General Chemistry (CH101): Chemistry around Us

Department of Chemistry

KAIST

Chapter 7 Energy from Alternative Sources

- How much energy is used in the world?
- What is radioactivity, and what are some applications for radioactive elements in energy production?
- How do nuclear power plants produce electricity, and what are their environmental impacts relative to fossil-fuel power plants?
- What is solar energy?
- What are other types of renewable energy sources, and how are they assessed in terms of environmental impacts?

Reflect

Chapter 7 video

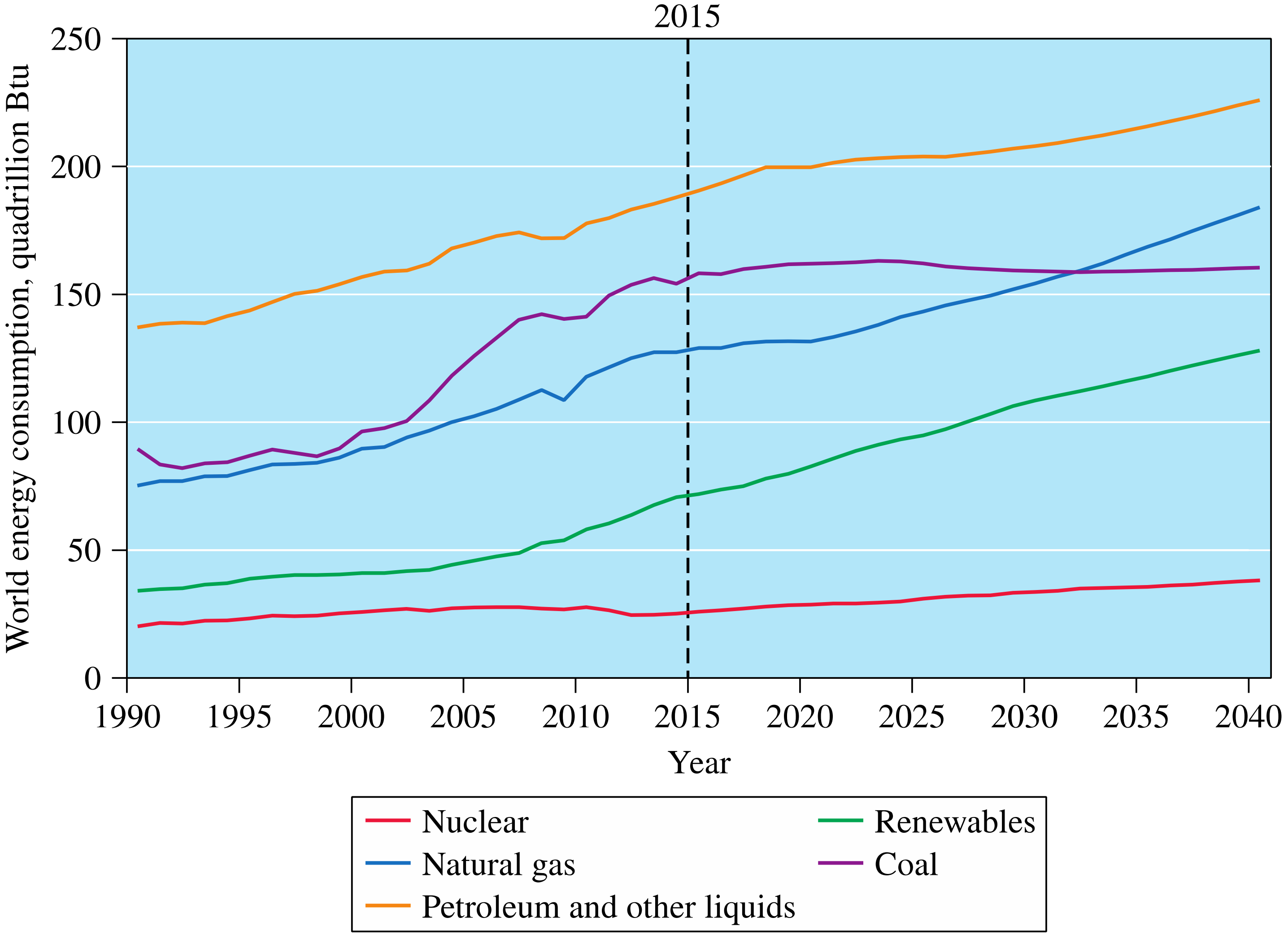
Where Does Your Energy Come From?
Watch the chapter opening video. Then, visit the U.S. Energy Information Administration's website to find a state-by-state comparison of energy production and consumption.

a. Choose one state or territory and select it on the map. Scroll down to look at the information provided. From which sources does this state or territory get the energy that it consumes? What types of energy sources are used to produce energy in this state? How do these sources differ?

b. Choose a second state and make a comparison with the state you chose in part **a**.

c. Of all the sources of energy you found in parts **a** and **b**, which are derived from fossil fuels? Which are not? This chapter will explore energy sources that are alternatives to fossil fuels.

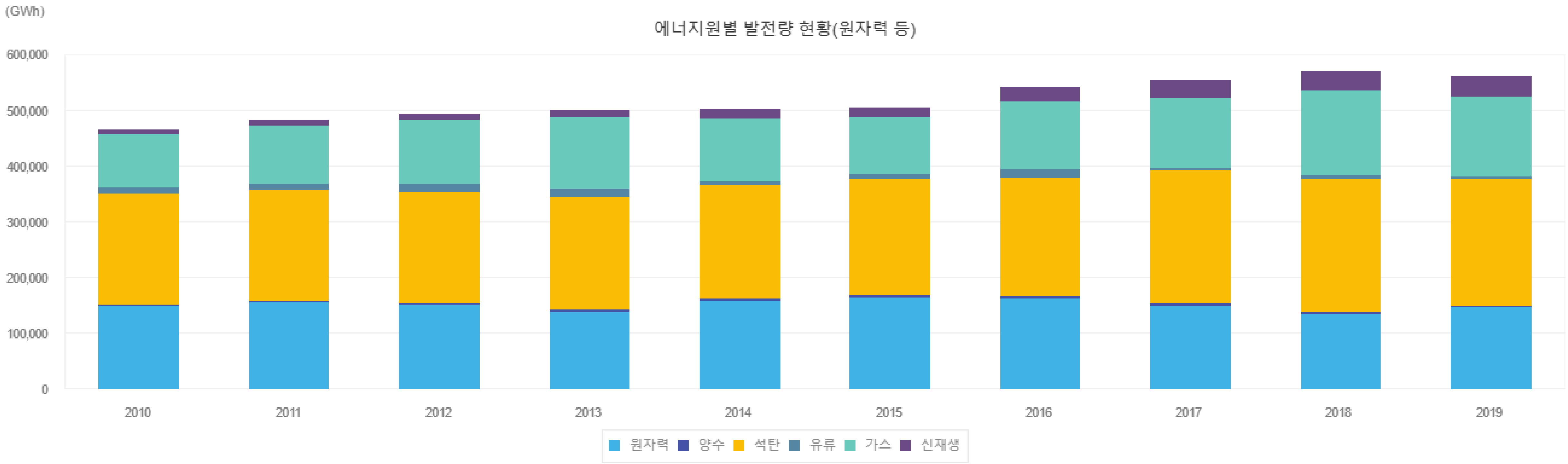
Sources of Electricity in US



- Electricity generation is driven by the availability of natural resources.

Source: U.S. Energy Administration, International Energy Outlook 2017.

Sources of Electricity in Korea



	Nuclear	Coal	LNG	Renewable	Oil	Water	Others
2022 (%)	29.6	32.5	27.5	8.9	0.3	0.6	0.5
2018 (%)	23.4	41.9	26.8	6.2	1.0	0.7	0
2013 (%)	26.8	38.9	24.7	2.8	2.9	0.8	3.1
2009 (%)	34.1	44.7	15.0	1.1	2.9	0.7	1.5

[지표서비스 | e-나라지표 (index.go.kr)]

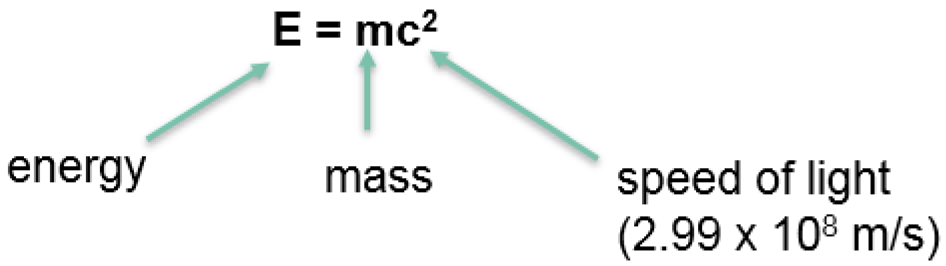
Nuclear Fission

Nuclear fission is the splitting of a large nucleus into smaller ones with the release of energy.

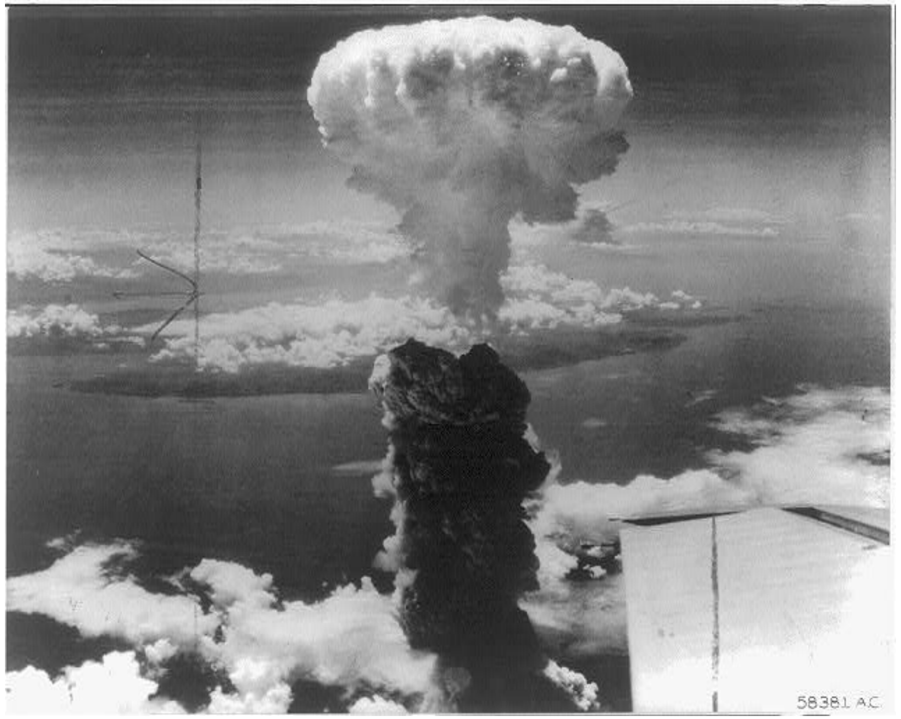
Why?

Energy is released because the total mass of products is slightly less than total mass of reactants.

