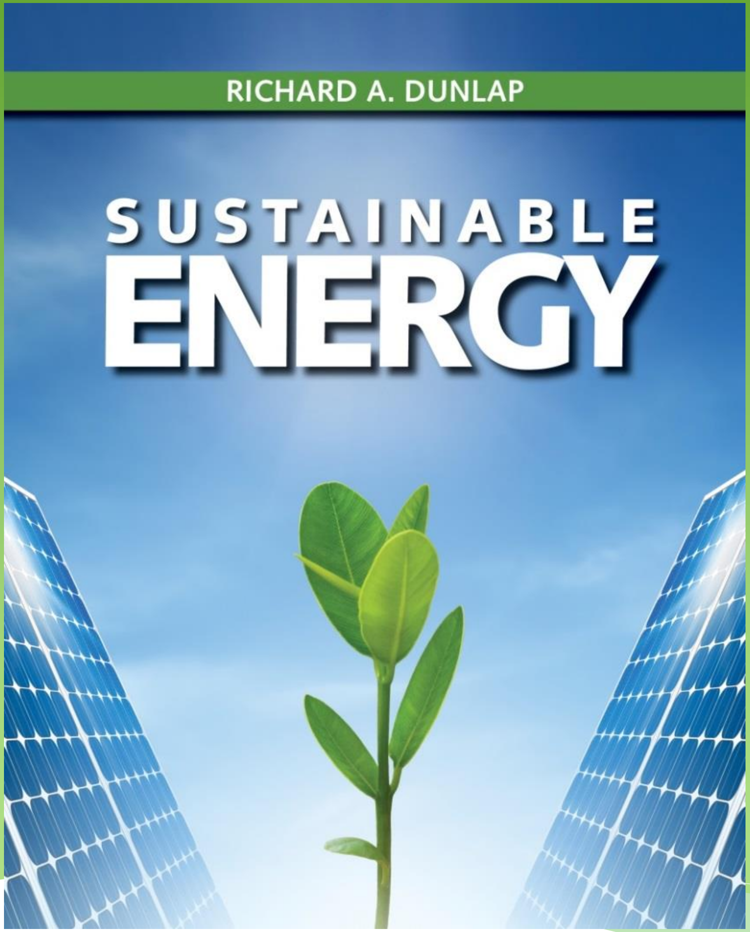
Sustainable Energy



Chapter 9

- Electricity from Solar Energy

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Learning Objectives

- The generation of electricity from solar energy through heat engines.
- The basic physics of semiconducting materials and the properties of n-type and p-type materials.
- The construction of a semiconducting junction device.
- The production of electricity through the interaction of photons on semiconducting junctions.
- The sensitivity and efficiency of photovoltaic devices.
- The application of photovoltaic devices for electricity generation worldwide.
- The availability of solar energy and economic viability of its utilization.

Solar Electric Generation

Electricity can be generated from solar radiation in two ways:

- Conversion of solar radiation into heat to run a heat engine to drive a generator
- Use of a photoelectric device

Solar heat engines

Sunlight must be focussed in order to achieve temperatures that are suitable to operate a heat engine.

The most notable types of solar focussing devices are

- Parabolic troughs
- Parabolic dishes
- Central receivers

Parabolic troughs

A working fluid is heated by circulating it through a pipe at the focus of a parabolic trough.

The largest facility of this kind is the Solar Electric Generating Station at Kramer Junction California.

Efficiency is limited by the Carnot efficiency of the heat engine at about 15% and maximum output is 350 MW_e.

Solar collectors at Kramer Junction, CA

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Figure 9.1: Parabolic trough solar collectors at Kramer Junction, California.

Parabolic dishes

An array of parabolic dishes is used to focus sunlight to either

- heat a working fluid to run a heat engine

or

- operate a heat engine directly (Stirling engine)

Parabolic dish collectors in Peoria, AZ

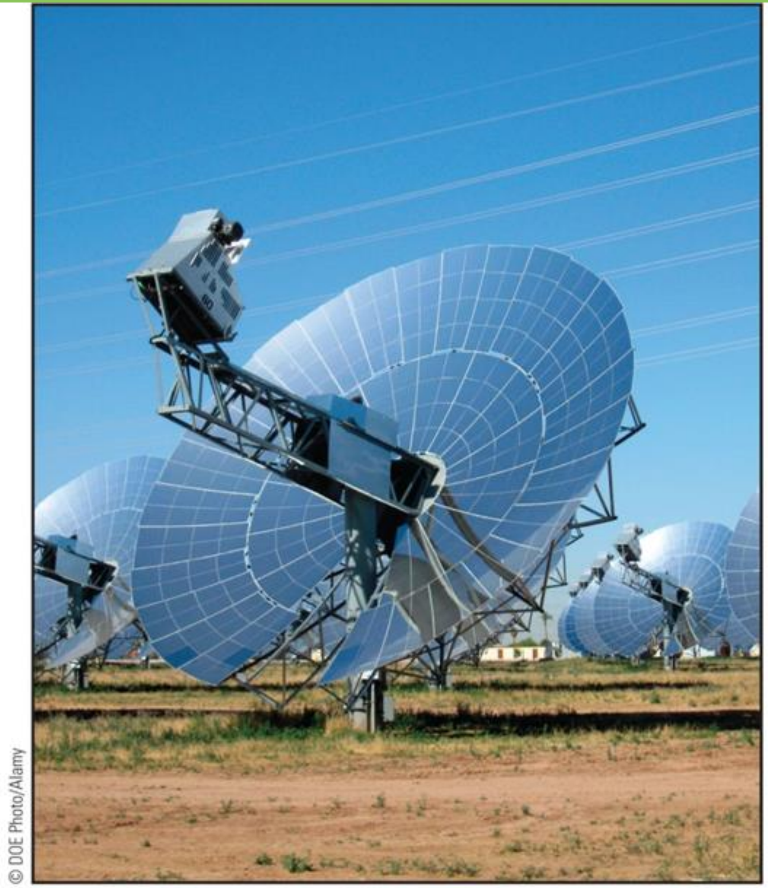

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Figure 9.3 Parabolic dish solar collectors at Maricopa Solar Project in Peoria, Arizona showing the Stirling engine used to convert heat to mechanical energy.

Central receiver

A large array of individual flat mirrors that can track the location of the sun, can be used to focus sunlight on a central receiver.

Notable experimental facilities have included

- Solar One in Daggett, California
- Solar Two, which replaced Solar One and had a rated output of 10 MW_e
- PS10 in Seville, Spain which has a rated output of 11 MW_e

Solar Two

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Figure 9.4: Solar Two in Daggett, California. The scale can be determined from the central tower that is about 90 m high.

Individual mirror from Solar Two

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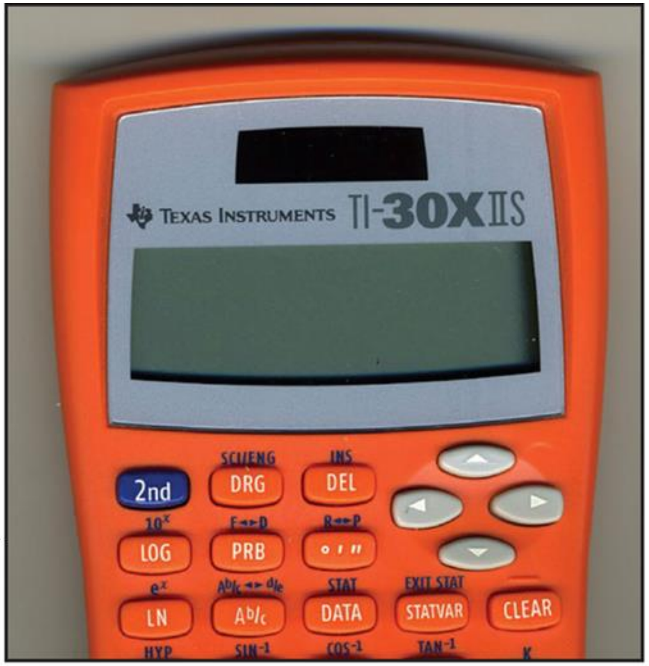
Figure 9.5: One of Solar Two's heliostats. The Solar Power Tower is reflected in the mirror.

