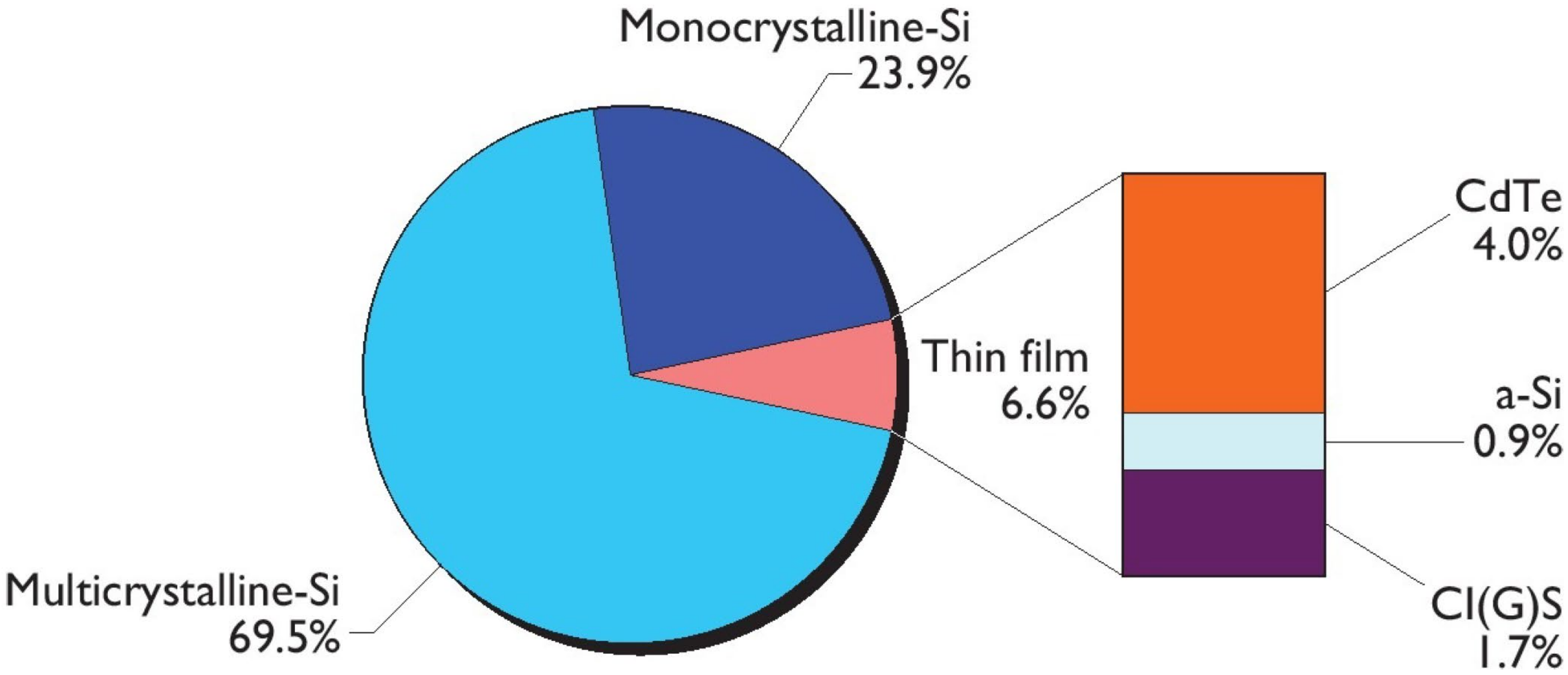
Group I	Group II	Group III	Group IV	Group V	Group VI
		Boron (B)	Carbon (C)		
		Aluminium (Al)	Silicon (Si)	Phosphorus (P)	Sulfur (S)
Copper (Cu)	Zinc (Zn)	Gallium (Ga)	Germanium (Ge)	Arsenic (As)	Selenium (Se)
	Cadmium (Cd)	Indium (In)	Tin (Sn)	Antimony (Sb)	Tellurium (Te)