This 'missing' mass (about 0.1 percent of the original mass) has been converted into energy according to Einstein's famous equation:



How Much Energy Is Released?



$$E = \Delta mc^2$$

For the fission of 1.0 kg of U-235, the mass of products is 0.1% less than the original U-235. Therefore,

$$\Delta m = 1 \times 10^{-3} \text{kg}$$

$$E = (1.0 \times 10^{-3} \text{kg})(3 \times 10^{8} \text{m/s})^2$$

$$E = (1.0 \times 10^{-3} \text{kg})(9.0 \times 10^{16} \text{m}^2/\text{s}^2)$$

$$E = 9.0 \times 10^{13} kg\ m^2/s^2 = 9.0 \times 10^{13} J$$

$$(\text{recall}: 1\ kg\ m^2 s^{-2} = 1 \text{ joule})$$

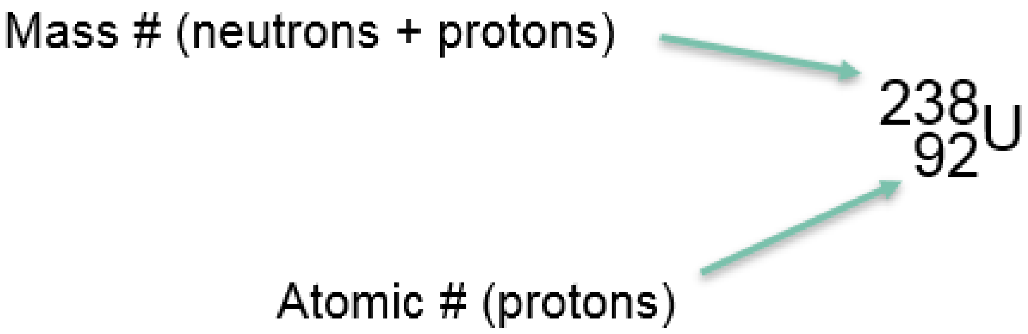
This is equivalent to 22,000 tons $(2 \times 10^{7} \text{kg})$ of the explosive TNT!

It is possible to obtain a tremendous amount of energy from a very small amount of matter traveling at the speed of light, whether in a power plant or in a weapon.

Library of Congress Prints & Photographs Division [LC-USZ62-36452]

Isotopes

Use both mass number and atomic number for isotopes. For instance, U-238 is written as:



For a neutral atom:

protons = # electrons

Table 7.1	Comparing Isotopes of Uranium				
Name	**Number of Protons**	**Atomic Number**	**Mass Number**	**Number of Neutrons**	**Atomic Symbol**
Uranium-235	92	92	235	235 – 92 = 143	$^{235}_{92}U$
Uranium-238	92	92	238	238 – 92 = 146	$^{238}_{92}U$

[Isotopes and atomic mass]

Isotope Practice

For the isotope $^{119}_{50}X$, what is the element X?

How many protons, neutrons, and electrons in $^{12}_{6}C$?

How many protons, neutrons, and electrons in $^{35}_{17}Cl$?

Nuclear Reactions

Nuclear fission is initiated by neutrons:

$$ {}^{1}_{0}\mathrm{n} + {}^{235}_{92}\mathrm{U} \rightarrow \left[{}^{236}_{92}\mathrm{U} \right] \rightarrow {}^{141}_{56}\mathrm{Ba} + {}^{92}_{36}\mathrm{Kr} + 3\ {}^{1}_{0}\mathrm{n} $$

For nuclear equations, the superscripts and subscripts on both sides of the arrow must add up to the same total:

	Left	Right
Superscripts:	1 + 235 = 236	141 + 92 + (3 × 1) = 236
Subscripts:	0 + 92 = 92	56 + 36 + (3 × 0) = 92

Chain Reactions

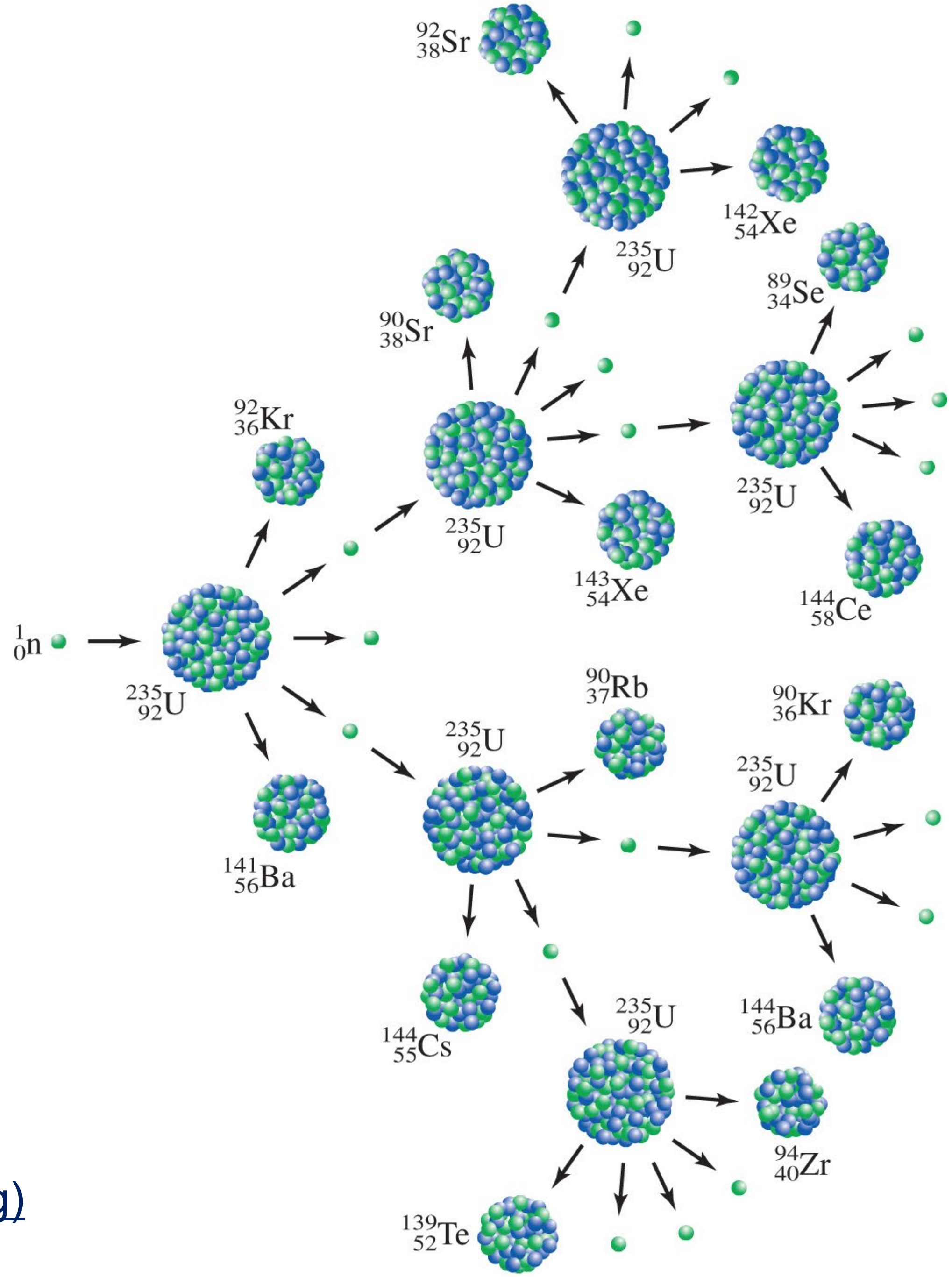
Nuclear fission is initiated by neutrons:

$$ {}^{1}_{0}\text{n} + {}^{235}_{92}\text{U} \rightarrow \left[{}^{236}_{92}\text{U}\right] \rightarrow {}^{141}_{56}\text{Ba} + {}^{92}_{36}\text{Kr} + 3\,{}^{1}_{0}\text{n} $$

1 neutron — 3 neutrons

- Each of the generated neutrons can initiate the fission of U-235, which will generate another 3 neutrons, and so on.
- The *critical mass* of U-235 is 15 kg (33 lb).

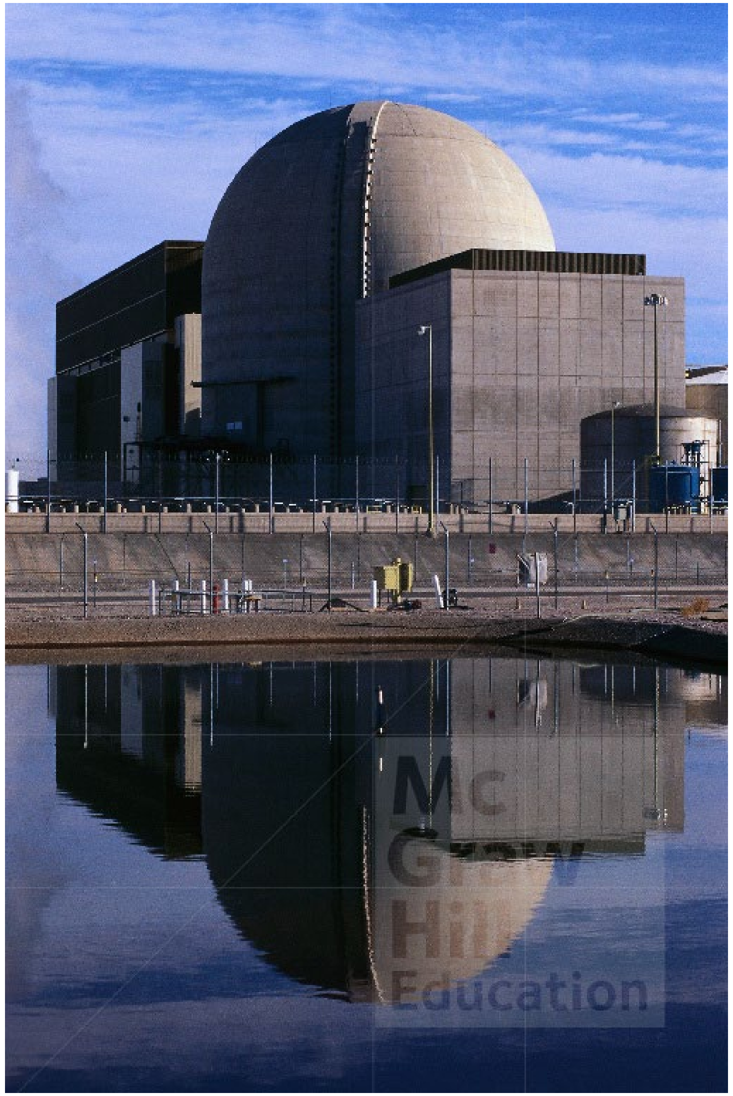
[Chain Reactions - American Chemical Society (acs.org)]



The Nuclear Test "Turk"