Photovoltaic devices

Photovoltaic devices are semiconducting devices that convert solar radiation (or any light) directly into electricity.

Example of a small photovoltaic device



Richard A. Dunlap

Figure 9.8: Photovoltaic device (black area above the model number) used to power a pocket calculator. The 1.5-cm^2 cell produces about 10 mW$_e$ in bright sunlight.

Electronic energy levels

The energy levels of electrons in a simple atom (hydrogen) are quantized according to the relationship

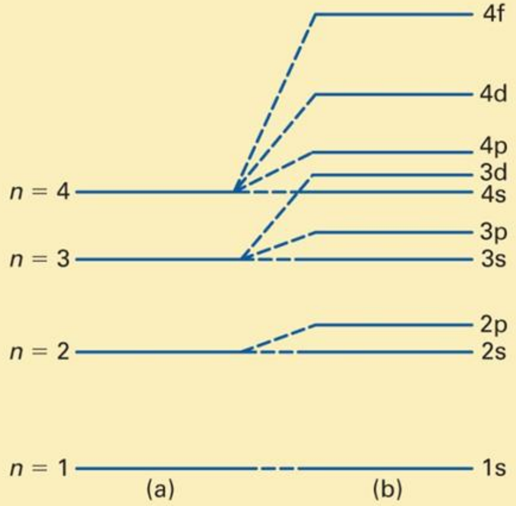
$$E = -\frac{2\pi e^4 m}{n^2 h^2} \qquad (9.1)$$

where the energy is related to the principal quantum number *n.*

Multielectron atoms

In a multielectron atom, electron -electron interactions cause the energy levels to split according to the electron orbital angular momentum.

Orbital angular momentum quantum number is designated s, p, d, f, ...



Based on R. A. Dunlap, An Introduction to the Physics of Nuclei and Particles, Brooks Cole, 2003.

Figure 9.10: Energy levels in (a) hydrogen and (b) a multielectron atom.

Electron level occupancy

Each electron level can accommodate a certain number of electrons

- 2 for an s level
- 6 for a p level
- 10 for a d level
- 14 for an f level

etc.

Electronic structure of silicon

A Si atom has 14 electrons which, in their ground state occupy the levels

$$1s^2 2s^2 p^6 3s^2 3p^2 \qquad (9.2)$$

Diagram of Si electronic structure

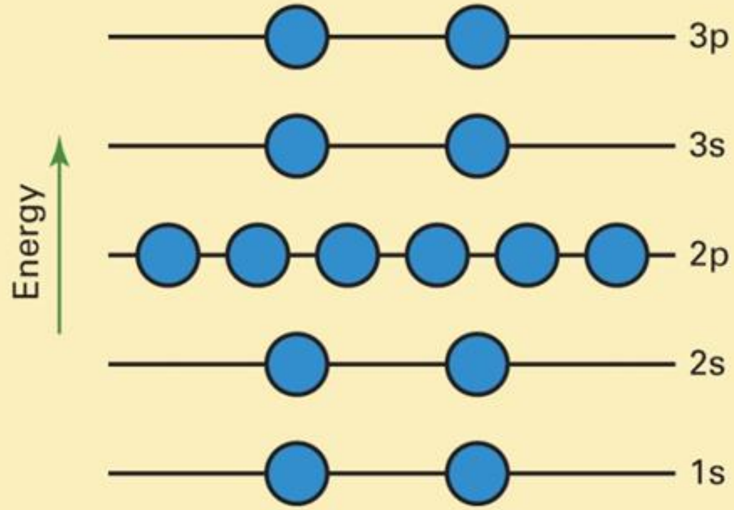


Figure 9.11: Occupation of electron energy levels in a Si atom in its ground state. The circles represent electrons.

Electronic structure of a solid

The above description applies to a single Si atom.

When Si atoms are combined into a solid the interactions between atoms cause the energy levels to smear out into bands and it also causes the p bands to split into three sub-bands with energy gaps between them.

This is the typical electronic structure of a semiconductor.

Band structure of silicon

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Figure 9.13: Band structure of a piece of Si. The solid boxes represent occupied bands, and the open boxes represent unoccupied bands.

The two 3p electrons fill the lowest of the three 3p sub-bands

Silicon bonding

In a piece of pure silicon each silicon atom has four silicon neighbors (in a tetrahedral configuration).

The valence electrons from each silicon atom are the two 3s electrons and the two 3p electrons.

Each silicon gives up one of its valence electrons to each of its four neighbors.

Each silicon bond is made up of two electrons, one from each of the neighboring atoms.

Two dimensional representation of silicon bonding

The tetrahedral bonds can be represented in a two dimensional square lattice

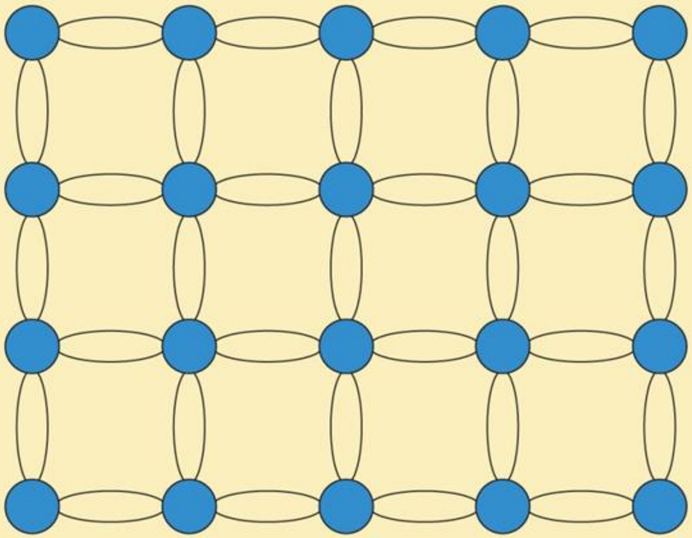

Figure 9.14: Two-dimensional representation of bonding in a piece of Si. Each of the lines between the atoms represents a 3s or 3p electron involved in bonding.

Photon energy

A photon has an energy related to its wavelength by

$$E = \frac{hc}{\lambda} \qquad (9.3)$$

For energy in eV and wavelength in nm, this is

$$E = \frac{1240\ \mathrm{eV \cdot nm}}{\lambda} \qquad (9.4)$$

Photon interactions with atoms

If a photon with sufficient energy interacts with atoms in a piece of silicon then one of the electrons in the first 3p band can be excited into the second 3p band.

The missing electron in the lowest 3p band is referred to as hole and acts like a positive charge.

Electron-hole formation

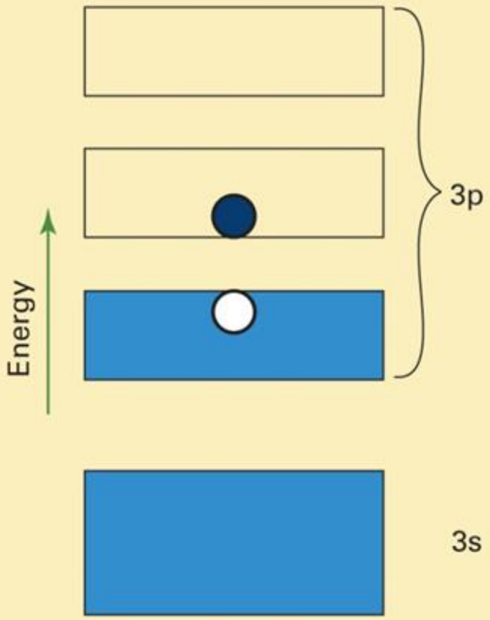

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Figure 9.15: Band structure (upper portion only) of Si, showing the excitation of an electron from the valence band to the conduction band caused by the absorption of a photon of sufficient energy.