Table 4.2 Semiconductor materials and their band gaps

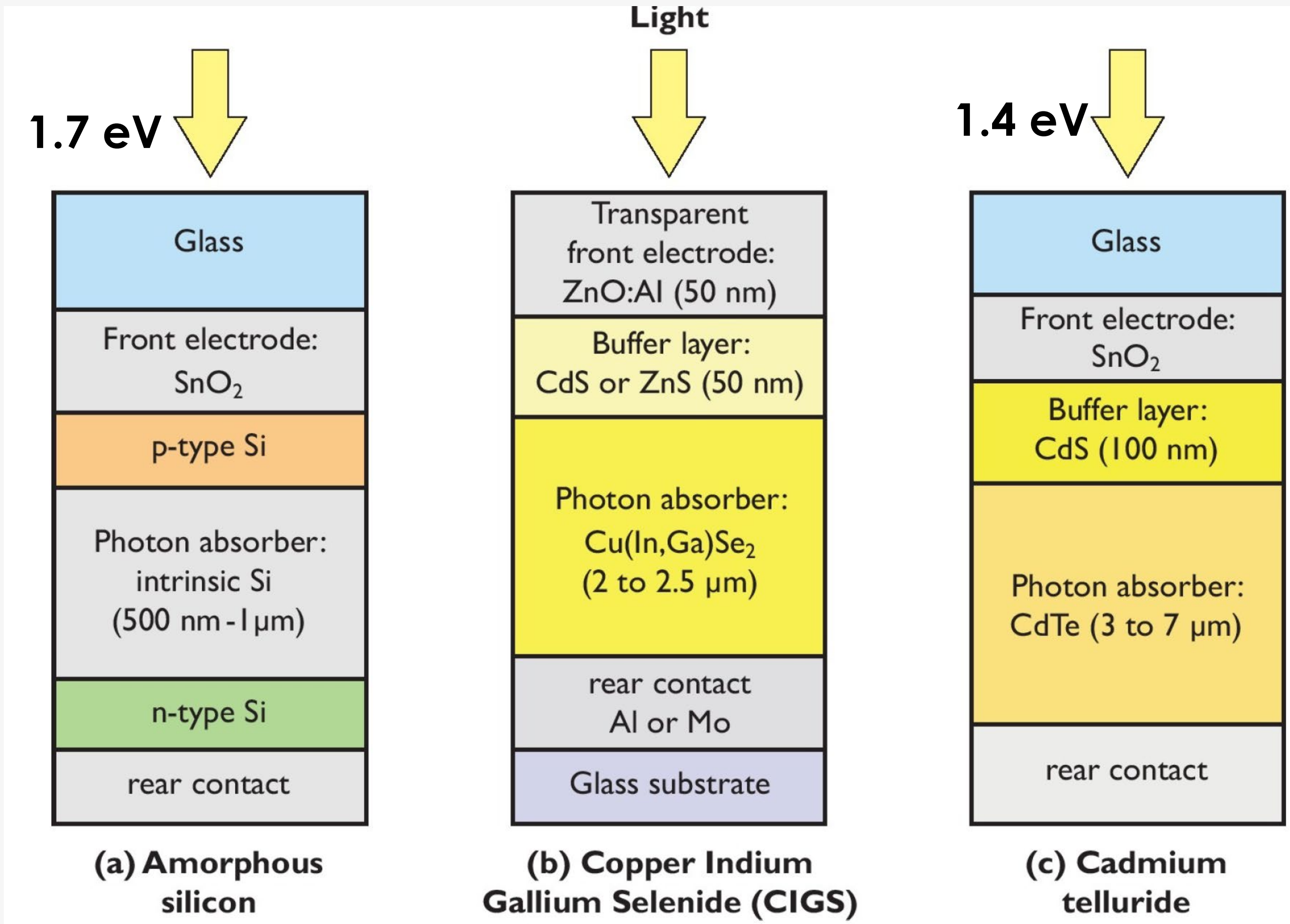
Semiconductor Material	Band Gap/eV
Germanium (Ge)	0.7
Crystalline silicon (Si)	1.1
Copper indium gallium diselenide (CIGS)	1.0 – 1.7 (depending on relative proportions of In and Ga)
Cadmium Telluride (CdTe)	1.4
Gallium Arsenide (GaAs)	1.4
Amorphous silicon (a-Si)	1.7
Gallium Indium Phosphide ($GaInP_2$)	1.9

Thin Film PV Cells

Global Market is Dominated by Si



High-Efficiency Thin Film PV



10% 21% 18%

Other PV Technologies

Multi-junction PV cells and modules

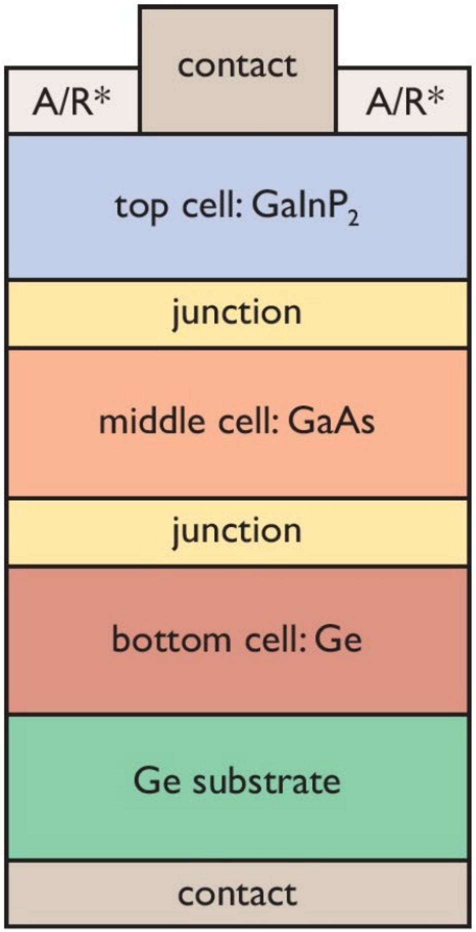
- The top layer is made of gallium indium phosphide ($GaInP_2$), which has a band gap of nearly 1.9 eV.