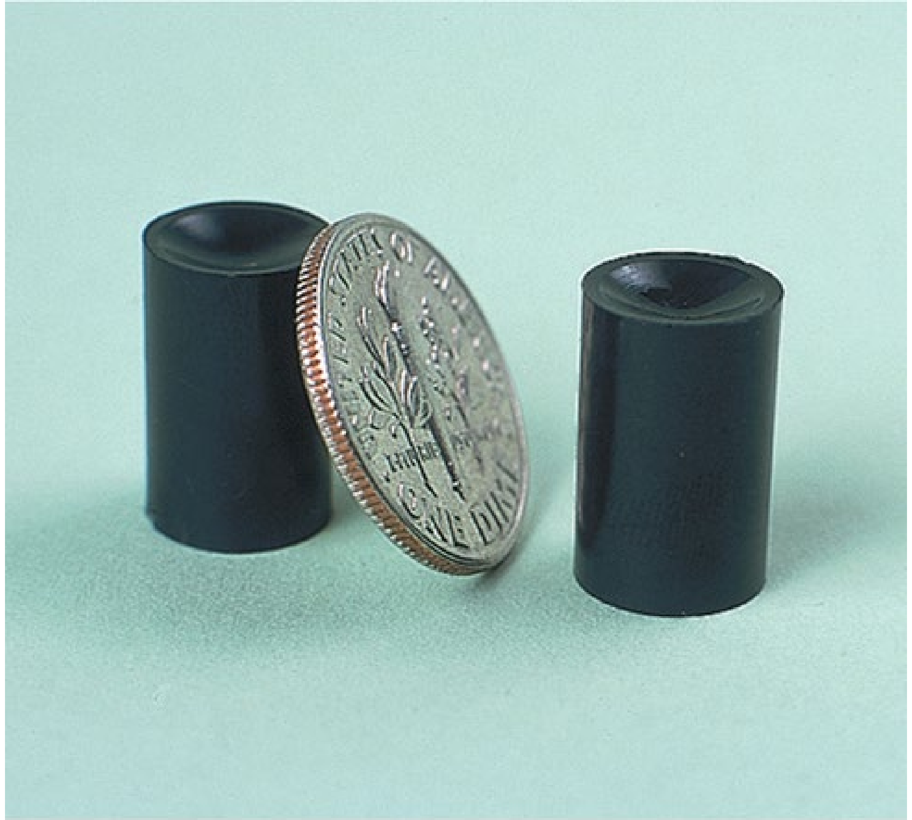
1955 Navada, more than five times than the bomb at Hiroshima

Nuclear Power

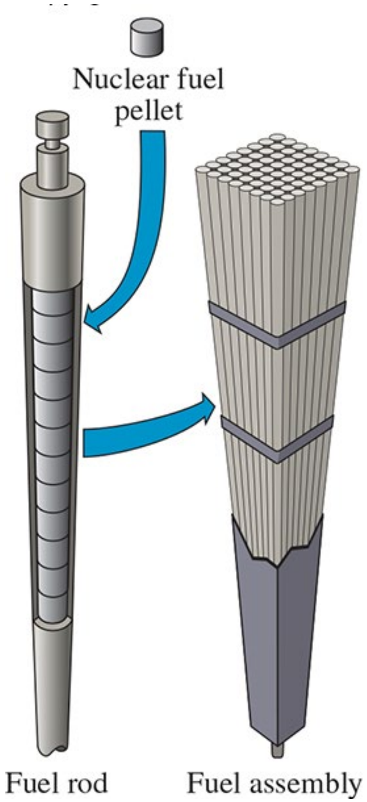


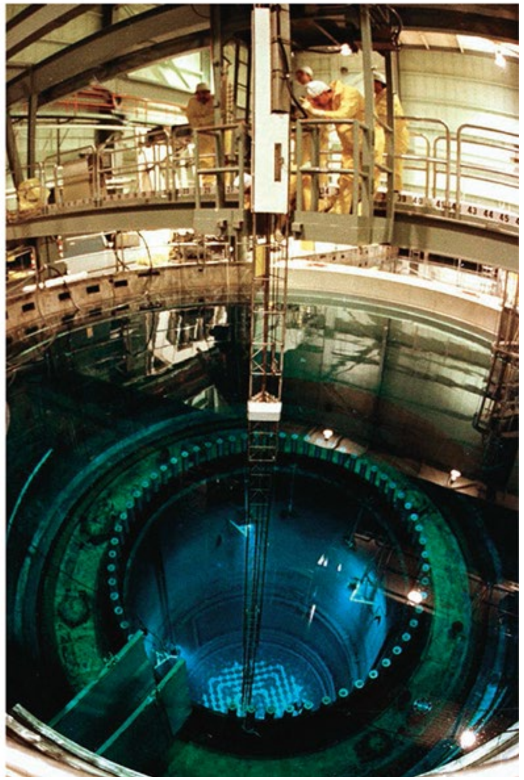
A nuclear reactor is a device in which nuclear chain reactions are initiated, controlled, and sustained at a steady rate (as opposed to a nuclear explosion, where the chain reaction occurs in a split second).

The Uranium Fuel Source



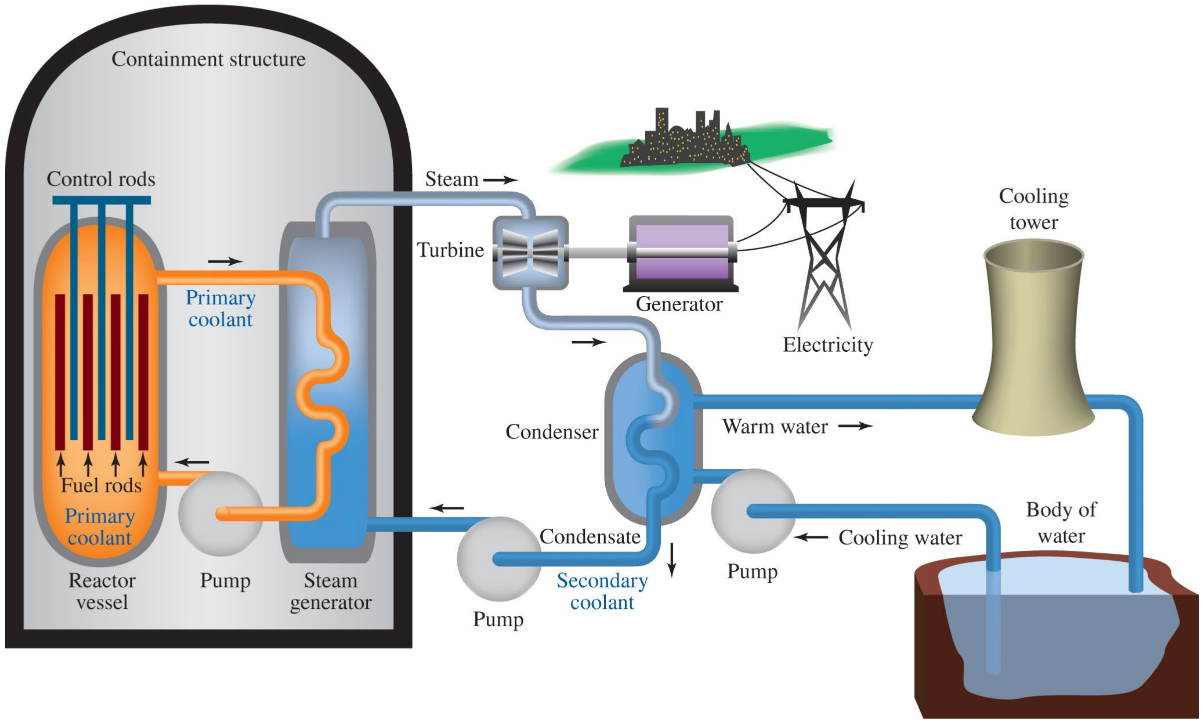
The uranium fuel in the reactor core is uranium(IV) oxide, UO_2, comparable in height to the diameter of a U.S. dime.



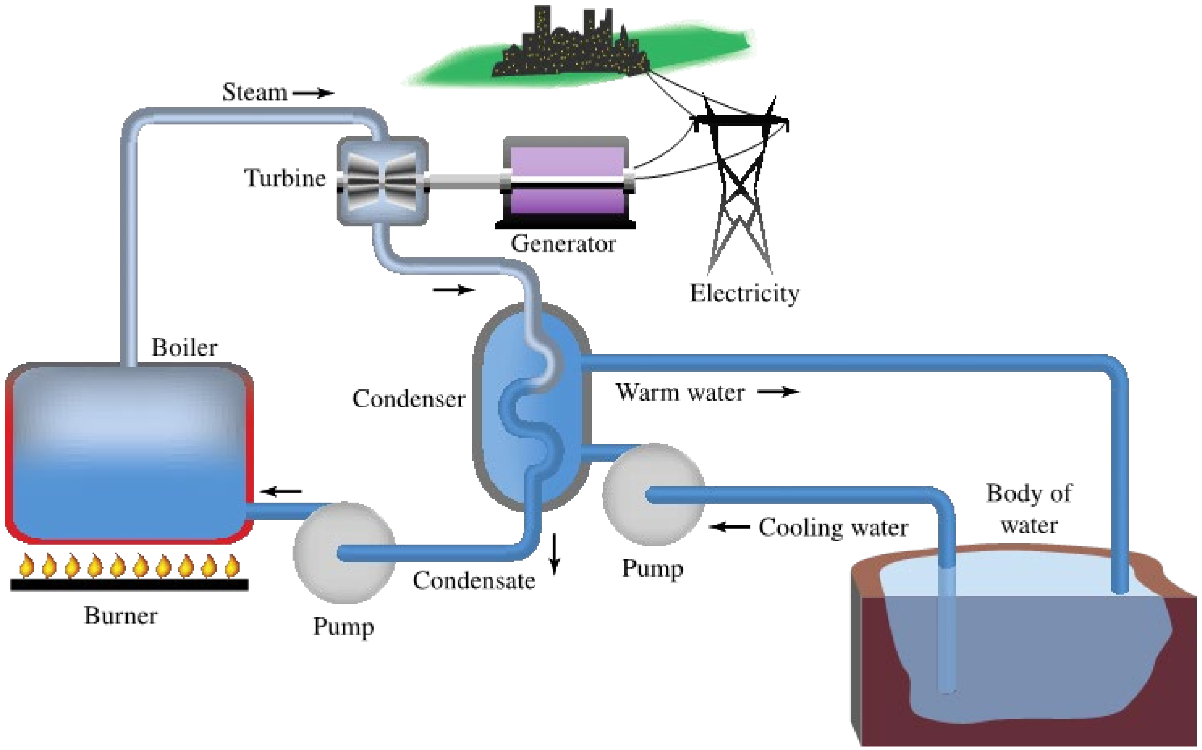


These pellets are placed end-to-end in tubes composed of an alloy of zirconium and other metals, which are grouped into stainless steel-clad bundles.

Nuclear versus Conventional Power Plants



Nuclear Power Plant



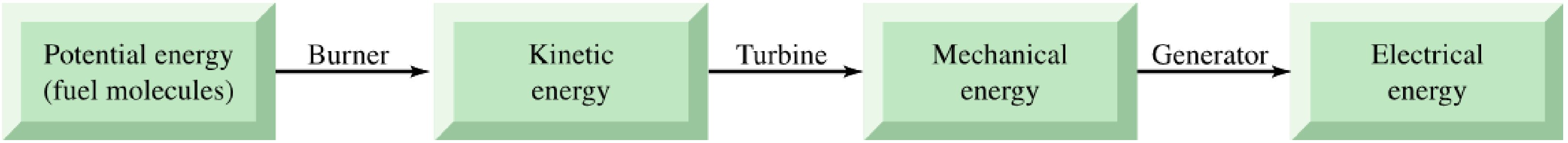
Fossil Fuel Power Plant

Source: United States Nuclear Regulatory Commission.