Bonding picture of electron-hole formation

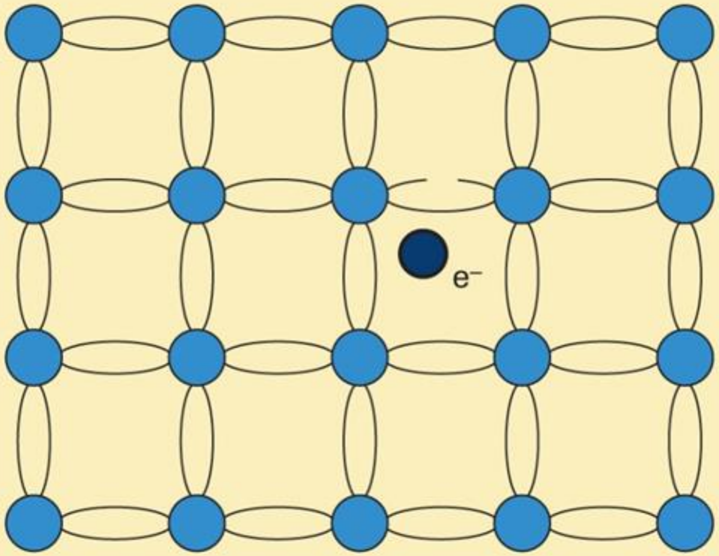

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Figure 9.16: Portion of a Si lattice showing broken bond and resulting conduction electron.

Electron-hole recombination

In principle the electron and hole could represent an electric except that they attract one another and will recombine.

In the band structure picture, the electron will fall back into the hole.

In the bonding picture the electron will fill the broken bond.

To avoid this we need to use two different types of semiconductor.

Doped semiconductors

A small amount of impurity can significantly alter the electrical properties of a semiconductor.

- n-type impurities (donors) have one more valence electron than the host

- p-type impurities (acceptors) have one less valence electron than the host

These impurities create excess electrons or holes, respectively.

Band structure of n- and p-type semiconductors

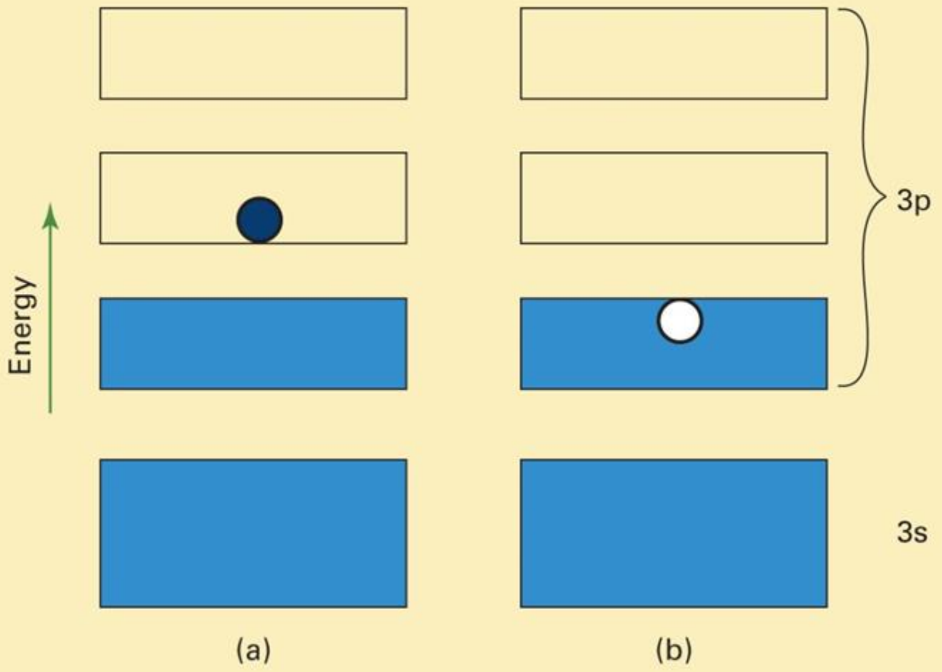

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Figure 9.17: Occupied electron states in a piece of Si with (a) donor impurity and (b) acceptor impurity.

Creation of electrons or broken bonds in doped semiconductors

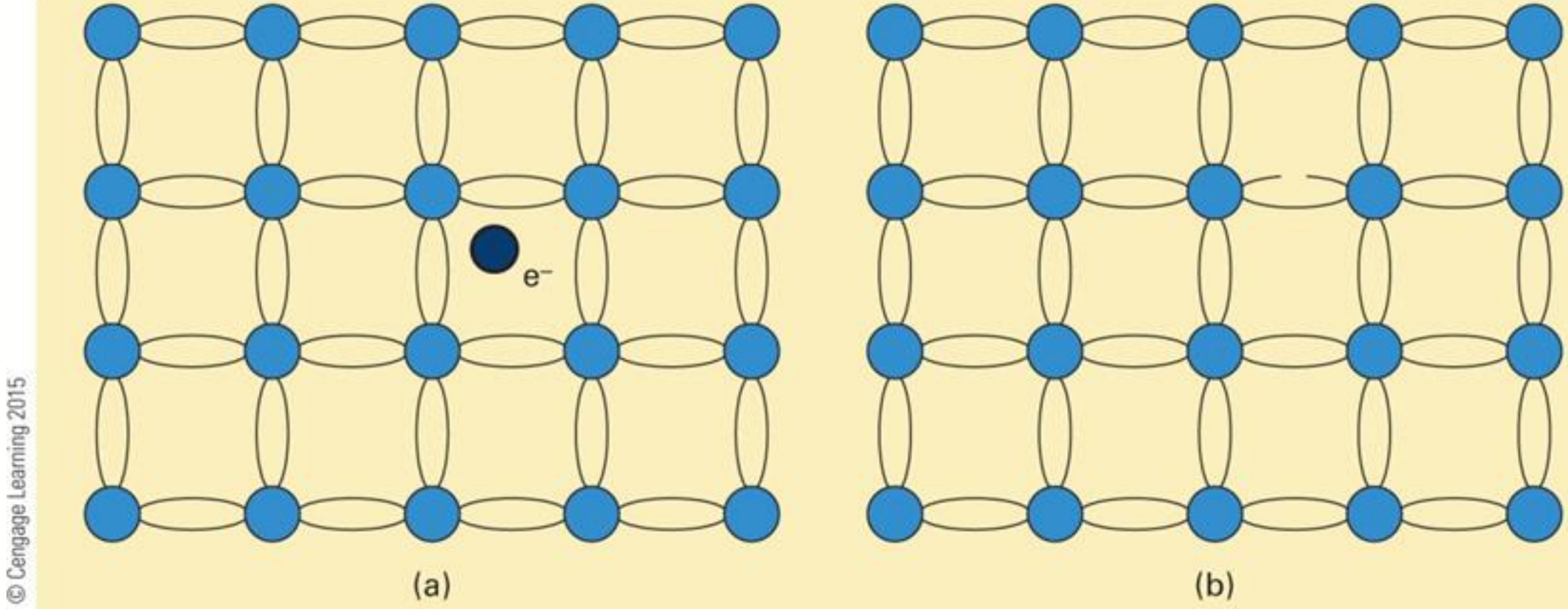


Figure 9.18: Portion of a Si lattice showing (a) conduction electron from donor impurity and (b) hole from acceptor impurity.

Charges in doped semiconductors

In a doped semiconductor the excess charge carriers have (-) or (+) charges and the impurity atoms have (+) or (-) charges, respectively, for n-type and p-type materials.

Semiconducting junctions

A junction made of an n-type and a p-type semiconductor is the simplest semiconducting device - a diode.

Charge distribution in a diode

The free electrons in the n-type material move away from the junction because they are repelled by the (-) impurity ions in the p-type material.

The free holes in the p-type material move away from the junction because they are repelled by the (+) impurity ions in the n-type material.

This behavior forms the depletion region around the junction.