- This absorbs light in the blue part of the spectrum.

- The remaining light passes through this cell to a gallium arsenide (GaAs) layer in the middle with a band gap of 1.4 eV that absorbs the yellow part of the spectrum.

- Finally the unabsorbed light passes to a germanium (Ge) layer at the bottom. This has a band gap of 0.7 eV, and absorbs light in the red portion and much of the infra-red spectrum.

- Such cells are very expensive, but they are very efficient. Modules have achieved efficiencies of over 30%



A/R*: anti-reflective coating

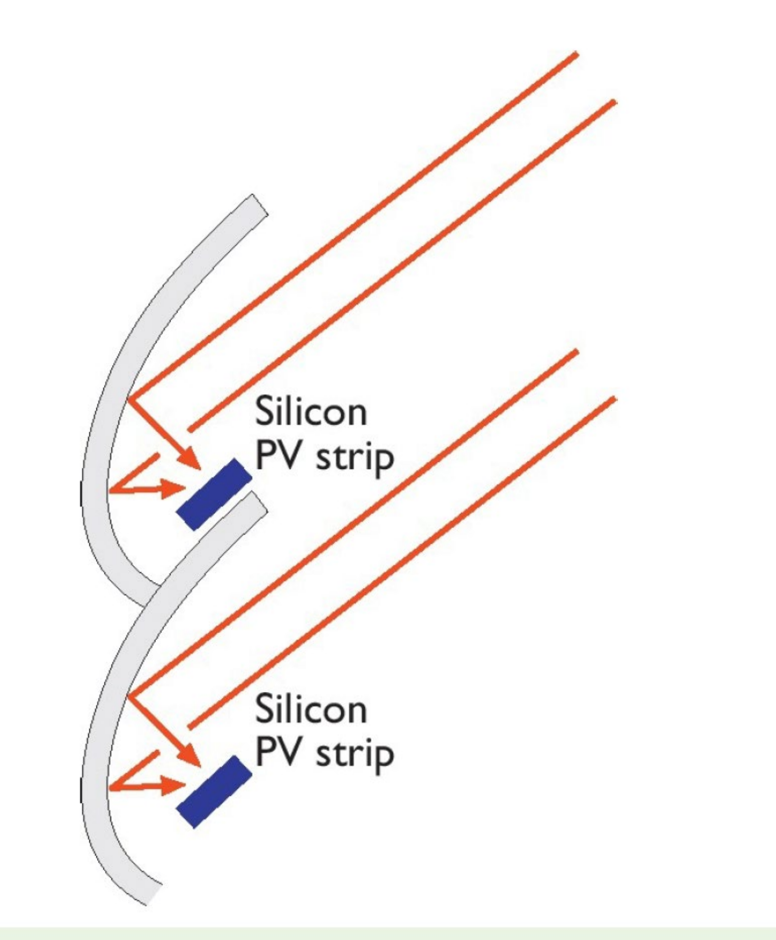
Concentrating PV (CPV) systems

The conversion efficiency of PV cells increase with more illumination, as long as the cell can be kept.

Module efficiencies of almost 40% have been measured with multilayer gallium arsenide cells