Nuclear Power Plant

The Sequoyah nuclear power plant in Tennessee.

Electricity Generation



Electricity generated by nuclear and fossil fuels is identical. Potential energy is converted to kinetic energy when a fuel is combusted. The kinetic energy turns the turbine, which corresponds to mechanical energy. Electrical energy is produced via an electrical generator.

The rate of energy production is **power**; a common unit of power is joule per second, J/s, or **watt**.

Single nuclear reactors have a maximum power capacity between 500 to 1300 megawatts, MW, as compared to 600 MW for typical coal-fired power plants.

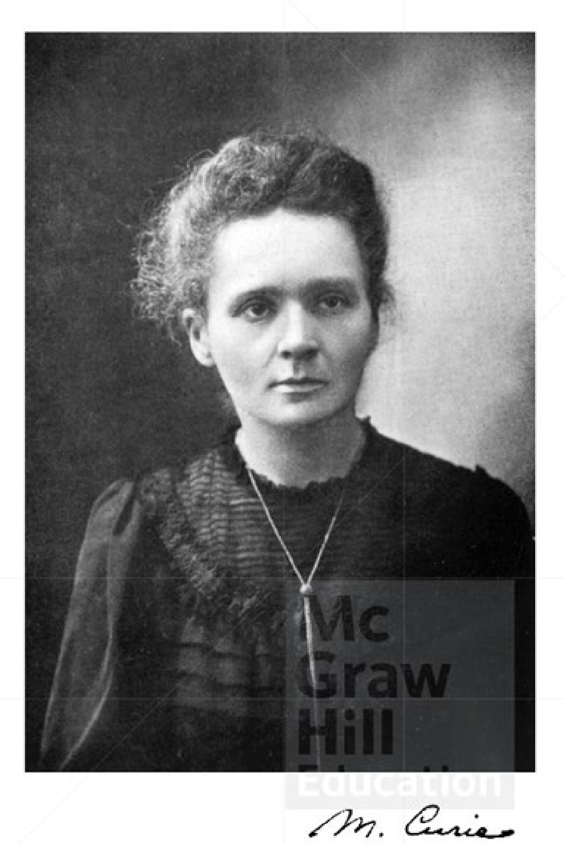
$$\text{Note : a MW} = 1 \times 10^6 \text{ watts}$$

열린원전운영정보 - 한국수력원자력 (khnp.co.kr)

Radioactivity

In 1899, Marie Sklodowska Curie applied the term **radioactivity** to the spontaneous emission of radiation by certain elements.

Marie Curie won two Nobel Prizes—one in chemistry, the other in physics—for her research on radioactive elements.



Photos.com/Getty Images

Types of Nuclear Radiation

Radioactivity includes alpha, beta, and gamma rays:

Table 7.2		Types of Nuclear Radiation		
Name	**Symbol**	**Composition**	**Charge**	**Change to the Parent Nucleus**
alpha	$^{4}_{2}He$ or α	2 protons 2 neutrons	2+	mass number decreases by 4 atomic number decreases by 2
beta	$^{0}_{-1}e$ or β	1 electron	1–	mass number does not change atomic number increases by 1
gamma	$^{0}_{0}\gamma$ or γ	photon	0	no change in either the mass number or the atomic number

Gamma rays are a part of the electromagnetic spectrum, with more energy (shorter wavelength) than X-rays.

“Radiation”?

Your Turn 7.10 “Radiation”

For each sentence, use the context to decipher whether the speaker is referring to nuclear or electromagnetic radiation.

a. “Name a type of radiation that has a shorter wavelength than visible light.”

b. “The gamma radiation from cobalt-60 can destroy a tumor.”

c. “Watch out for UV rays! If you have lightly pigmented skin, this radiation may cause a sunburn.”

d. “Rutherford detected the radiation emitted by uranium.”

Neutron Generation

One way to generate neutrons is to use plutonium-238, beryllium-9, and alpha (α) particles:

alpha (α) particle

$$^{238}_{94}Pu \rightarrow {}^{234}_{92}U + {}^{4}_{2}He$$

$$^{4}_{2}He + {}^{9}_{4}Be \rightarrow {}^{12}_{6}C + {}^{0}_{0}\gamma + {}^{1}_{0}n$$

alpha (α) particle

gamma radiation

neutron

Radioactive Decay [1]

$$^{238}_{92}U \rightarrow ^{234}_{90}Th + ^{4}_{2}He \text{ (alpha emission)}$$

$$^{234}_{90}Th \rightarrow ^{234}_{91}Pa + ^{0}_{-1}e \text{ (beta emission)}$$

Beta emission:

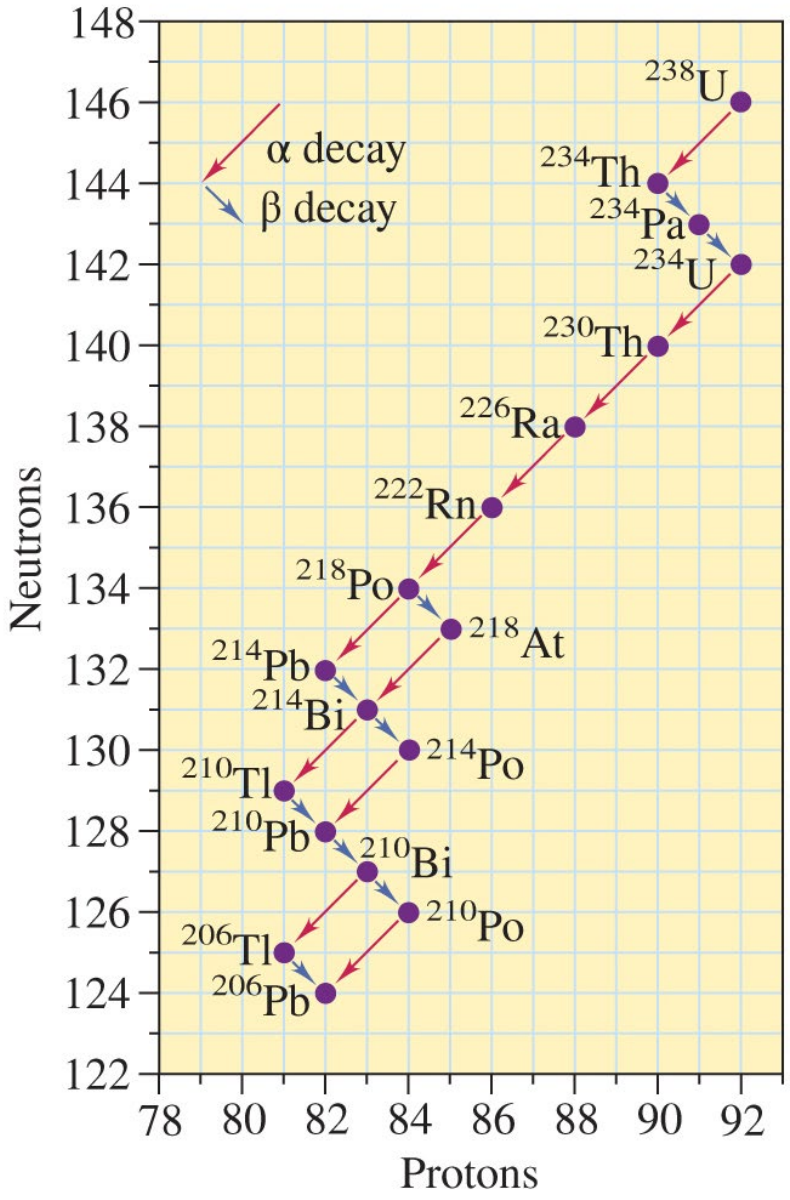
$$^{1}_{0}n \rightarrow ^{1}_{1}P + ^{0}_{-1}e$$

loss of an electron balanced by formation of a proton.

Wilson Cloud Chamber

We put a small lump of Uranite in a Wilson Cloud Chamber full of Ethanol vapor. The lines are the alpha and beta particle ejected due to radioactive decay.

Radioactive Decay



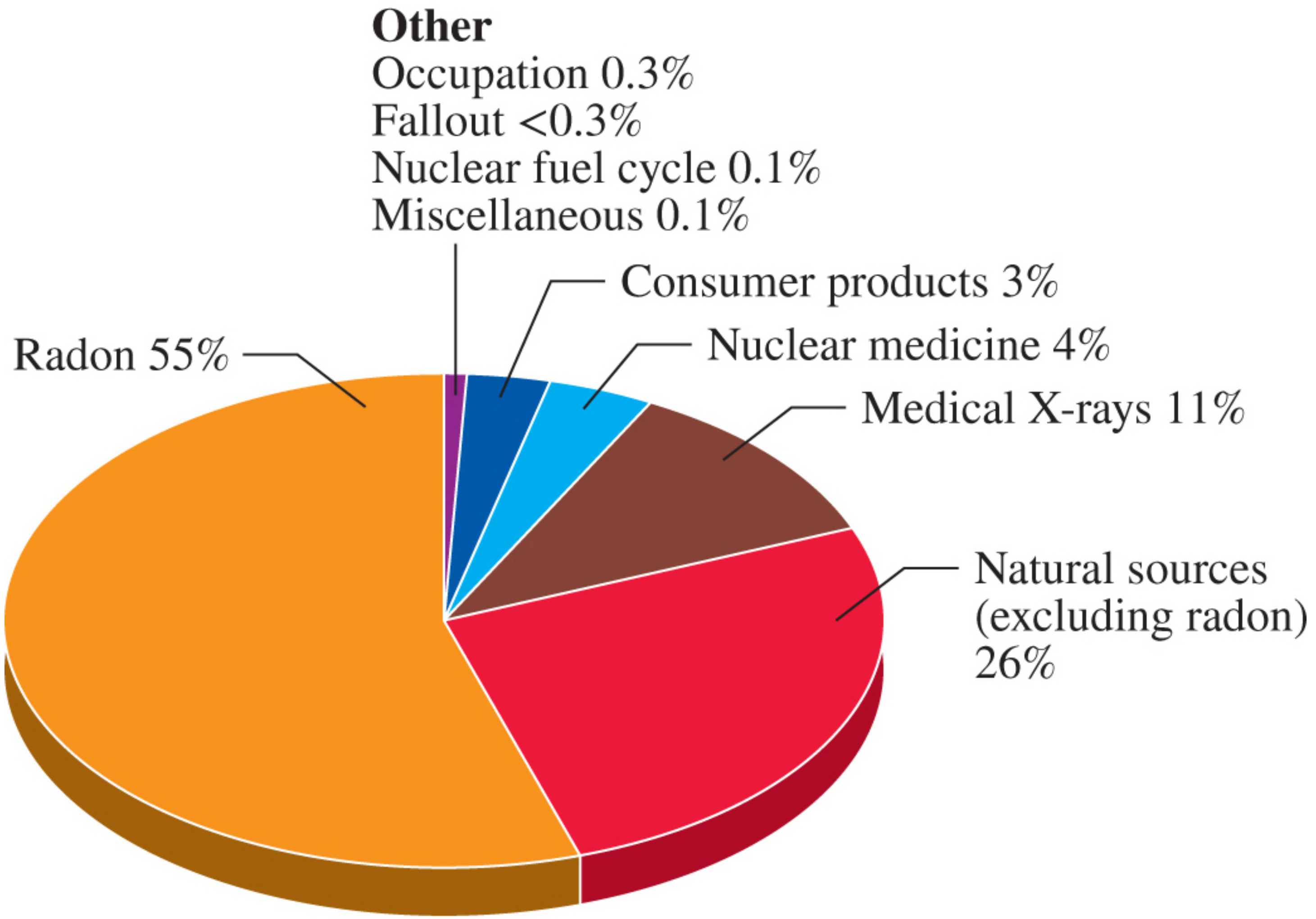
Radioactive isotopes undergo decay until they reach a stable species.