A diode

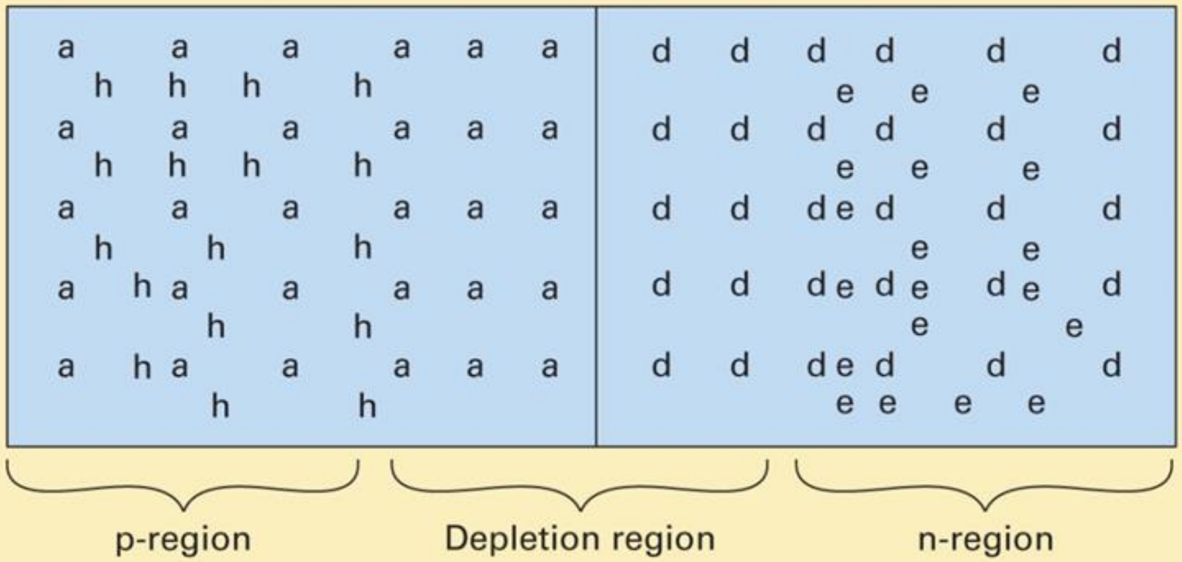


Figure 9.19: Semiconducting junction formed from a piece of p-type and n-type semiconducting material showing acceptor impurities (a) holes (h), donor impurities (d) and electrons (e).

Based on R. A. Dunlap, Experimental Physics. Modern Methods. Oxford University Press Inc, 1988

Operation of a photodiode

If a photon creates an electron-hole pair in the depletion region of a diode then the electron and the hole are carried in opposite directions across the depletion region before they can recombine.

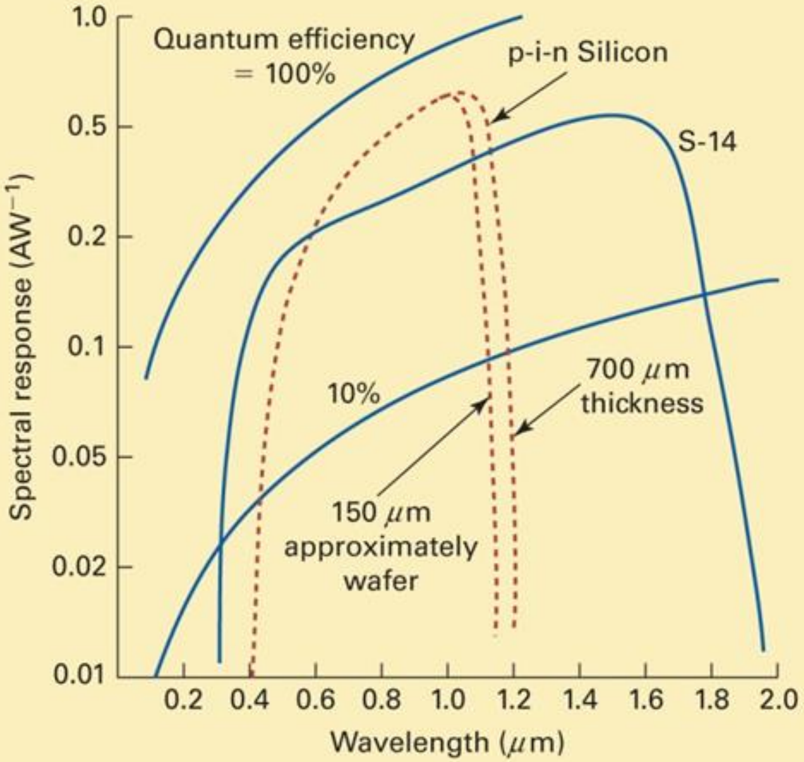
This is the basis of operation of a photodiode or photovoltaic cell and shows how light (photons) can be converted directly into an electric current.

Characteristics of photovoltaic cells

In order to create electron-hole pairs (an hence an electric current) photons must have energy equal to (or greater than) the energy associated with the energy gap.

Different semiconducting materials have different energy gaps and hence different spectral responses.

Spectral response of some silicon and germanium photovoltaic cells



Based on RCA Solid State Division, Lancaster, Pennsylvania

Figure 9.20: Spectral response of silicon (p-i-n Si) and germanium (S-14) based photovoltaic cells.

Photovoltaic efficiency

The efficiency of a photovoltaic device depends on the details of the device and also the spectrum of the incident light

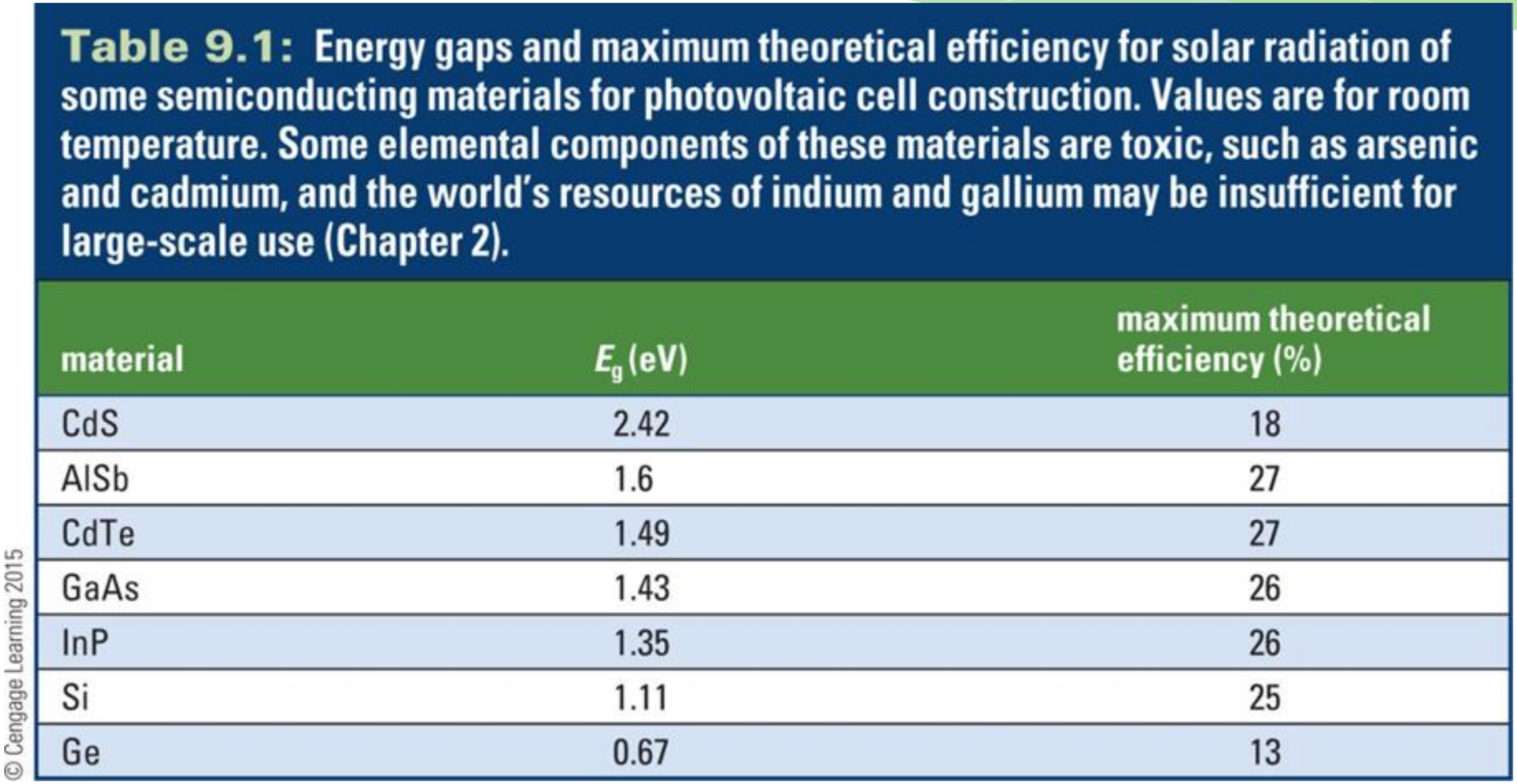


Table 9.1: Energy gaps and maximum theoretical efficiency for solar radiation of some semiconducting materials for photovoltaic cell construction. Values are for room temperature. Some elemental components of these materials are toxic, such as arsenic and cadmium, and the world's resources of indium and gallium may be insufficient for large-scale use (Chapter 2).