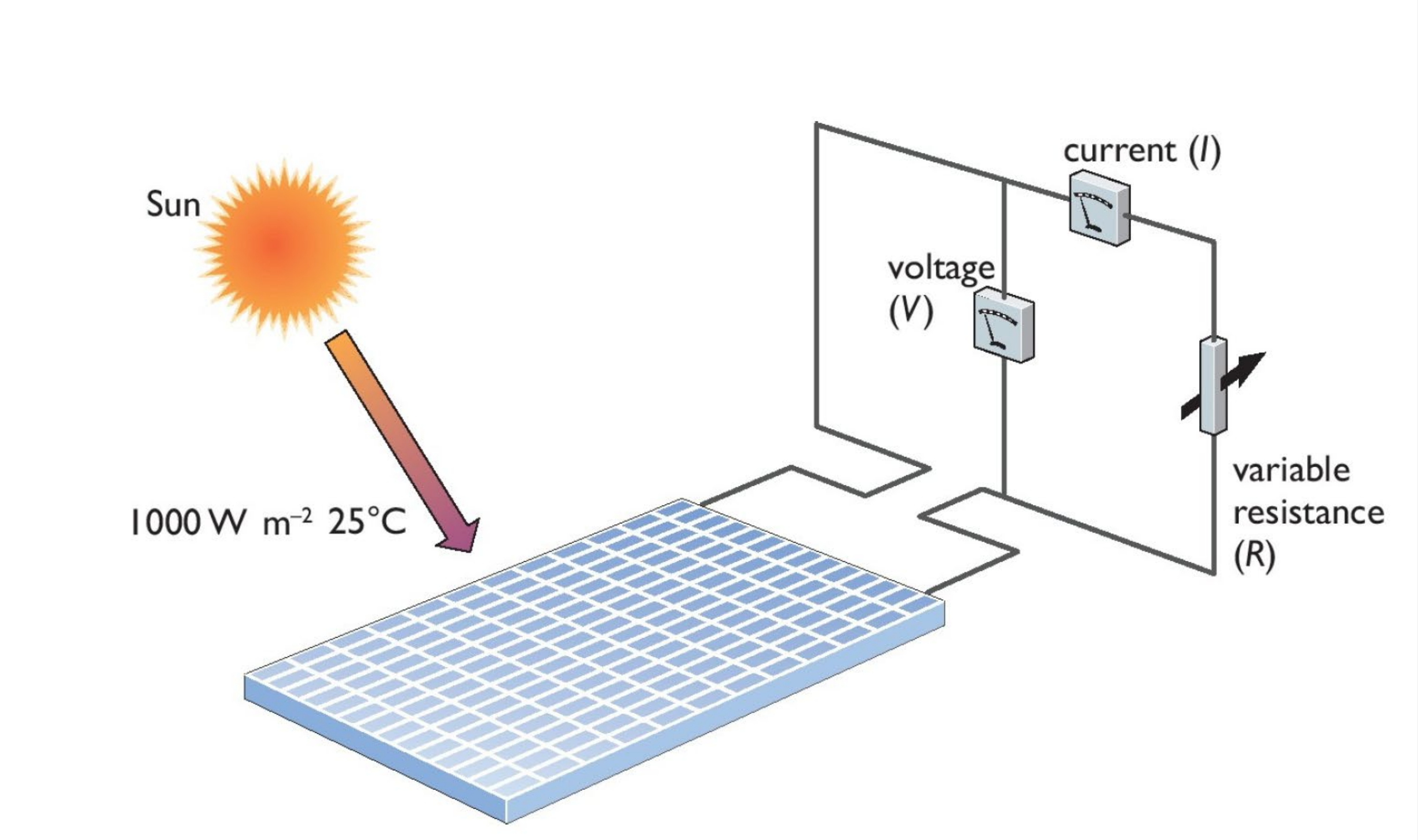
CPV Systems require clear skies and direct solar radiation; they cannot concentrate diffuse radiation.

These systems need to track the Sun, ensuring that the cells always receive the maximum amount of direct solar radiation.