All isotopes of all elements with atomic number 84 (Po) and higher are radioactive.

Radioactivity & You: Sources

Ionizing radiation: X-rays and nuclear radiation that can remove electrons from atoms/molecules with which they collide.

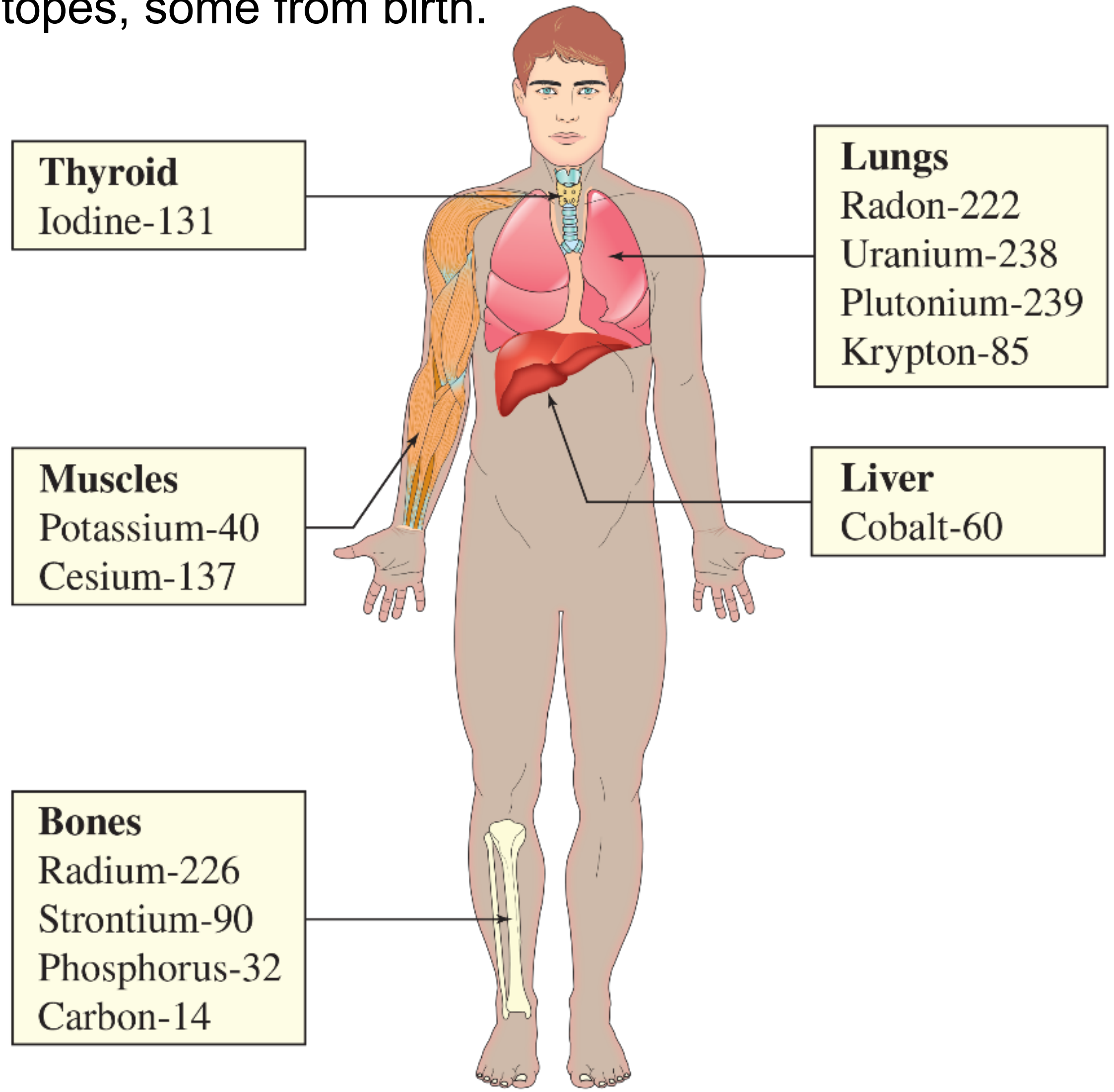
Background radiation: Our world naturally contains radioactive substances



<집중1> 유성온천 '우라늄·라돈' 검출 논란…실태조사 필요 | KBS 뉴스

Radioactivity & You: Body Accumulation

- All humans have internal radiation, which is mainly from the accumulation of radioactive isotopes, some from birth.



Radioactivity & You: Annual Dose

- **Annual Dose:** a measure of the damage that occurs to human tissue when the dose is absorbed.
- **rem** = "roentgen equivalent man": Q × number of **rads**, where Q is a relative biological effectiveness factor.
- 1 **sievert** (Sv) = 100 rem.
- **rad** = "radiation absorbed dose": absorption of 0.01 J of radiant energy/kg tissue.

Dose (Sv)	Dose (rem)	Likely Effect
0 to 0.25	0 to 25	No observable effect
0.25 to 0.50	25 to 50	White blood cell count decreases slightly
0.50 to 1.00	50 to 100	Significant drop in white blood cell count, lesions
1.00 to 2.00	100 to 200	Nausea, vomiting, loss of hair
2.00 to 5.00	200 to 500	Hemorrhaging, ulcers, possible death
5.00	>500	Death

Your Radiation Dose

Your Turn 7.12 Your Annual Ionizing Radiation Dose.

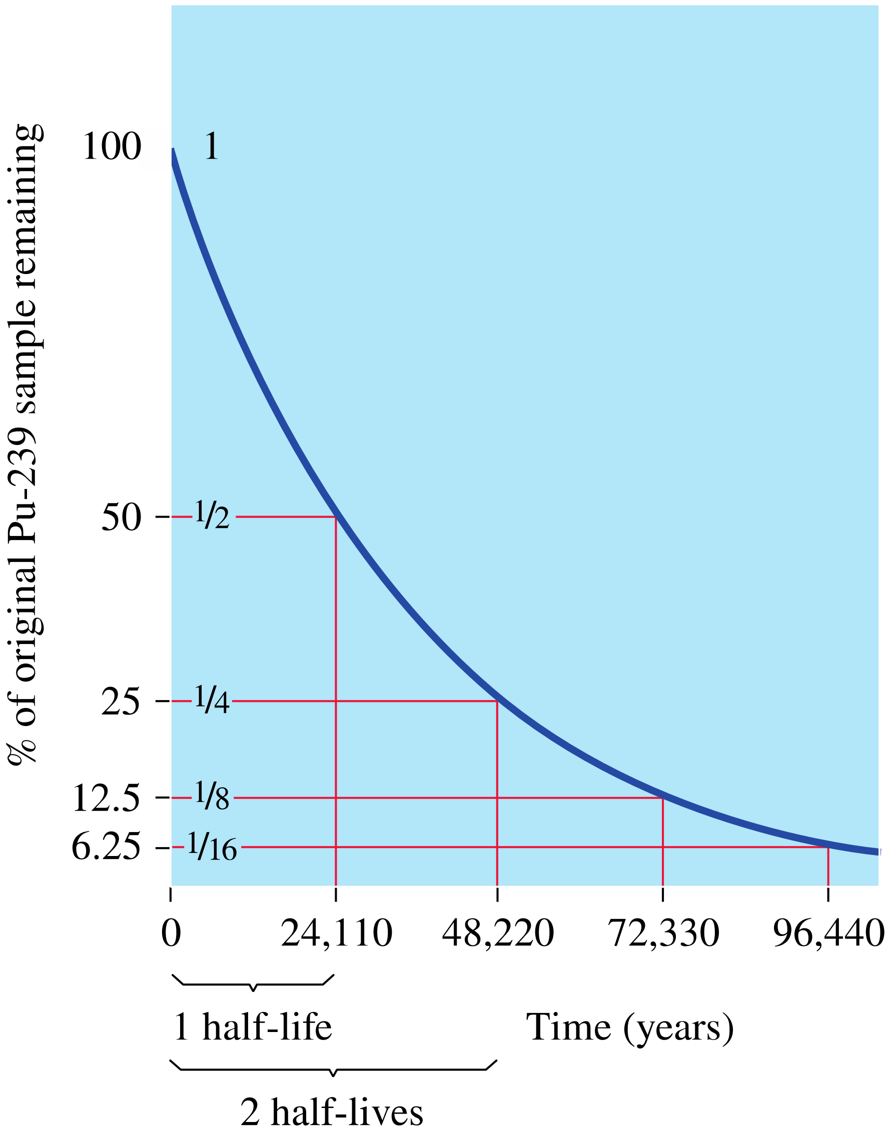
Explore EPA's Rad Town website, which demonstrates the various sources of radiation that we are exposed to on a daily basis. Using the U.S. Nuclear Radiation Commission (NRC) radiation calculator, determine your personal annual radiation dose.

a. How does your annual dosage compare to the annual dosages of others in your class, or to the average level of radiation exposure in the U.S.?

b. How do geographic factors affect your annual radiation dose?

c. How could you adjust your lifestyle to reduce exposure to ionizing radiation?