material	E_g (eV)	maximum theoretical efficiency (%)
CdS	2.42	18
AlSb	1.6	27
CdTe	1.49	27
GaAs	1.43	26
InP	1.35	26
Si	1.11	25
Ge	0.67	13

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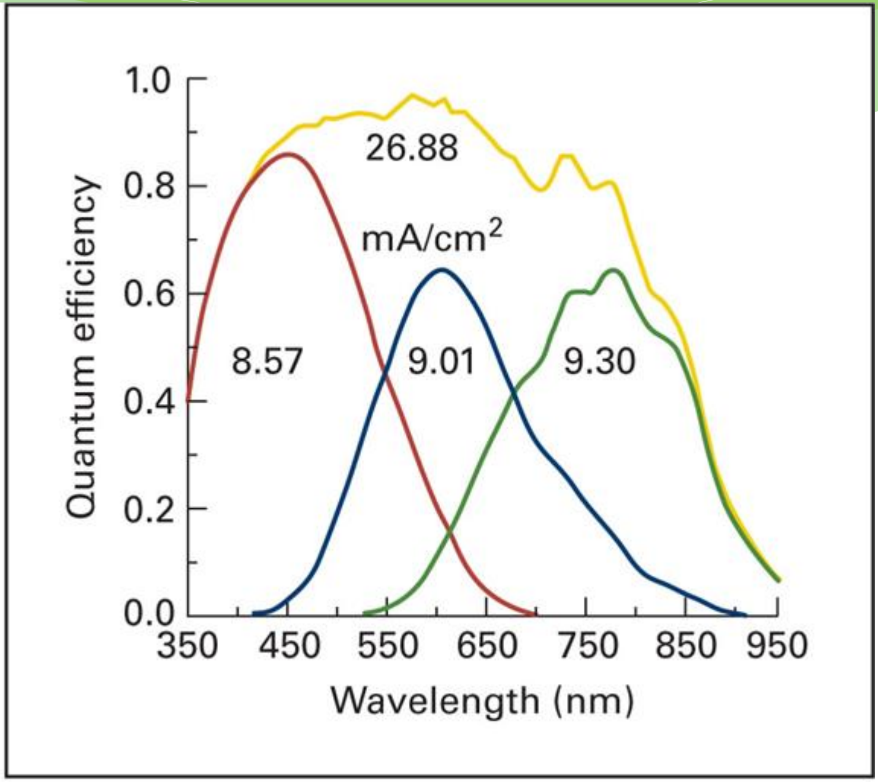
Triple junction devices

Efficiency can be improved for white light by combining devices with spectral response that better covers the range of incident wavelengths.



S. Guha, "High-Efficiency Triple-Junction Amorphous Silicon Alloy Photovoltaic Technology" National Renewable Energy Laboratory, Report NREL/SR-520-26648 (1999)

Spectral responses of the three layers of a triple-junction and the total response.

Cost of photovoltaic electricity

A major difficulty with photovoltaic cells is the cost of electricity compared to other technologies.

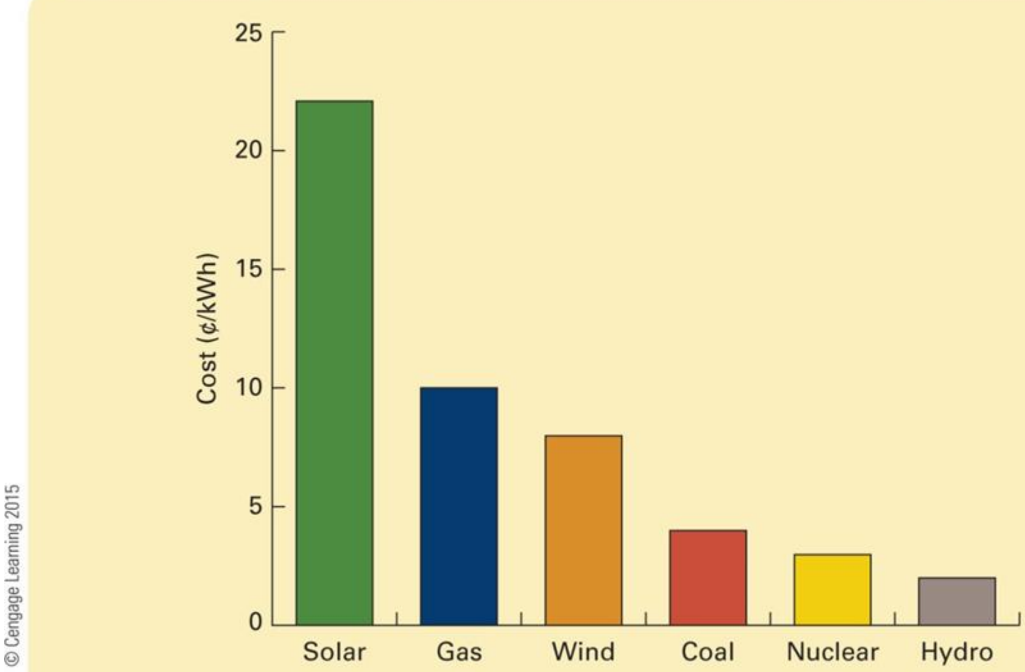


Figure 9.22: Cost per unit energy in 2008 for energy produced by different methods.

Decrease in photovoltaic cost over 30 years

Cost of photovoltaics has continued to decline.

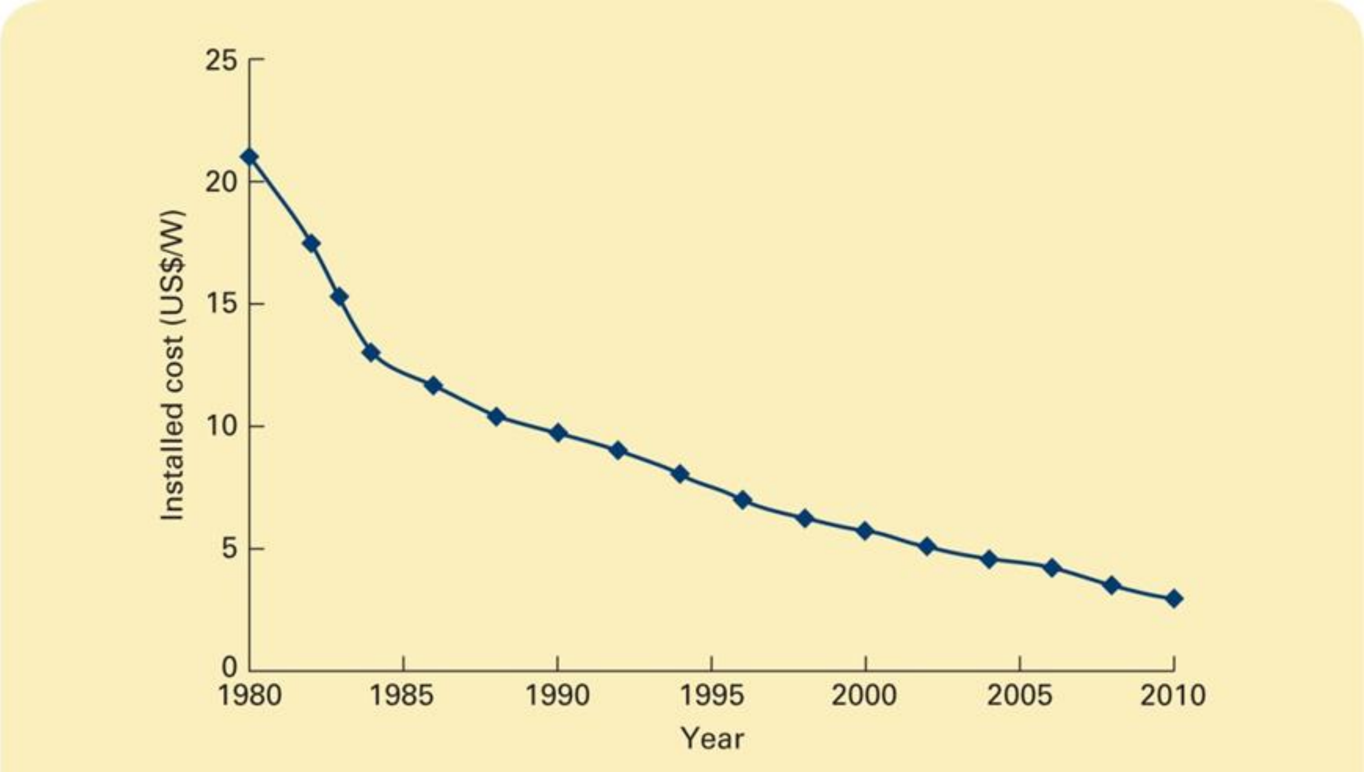


Figure 9.21: Cost per W_e installed for photovoltaic systems in recent years.