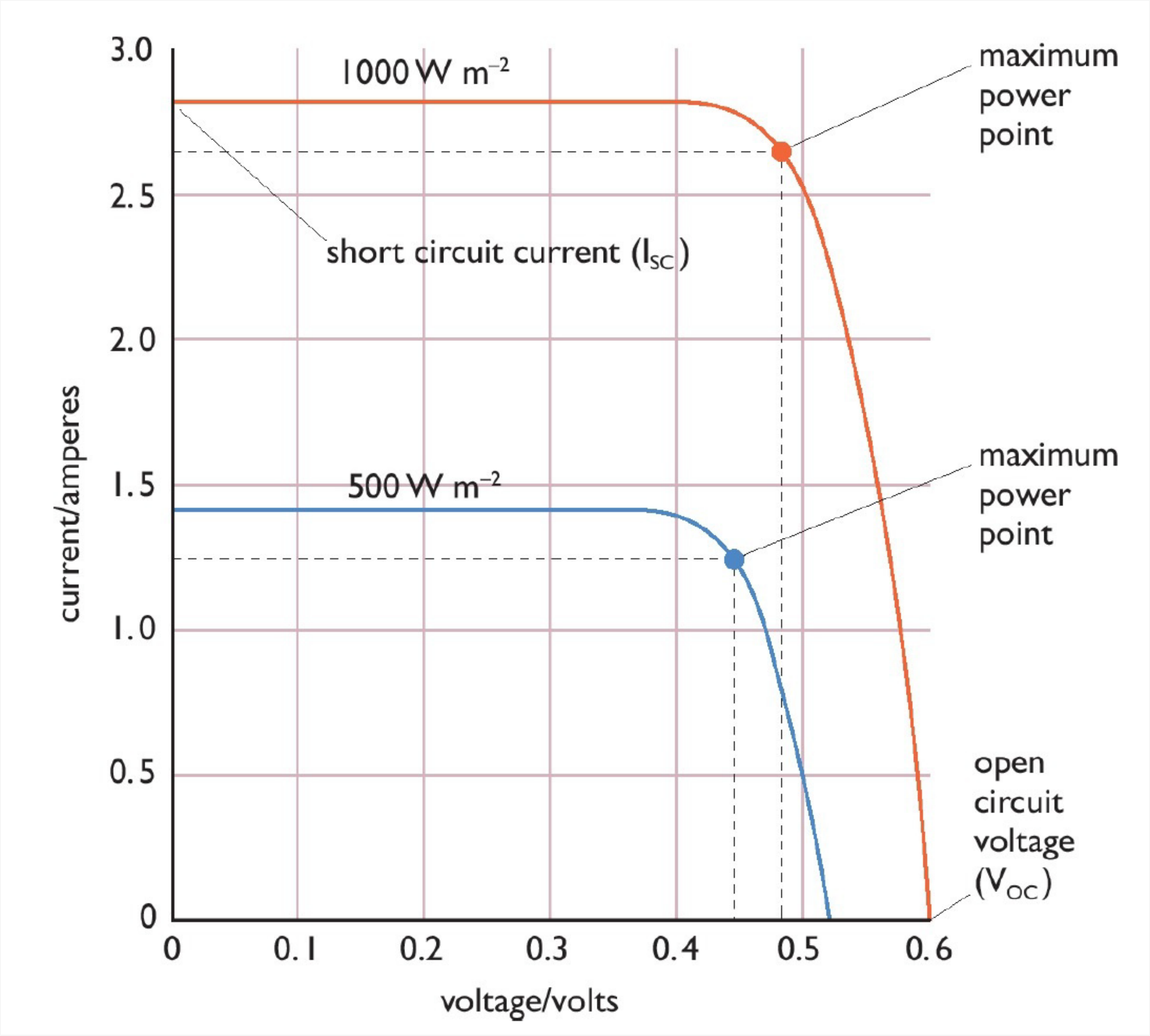


Electrical Characteristics

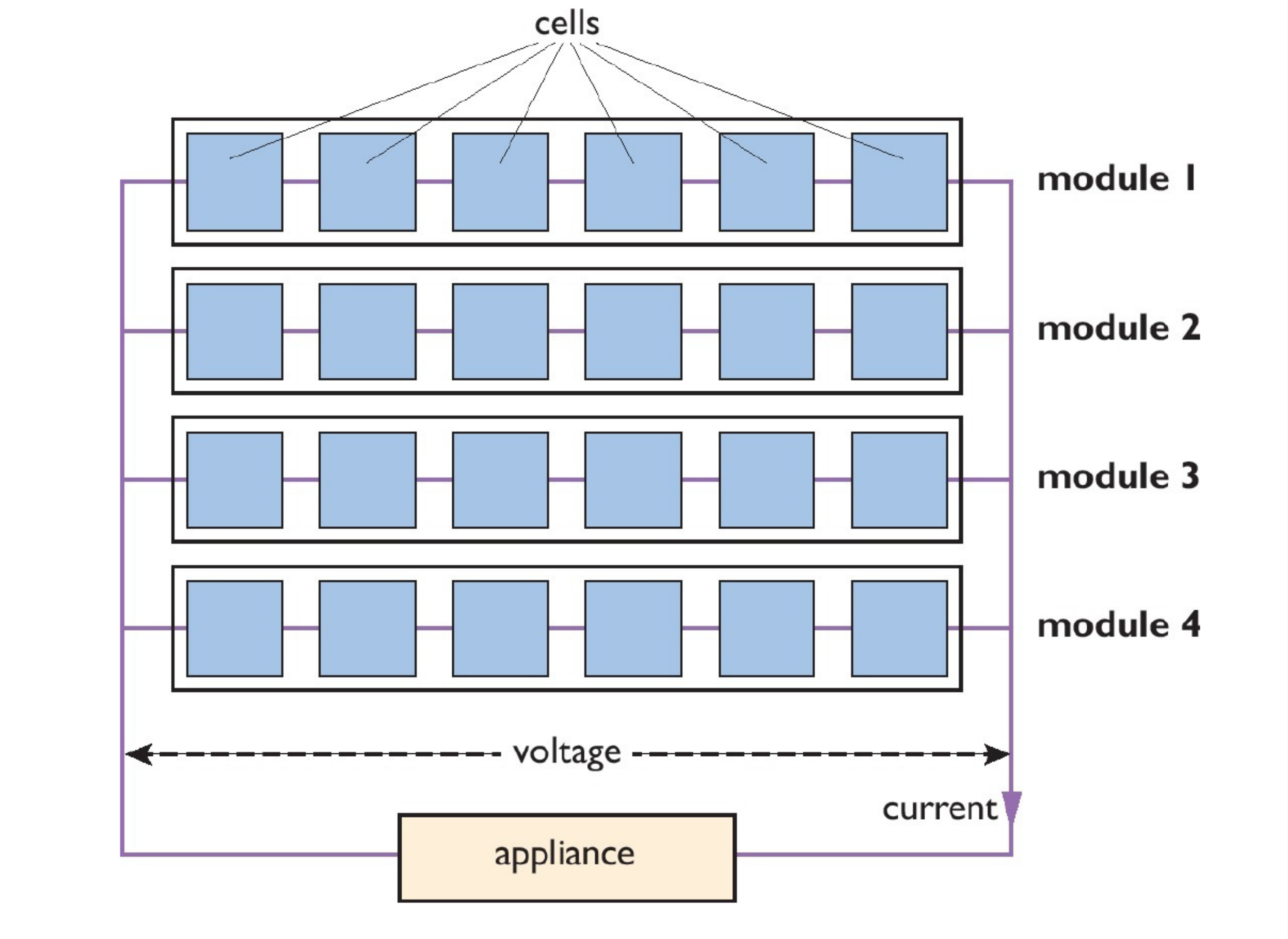
Open-circuit voltage and short-circuit current



Voltage-Current Characteristics



modules are around 1.4 to 1.7 square metres in area, incorporate 60–72 PV cells connected in a series – parallel combination, and have a peak power output of 120–300 watts.