Half-Life



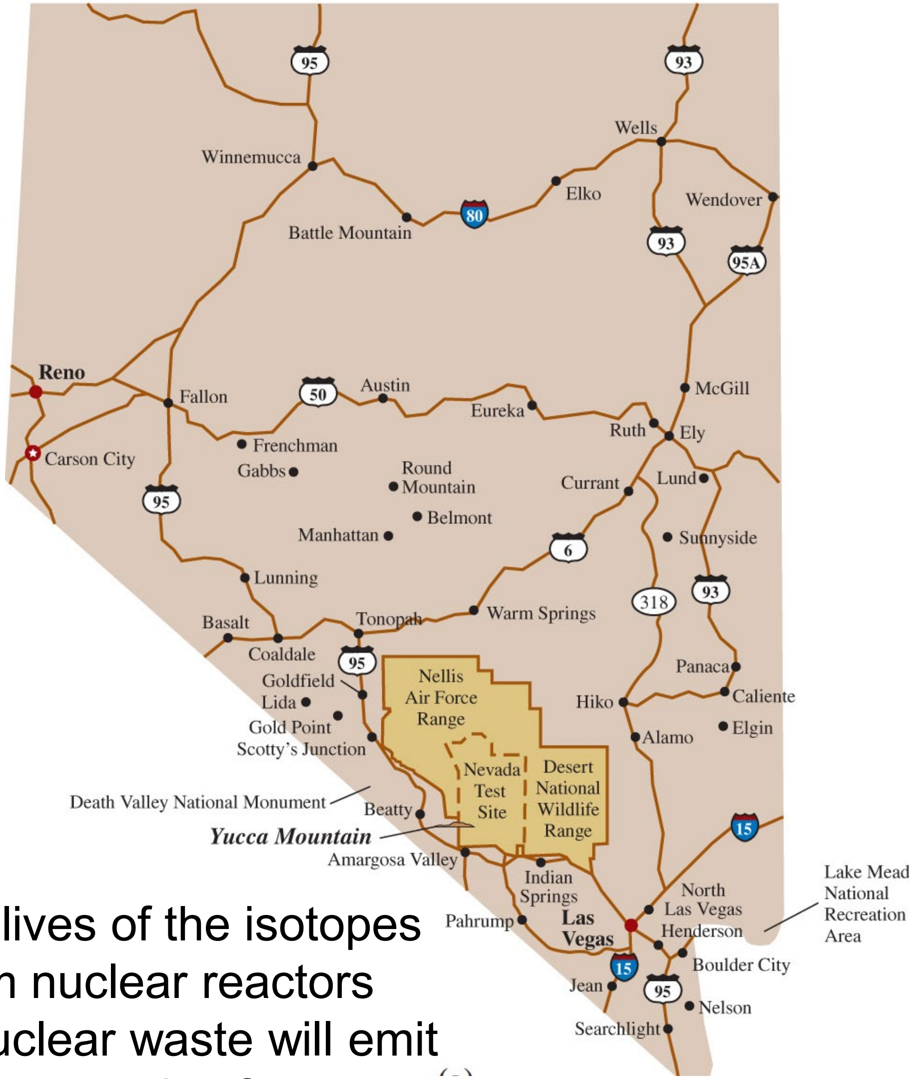
A half-life, $t_{1/2}$, is the time required for the level of radioactivity to fall to one-half of its initial value.

Half-Lives of Selected Radioisotopes

Table 7.3	Half-Life of Selected Radioisotopes	
Radioisotope	**Half-Life ($t_{1/2}$)**	**Found in the Used Fuel Rods of Nuclear Reactors?**
uranium-238	4.5×10^9 years	Yes. Present originally in fuel pellet.
potassium-40	1.3×10^9 years	No
uranium-235	7.0×10^8 years	Yes. Present originally in fuel pellet.
plutonium-239	24,110 years	Yes. See Equation 7.4.
carbon-14	5715 years	No.
cesium-137	30.2 years	Yes. Fission product.
strontium-90	29.1 years	Yes. Fission product.
thorium-234	24.1 days	Yes. Small amount generated in natural decay series of U-238.
iodine-131	8.04 days	Yes. Fission product.
radon-222	3.82 days	Yes. Small amount generated in natural decay series of U-238.
plutonium-231	8.5 minutes	No. Half-life is too short.
polonium-214	0.00016 second	No. Half-life is too short.

Each radioisotope has its own half-life. Some, like plutonium-239, take a very long time (24,110 years), whereas others, like plutonium-231 (8.5 minutes), decay very quickly.

Radioactive Waste: Here Today…

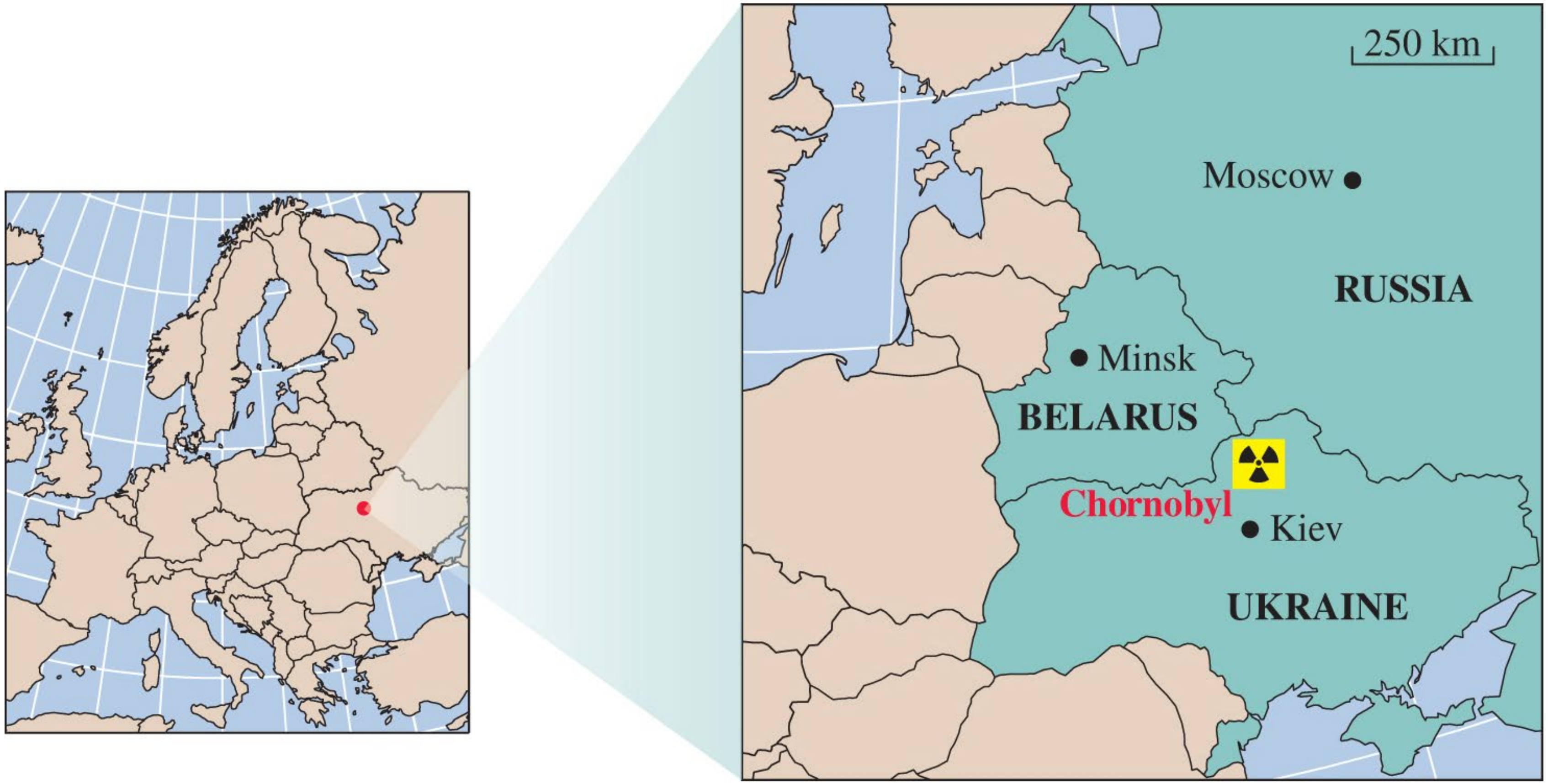


The long half-lives of the isotopes produced from nuclear reactors means that nuclear waste will emit radiation for thousands of generations to come.

Most nuclear waste is stored onsite; however, countries are trying to develop long-term underground storage options, like Yucca Mountain in Nevada. As of 2019, it appears that this repository will not be completed due to ongoing scientific concerns.

Source: U.S. Dept. of Energy.

The Risks of Nuclear Power: Chornobyl



On 26 April 1986, reactor # 4 at the Chornobyl Nuclear Power Station, 100 km north from Kiev, blew up during a routine daily operation. Nearly nine tons of radioactive material - 100 times as much as the Hiroshima bomb - were hurled into the sky. Winds over the following days, mostly blowing north and west, carried, fallout into Belarus, as well as Russia, Poland, the Baltic region, and Scandinavia.

Control rods were made of graphite (unlike those used in the U.S.) which caught on fire.

Chornobyl: What Happened?

I. While performing a safety test on Reactor 4, technicians allowed a power surge that reached 120 times the rated capacity of the reactor.
II. The surge, or "slow nuclear explosion", ripped open the core, including cooling water pipes, and caused a huge steam explosion.

$$2\ H_2O(l) + C(s,\ graphite) \rightarrow 2\ H_2(g) + CO_2(g)$$

$$2\ H_2(g) + O_2(g) \rightarrow 2\ H_2O(g)$$

III. The 4,000-ton concrete covering over the reactor was blown away. Fires broke out in many places all over the site.
IV. Fifty different radioactive isotopes were released, with half-lives spanning from two hours to 24,000 years. These isotopes were shot 1.5 miles into the sky. One of the hazardous radioisotopes released was iodine-131, a beta-emitter with an accompanying gamma ray. If ingested, this radioisotope can cause thyroid cancer.

$$^{131}_{53}\mathrm{I} \rightarrow\ ^{131}_{54}\mathrm{Xe} +\ ^{0}_{-1}\mathrm{e} +\ ^{0}_{0}\gamma$$

The Chernobyl Disaster

Chornobyl: The Consequences

- Over 1,000 injuries and thirty-one deaths of firefighters and others who reported to scene of accident.
- 150,000 people evacuated from their Ukraine homes.
- Radioactive cloud released over a large part of Europe. Health threatening levels of radioactive materials were found in at least twenty nations, and as far away as 2,000 km from Chornobyl. Estimated 250 million people were exposed to unhealthy amounts of radiation.
- Estimates of future cancers from the accident range anywhere from 7,500 to 1 million.
- Radioactive particles in the environment and in the food chain.
- Large amount of uncertainty and fear in the population.

Chornobyl: Political Consequences

- Distrust of government.
- Soviet Union cover-up: Sweden and Poland were the first nations to bring attention to the accident.
- Other nations attempted to downplay the health effects of the accident in their own nations.
- Public opposition to building additional nuclear power plants increased significantly worldwide.