Resource considerations

Many current photovoltaic devices utilize materials that are of limited availability (see Chapter 2).

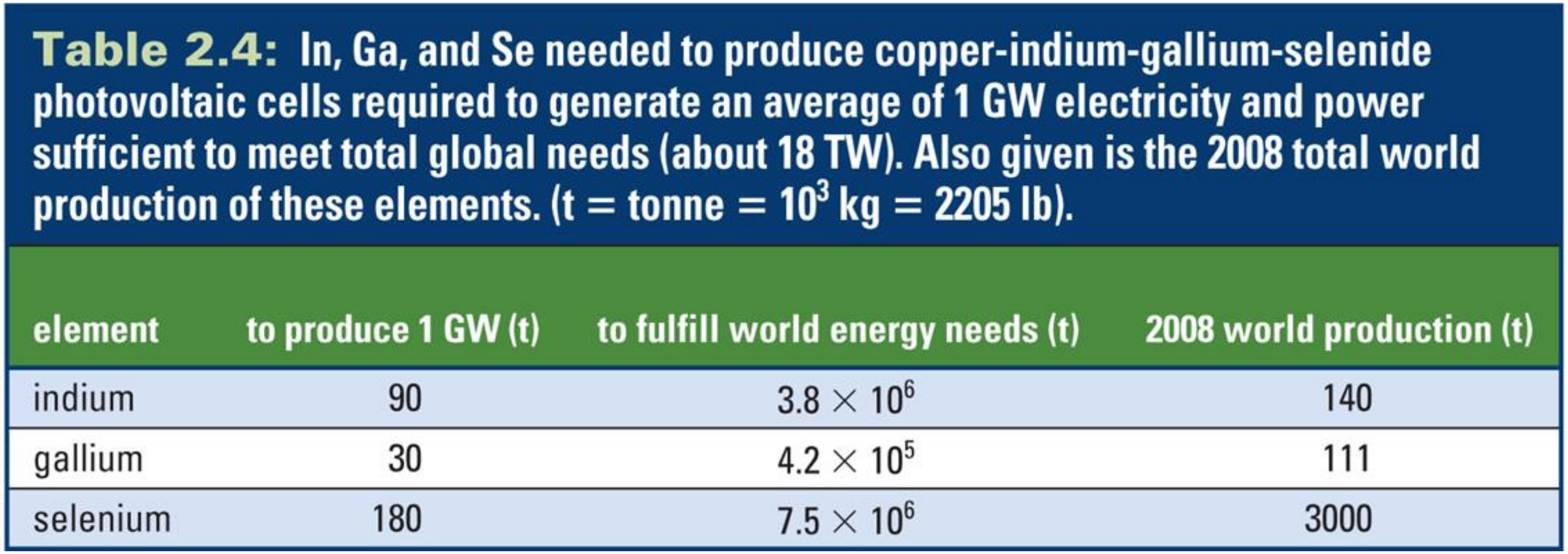


Table 2.4: In, Ga, and Se needed to produce copper-indium-gallium-selenide photovoltaic cells required to generate an average of 1 GW electricity and power sufficient to meet total global needs (about 18 TW). Also given is the 2008 total world production of these elements. (t = tonne = 10^3 kg = 2205 lb).

element	to produce 1 GW (t)	to fulfill world energy needs (t)	2008 world production (t)
indium	90	3.8×10^6	140
gallium	30	4.2×10^5	111
selenium	180	7.5×10^6	3000

Data adapted from "Byproduct Mineral Commodities Used for the Production of Photovoltaic Cells" U.S. Geological Survey, Circular 1365.

Environmental impact of photovoltaics

Low energy density of sunlight requires substantial manufacturing to produce photovoltaic infrastructure (see Chapter 2).

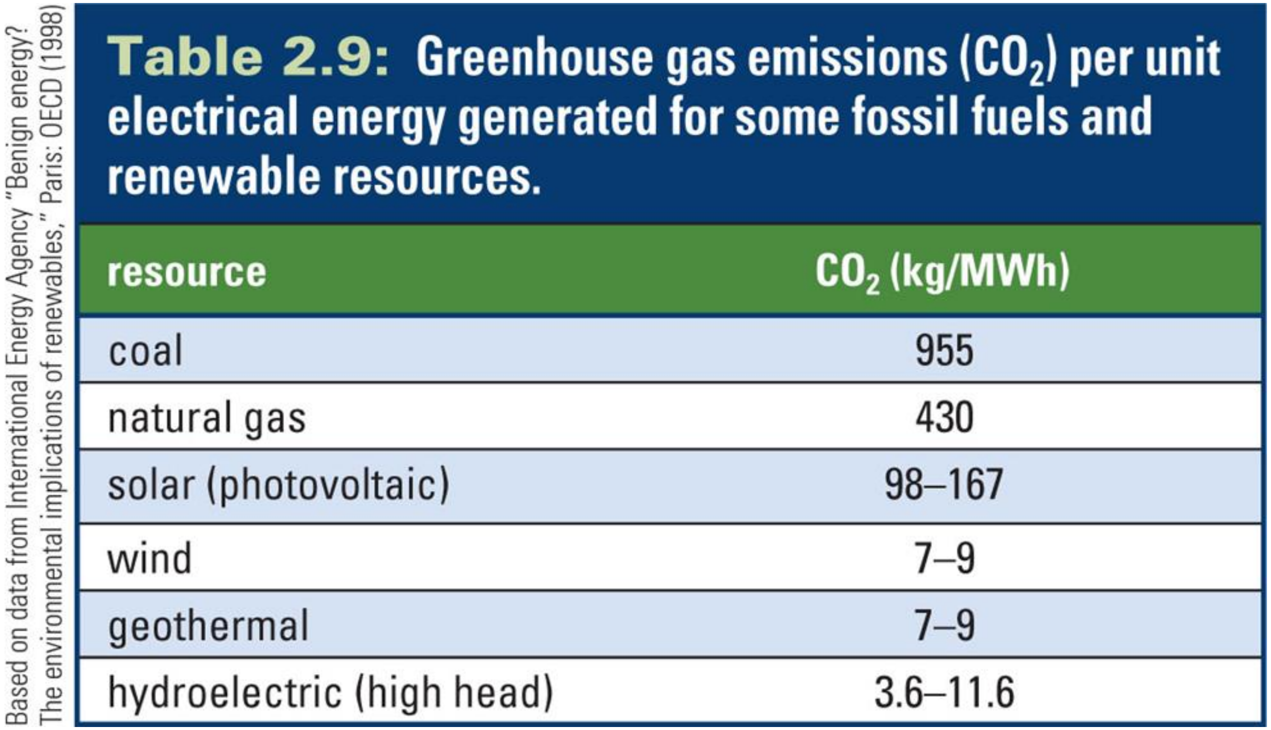


Table 2.9: Greenhouse gas emissions (CO_2) per unit electrical energy generated for some fossil fuels and renewable resources.

resource	CO_2 (kg/MWh)
coal	955
natural gas	430
solar (photovoltaic)	98–167
wind	7–9
geothermal	7–9
hydroelectric (high head)	3.6–11.6

Based on data from International Energy Agency "Benign energy? The environmental implications of renewables," Paris: OECD (1998)

Human risk

Low energy density of sunlight also means significant human risk (see Chapter 6).