PV Systems for Remote Power

Remote Applications of PV Solar Systems

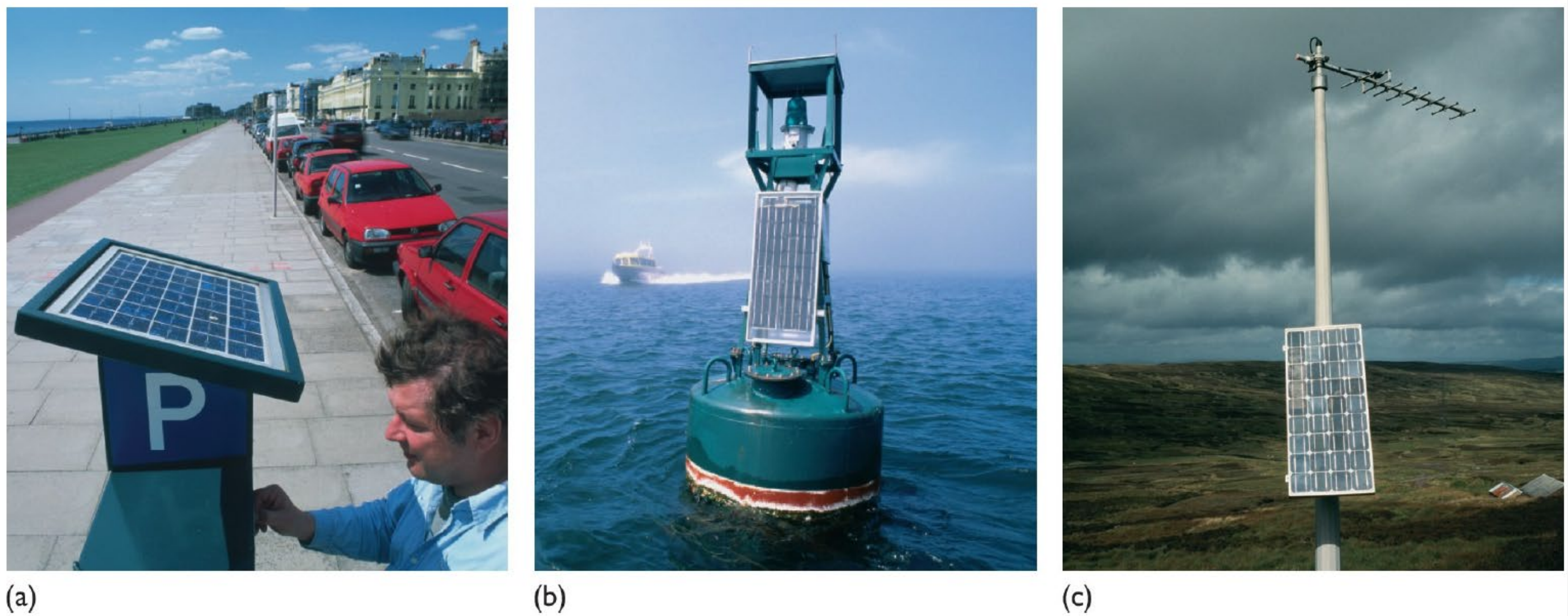


Figure 4.23 (a) PV parking meter (b) PV navigation buoy (c) PV telemetry

- Off-grid PV systems may also be used to provide a basic electricity supply for rural houses
- Battery-powered solar lanterns
- PV-powered micro-grids for rural homes.

Grid-Connected PV Systems

Domestic, grid-connected PV power plants

- PV energy systems use the grid as a giant 'battery'.
- The grid can absorb PV power which is surplus to current needs and at night or on cloudy days, it can provides backup energy from conventional sources.
- In these grid-connected PV systems, a so-called 'grid commutated inverter' (or 'synchronous inverter') transforms the direct current (DC) power from the PV arrays into alternating current (AC) power at a voltage and frequency that can be accepted by the grid.
- The yearly electricity output in northern climates is around 1000 kWh m^{-2} y^{-1} but in very sunny countries the figure can rise to well over 2000 kWh m^{-2} y^{-1}.
- A 1000 peak watt module would occupy 5-7 m^2.

Large, grid-connected PV power plants

Figure 4.29 A 48 MW_p solar PV facility in Boulder City, Nevada, USA commissioned in 2011. It uses cadmium telluride cells (Source: Sempra generation).