Fotokon/Shutterstock

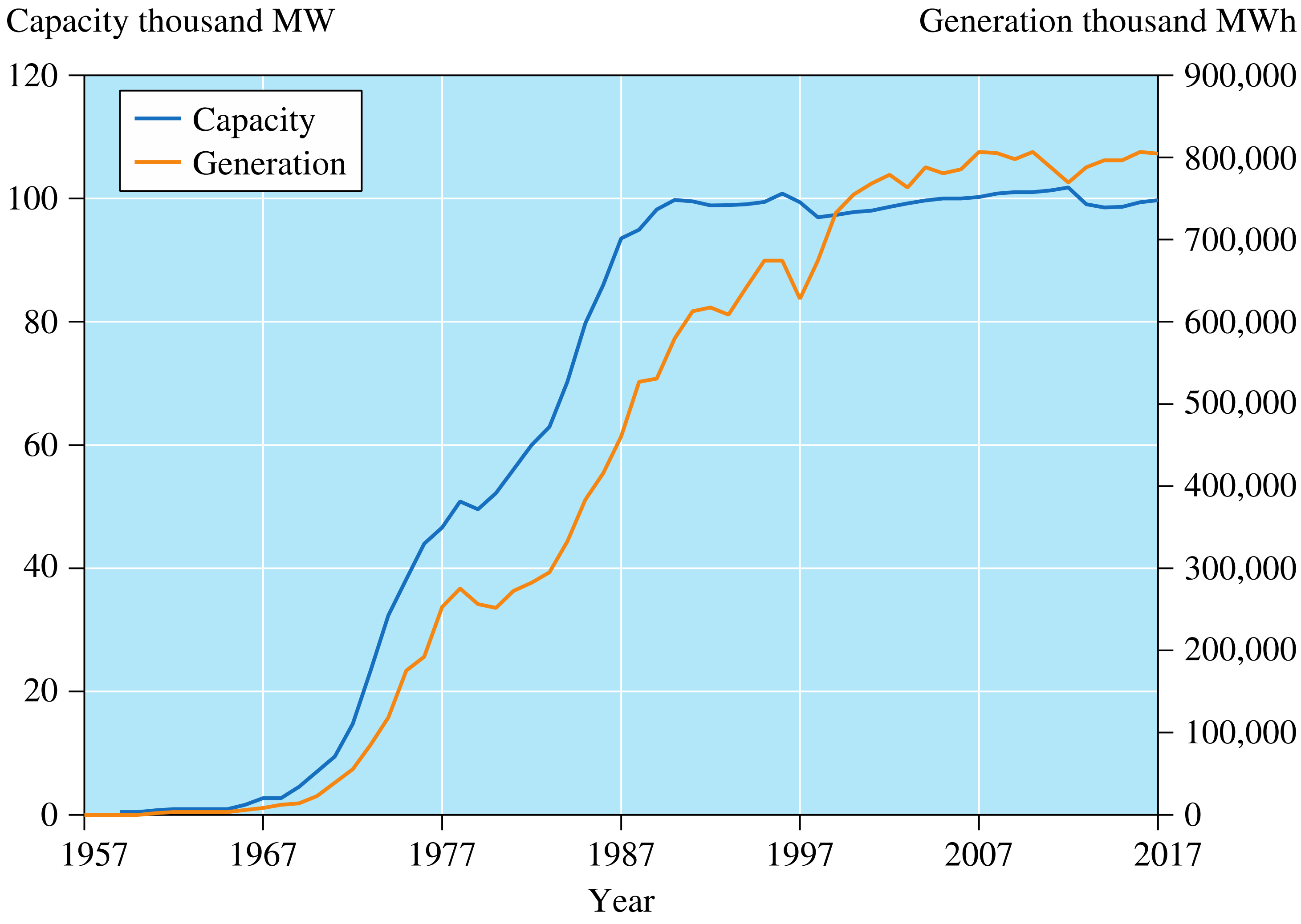
Another Disaster: Fukushima

- Caused by two natural disasters, an earthquake and tsunami, which resulted in the meltdown of three reactors.
- Flood waters knocked out the electrical generators needed for cooling water. This caused overheating of the fuel, which then started a chemical reaction that generated hydrogen gas. Fearing Chernobyl, the hydrogen was vented, which released I-131 to the surrounding countryside.
- Despite venting, explosive reactions occurred at four of the six reactors, which released radioisotopes.

[The Fukushima Nuclear Disaster - Epidemic of Ghosts (youtube.com)]

Flooding from tsunami that followed the 2011 Tohoku earthquake

The Future of Nuclear Power



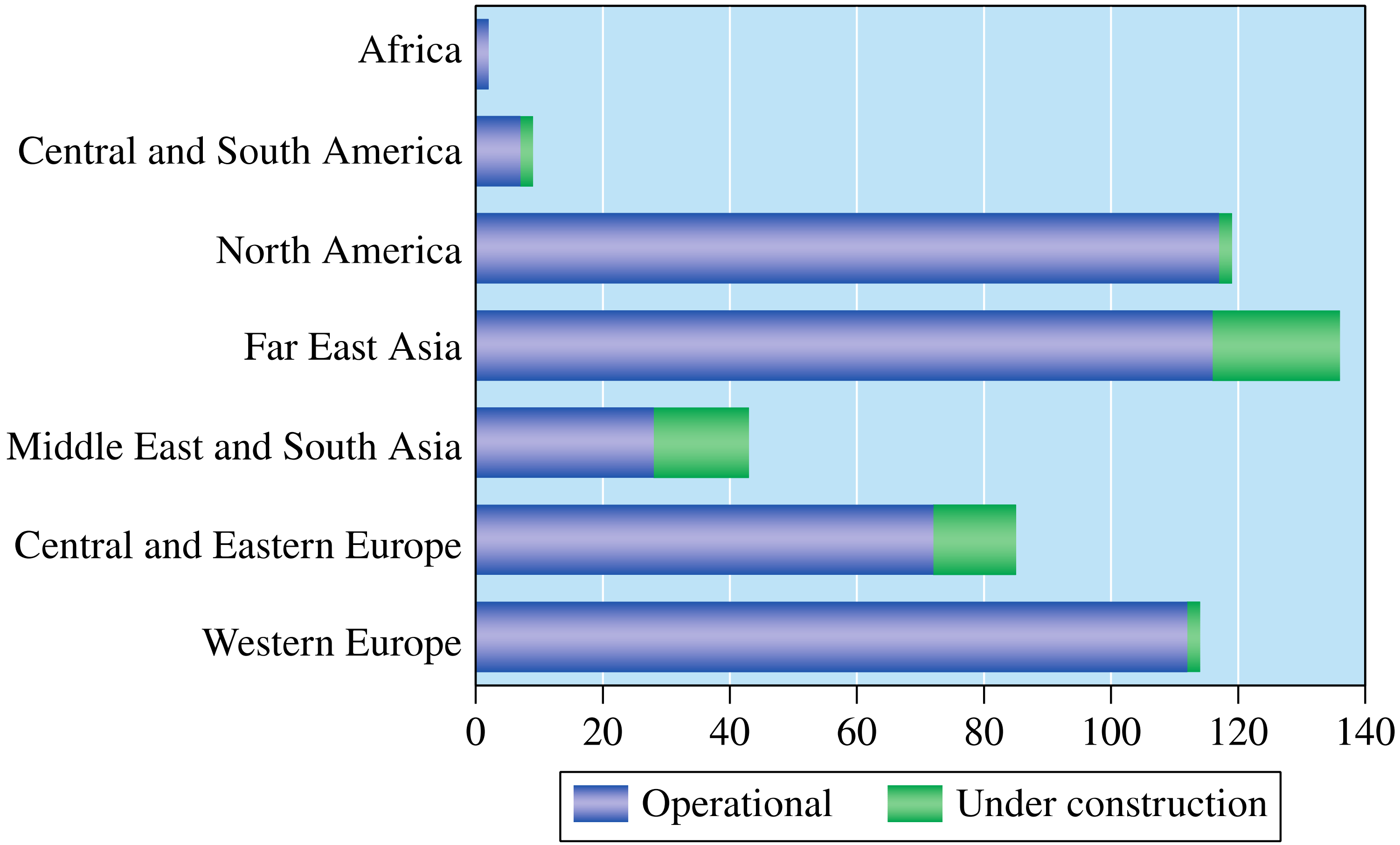
Nuclear power generation and capacity in the US

Electricity generation by nuclear plants has increased steadily since 1970 & remained steady since its peak of 112 in 1990.

The power increase over time stems from both improved reactor efficiencies and upgrades to reactor components.

Source: U.S. Energy Information Administration, Monthly Energy Review, *Table 8.1, March 2018.*

Worldwide Expansion of Nuclear Power



Significant expansion of nuclear power facilities are underway in most developed countries, especially in Asia and Europe.

Worldwide distribution of nuclear power plants (May 2018)

Source: International Atomic Energy Agency.

Can We Prevent Another Disaster?

- The U.S. Nuclear Regulatory Commission (NRC) has issued the following requirements for all nuclear power facilities:
- All facilities must obtain sufficient portable safety equipment, such as devices that could burn off hydrogen generated in an accident.
- Facilities should improve their venting systems to prevent a backup of steam and control the temperature.
- New equipment must be installed to monitor water levels in each plant's spent fuel pool.

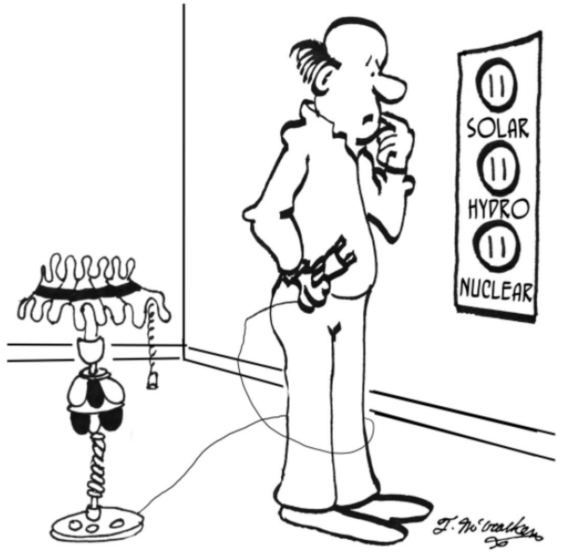
Your Turn 7.22 Pros and Cons of Nuclear Power

a. Explain your own thoughts on nuclear waste, mining, effects on climate change, cost, and human fear.

b. What countries, if any, have long-term plans for dealing with nuclear waste?

c. What does the cartoon show about future energy concerns?

d. What do you feel is the future of nuclear power?



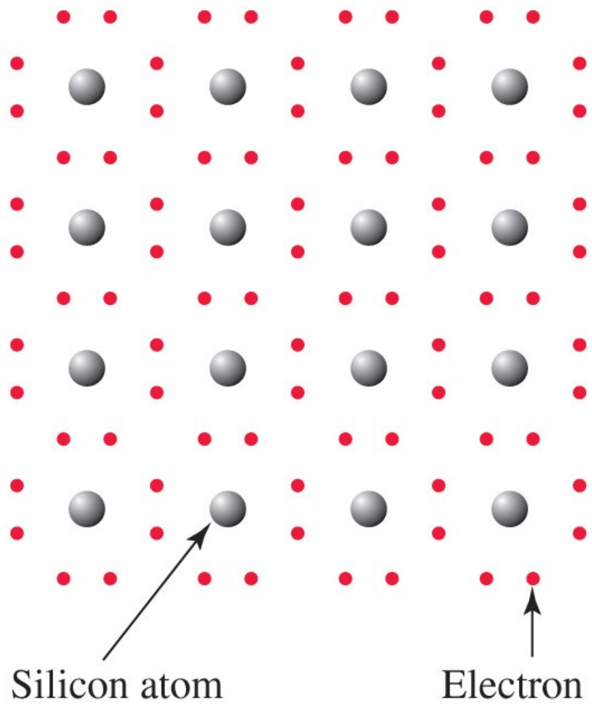
Source: McGraw-Hill Education.