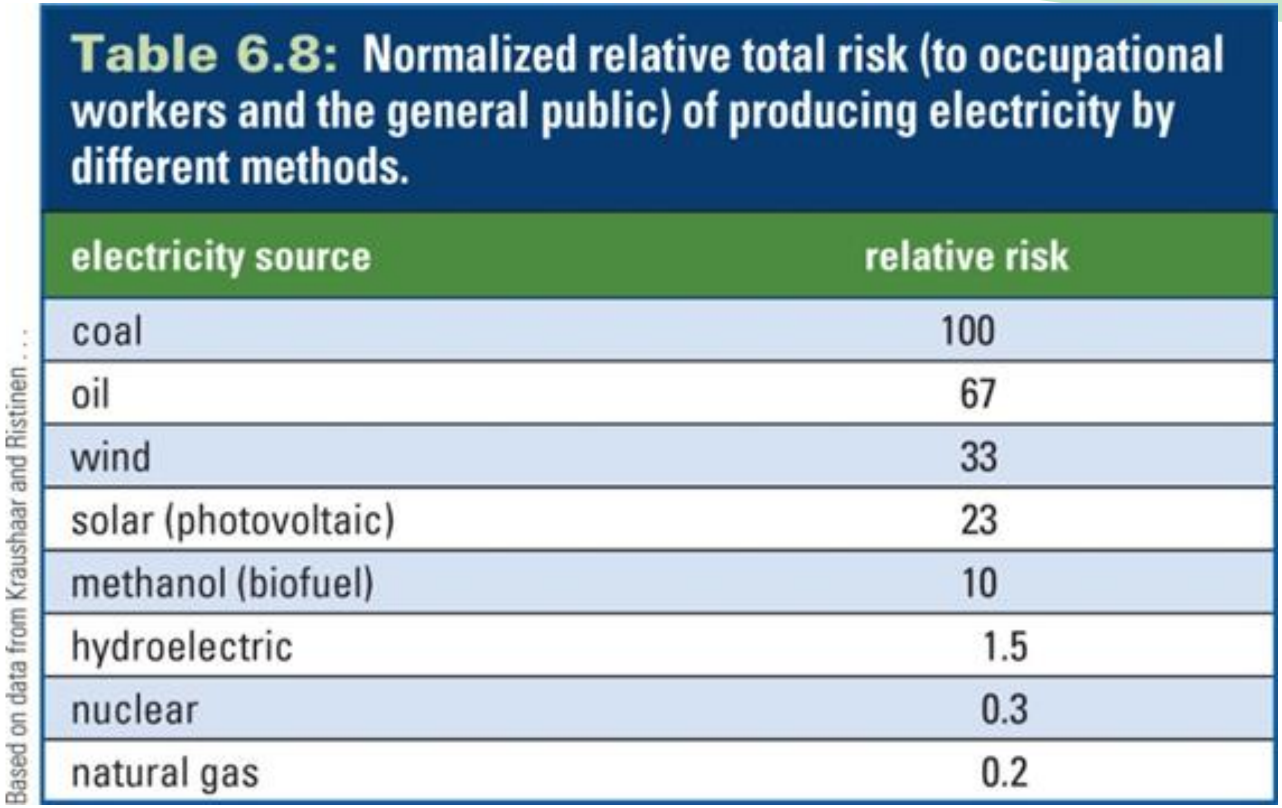


Table 6.8: Normalized relative total risk (to occupational workers and the general public) of producing electricity by different methods.

electricity source	relative risk
coal	100
oil	67
wind	33
solar (photovoltaic)	23
methanol (biofuel)	10
hydroelectric	1.5
nuclear	0.3
natural gas	0.2

Based on data from Kraushaar and Ristinen . . .

Applications of photovoltaic devices

Photovoltaic devices may be of a variety of sizes for different applications

- Small units for portable electronics
- Power for isolated locations
- Residential electric power
- Large installations for grid power

Photovoltaic array for remotely located radio transmitter


Richard A. Dunlap

Figure 9.25: Photovoltaic array for providing power at a remote radio transmitter station.

Photovoltaic panels for residential power

Solar settlement, Freiberg, Germany

© imagebroker/Alamy

Figure 9.26: Photovoltaic solar panels on homes in the Solar Settlement in Freiberg, Germany.

Photovoltaics for grid power

14 $\mathrm{MW_e}$ photovoltaic facility at Nellis Air Force Base, NV

U.S. Air Force photo by Airman 1st Class Nadine Y. Barclay

Figure 9.30: Photovoltaic arrays at Nellis Air Force Base, Nevada.

Global use of photovoltaics

Germany is the leader (on a per capita basis) for photovoltaic use.

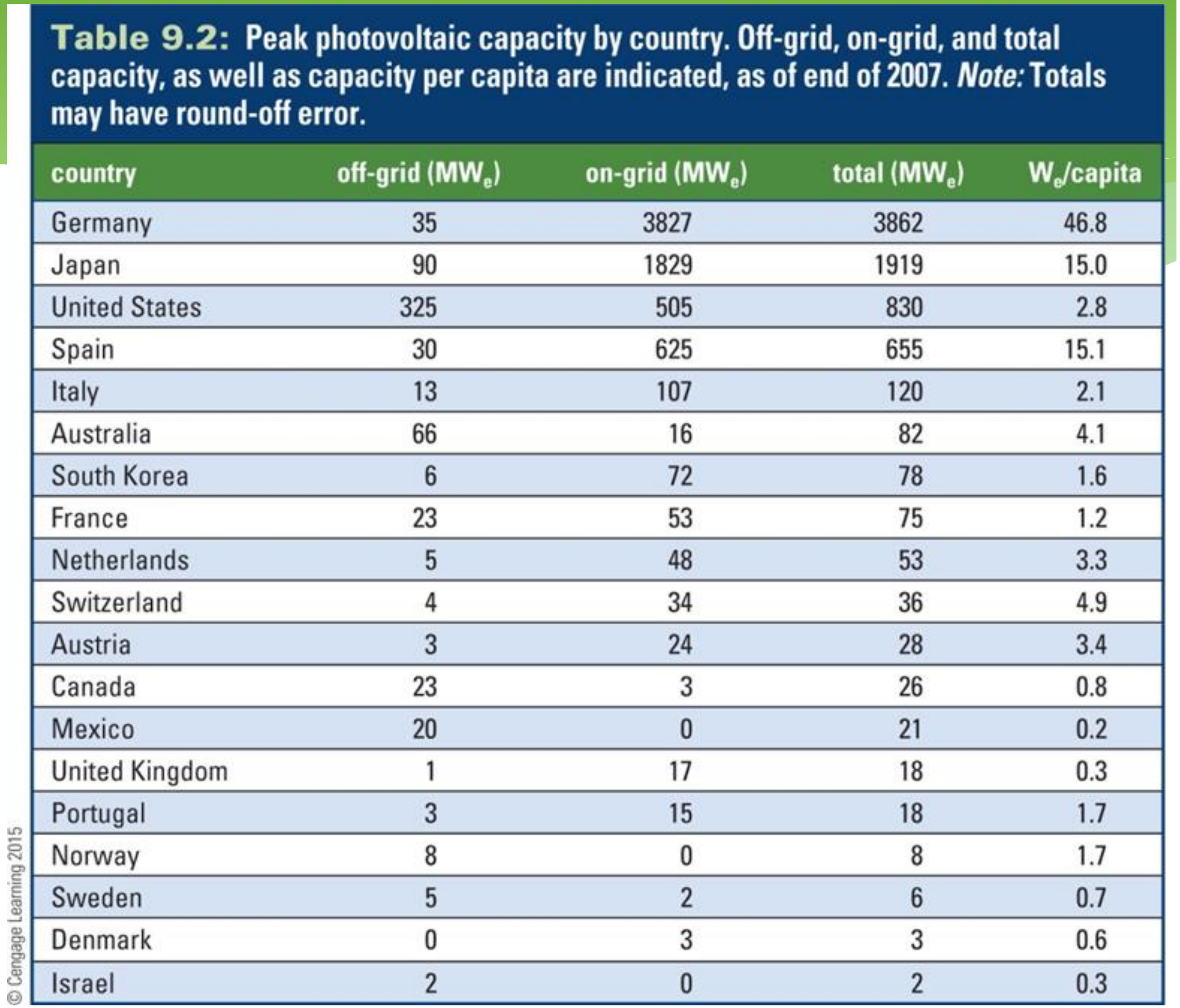


Table 9.2: Peak photovoltaic capacity by country. Off-grid, on-grid, and total capacity, as well as capacity per capita are indicated, as of end of 2007. *Note:* Totals may have round-off error.