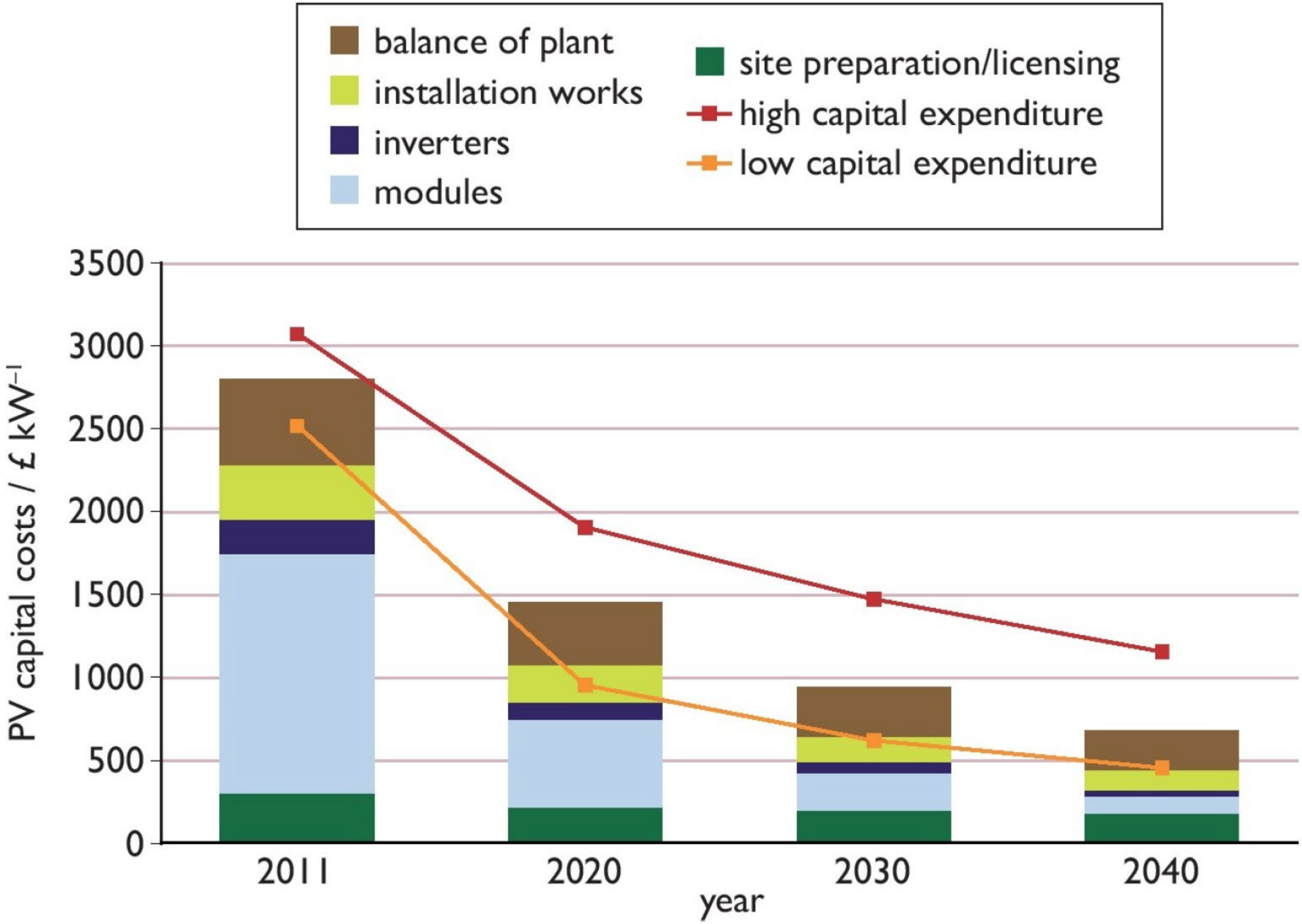
- Large stand-alone PV plants can take advantage of economies of scale .
- The electricity they produce is not used onsite and has to be distributed by the grid, thus involving transmission losses.
- Large plants also require substantial areas of land

Table 4.3 World's largest PV power plants, 2016

Location	Power / MW_p	Area /km^2
Longyangxia Dam Solar Park, Qinghai province, China	850	14
Kamuthi Solar Power Project, Tamil Nadu, India	648	10
Solar Star Projects, California, USA	579	13
Desert Sunlight Solar Farm, California, USA	550	9.5
Topaz Solar Farm, California, USA	550	16

(source: Wikipedia)

Discussion on Cost and Environmental Impact


balance of plant
installation works
inverters
modules
site preparation/licensing
high capital expenditure
low capital expenditure
3500
3000
2500
2000
1500
1000
500
0
PV capital costs / £ kW⁻¹
2011
2020
2030
2040
year

Environmental impact and safety

- The environmental impact of PV is probably among the lowest of all renewable or non-renewable electricity generating systems.
- In normal operation, PV electricity systems emit no gaseous or liquid pollutants and no radioactive substances.
- Crystalline silicon PV modules contain relatively safe materials and pose little hazard either during their working life or in their eventual disposal.
- CdTe modules (and some CIS modules) contain cadmium, a toxic heavy metal. Although this poses little risk during operation, it is important that these cells are eventually recycled properly.
- A kilowatt peak PV array is likely to contain 6 kg or more of very highly purified silicon.

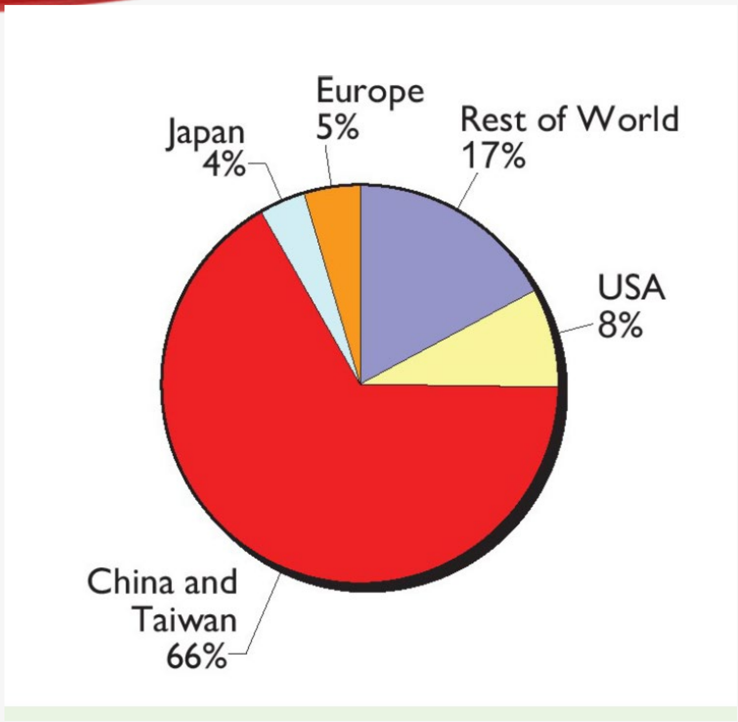
The energy balance of PV systems and potential materials constraints

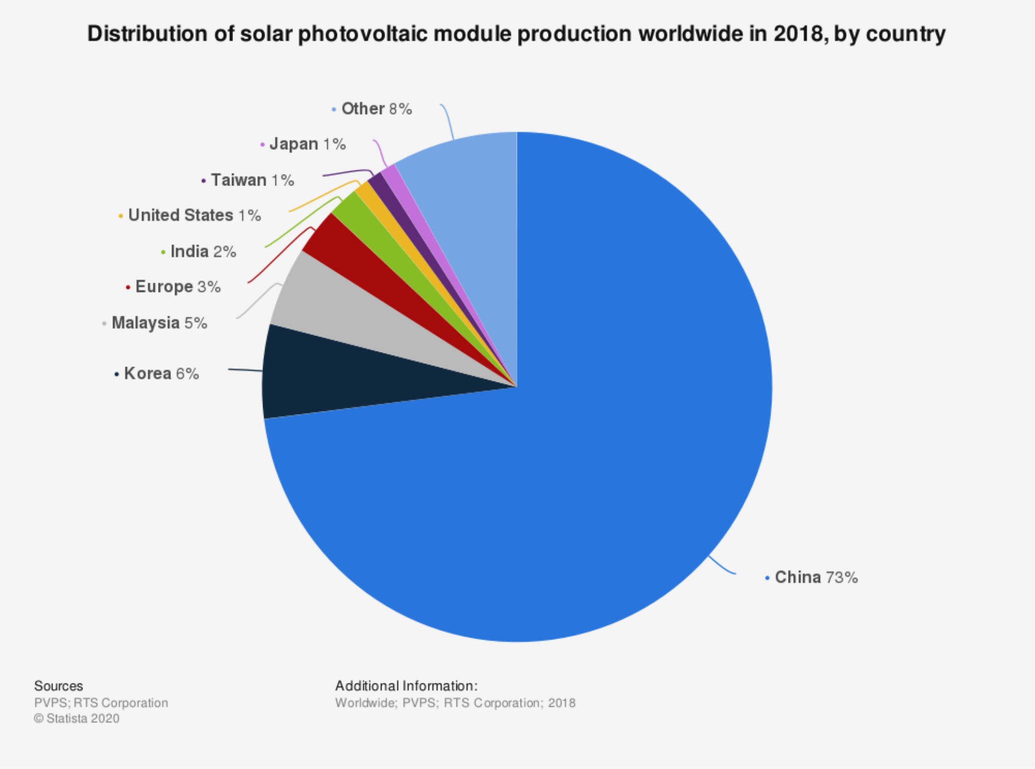
- A common misconception about PV cells is that as much energy is used in their manufacture as they generate during their lifetime.

- Modern cells are more electrically efficient and the use of modern PV production processes and thin film cells has made the energy balance of PV much more favorable.

- The energy payback time for new multicrystalline silicon PV rooftop systems in UK conditions is about 2.1 years. This falls to only 1.2 years for systems in southern Europe.

PV Module World Production





2015

2018

Installed World Solar PV Capacity