country	off-grid ($\mathrm{MW_e}$)	on-grid ($\mathrm{MW_e}$)	total ($\mathrm{MW_e}$)	$\mathrm{W_e}$/capita
Germany	35	3827	3862	46.8
Japan	90	1829	1919	15.0
United States	325	505	830	2.8
Spain	30	625	655	15.1
Italy	13	107	120	2.1
Australia	66	16	82	4.1
South Korea	6	72	78	1.6
France	23	53	75	1.2
Netherlands	5	48	53	3.3
Switzerland	4	34	36	4.9
Austria	3	24	28	3.4
Canada	23	3	26	0.8
Mexico	20	0	21	0.2
United Kingdom	1	17	18	0.3
Portugal	3	15	18	1.7
Norway	8	0	8	1.7
Sweden	5	2	6	0.7
Denmark	0	3	3	0.6
Israel	2	0	2	0.3

Solar power resources

Solar power is the only renewable source that can easily fulfill world needs.

Total insolation on the earth's surface 9×10^{16} W.

Total current world power use 1.8×10^{13} W.

At a photovoltaic efficiency of 15% world power requirements are fulfilled by 0.14% of insolation.

Comparison of land requirements for solar to fulfill all primary energy needs for the U.S. and Canada

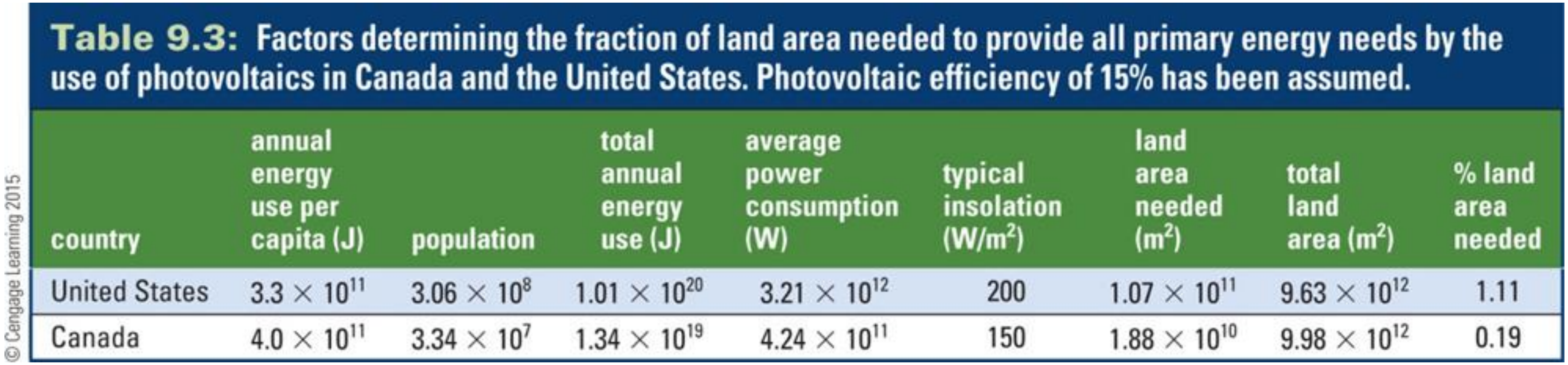


Table 9.3: Factors determining the fraction of land area needed to provide all primary energy needs by the use of photovoltaics in Canada and the United States. Photovoltaic efficiency of 15% has been assumed.

country	annual energy use per capita (J)	population	total annual energy use (J)	average power consumption (W)	typical insolation (W/m^2)	land area needed (m^2)	total land area (m^2)	% land area needed
United States	3.3×10^{11}	3.06×10^{8}	1.01×10^{20}	3.21×10^{12}	200	1.07×10^{11}	9.63×10^{12}	1.11
Canada	4.0×10^{11}	3.34×10^{7}	1.34×10^{19}	4.24×10^{11}	150	1.88×10^{10}	9.98×10^{12}	0.19

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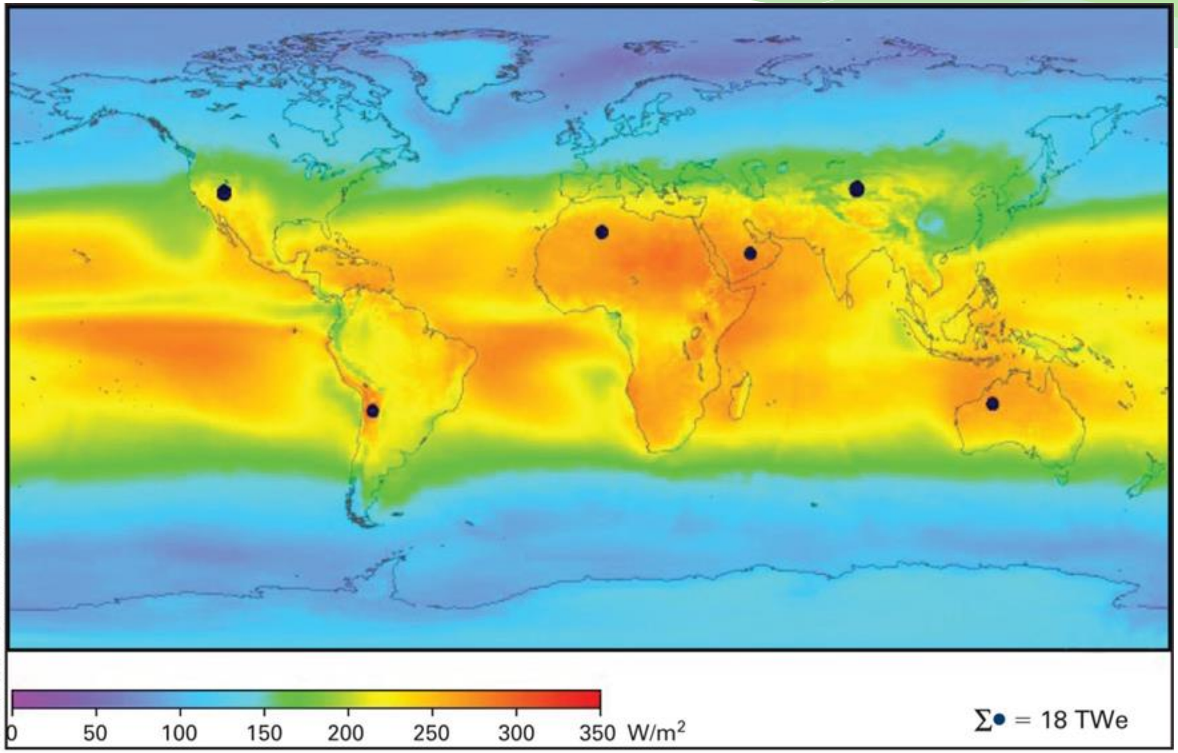
World energy requirements

Six 300×300 km^2 arrays would fulfill all world needs



Matthais Loster, http://www.ez2c.de/ml

Figure 9.31: Land area needed to supply the world's energy needs from solar. Average insolation is illustrated.

Advantages of solar photovoltaics

Advantages

- Easily fulfills world power needs
- Indefinitely renewable
- Relatively low environmental impact

Disadvantages of solar photovoltaics

Disadvantages

- Currently expensive per unit energy produced
- Limits land use
- Some environmental impact due to low energy density
- Concerns over availability of materials

Summary

- Solar radiation can be converted into electricity through heat engines or photovoltaics
- Applications of heat engines for solar electricity have been limited
- Photovoltaic devices are semiconducting diodes that produce currents when irradiated with photons
- Photovoltaic systems cover a wide range of sizes
- Small devices are suitable for powering watches or calculators
- Large systems provide power for the grid
- Solar energy is the only renewable source that can easily fulfill all primary energy needs worldwide