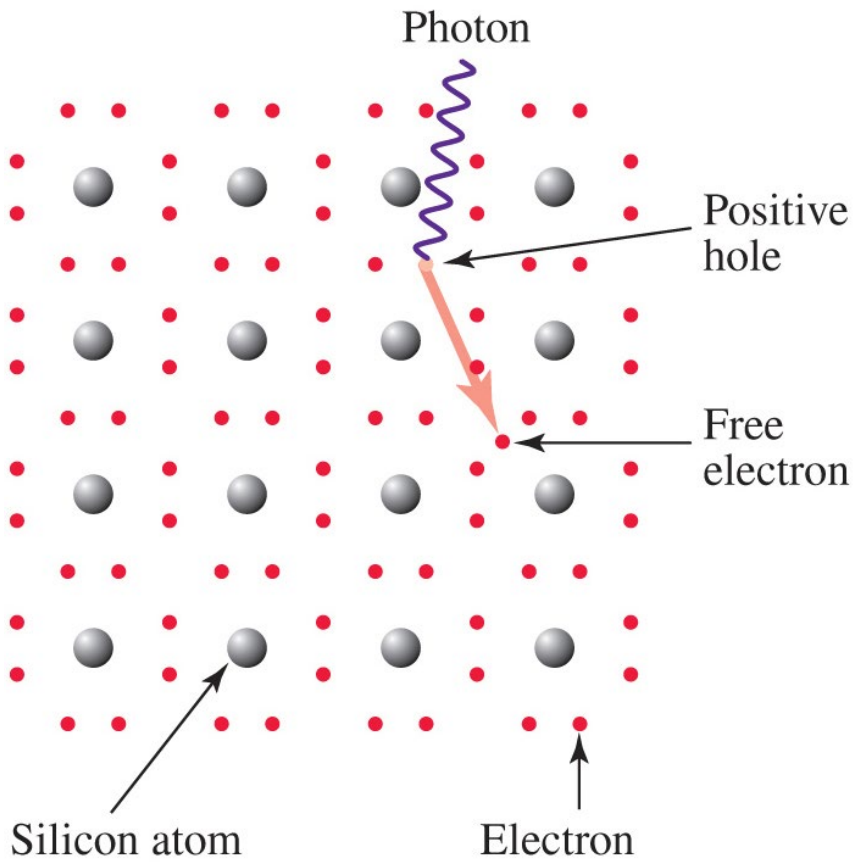
Solar Power

The Sun's rays hit Earth every hour with enough energy to meet the world's energy demand for an entire year!

However, currently less than 1% of the electric power generated in the U.S. comes directly from solar energy.

Silicon: The Heart of a Photovoltaic Cell

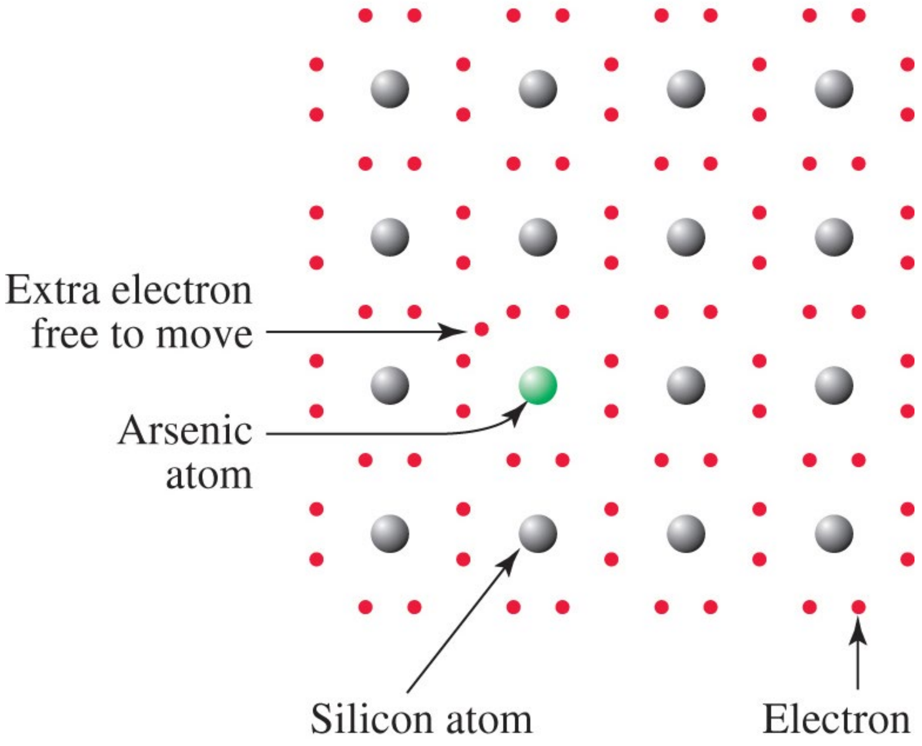


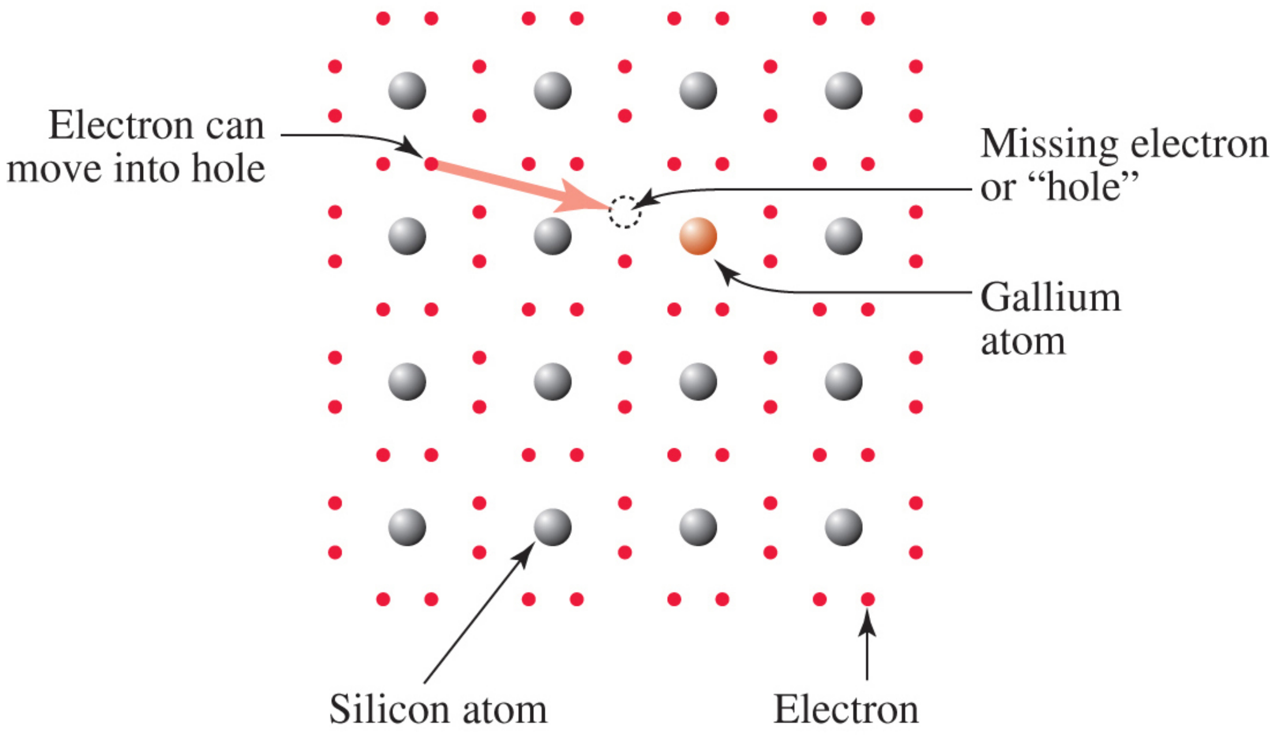


Light of certain energies can free an electron between silicon atoms in the solid. This electron then moves through the crystal lattice, making silicon an electrical conductor.

In order to increase this efficiency, silicon is doped with atoms containing either excess electrons (n-type) or fewer electrons (p-type).

Doped Silicon: Fine-Tuning Electrical Conductivity



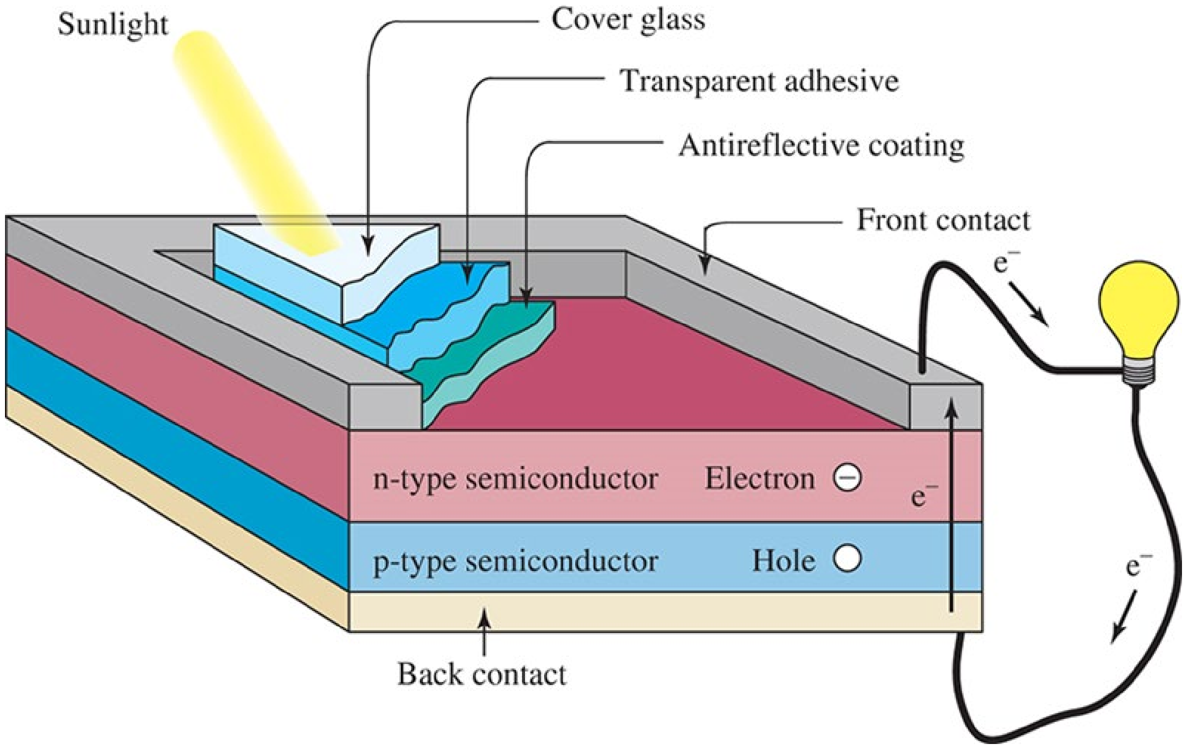


n-type: doped with an element with more electrons than Si (for example, P, As).

p-type: doped with an element with less electrons than Si (for example, B).

[Extrinsic Semiconductors]

p-n Junctions in Solar Cells

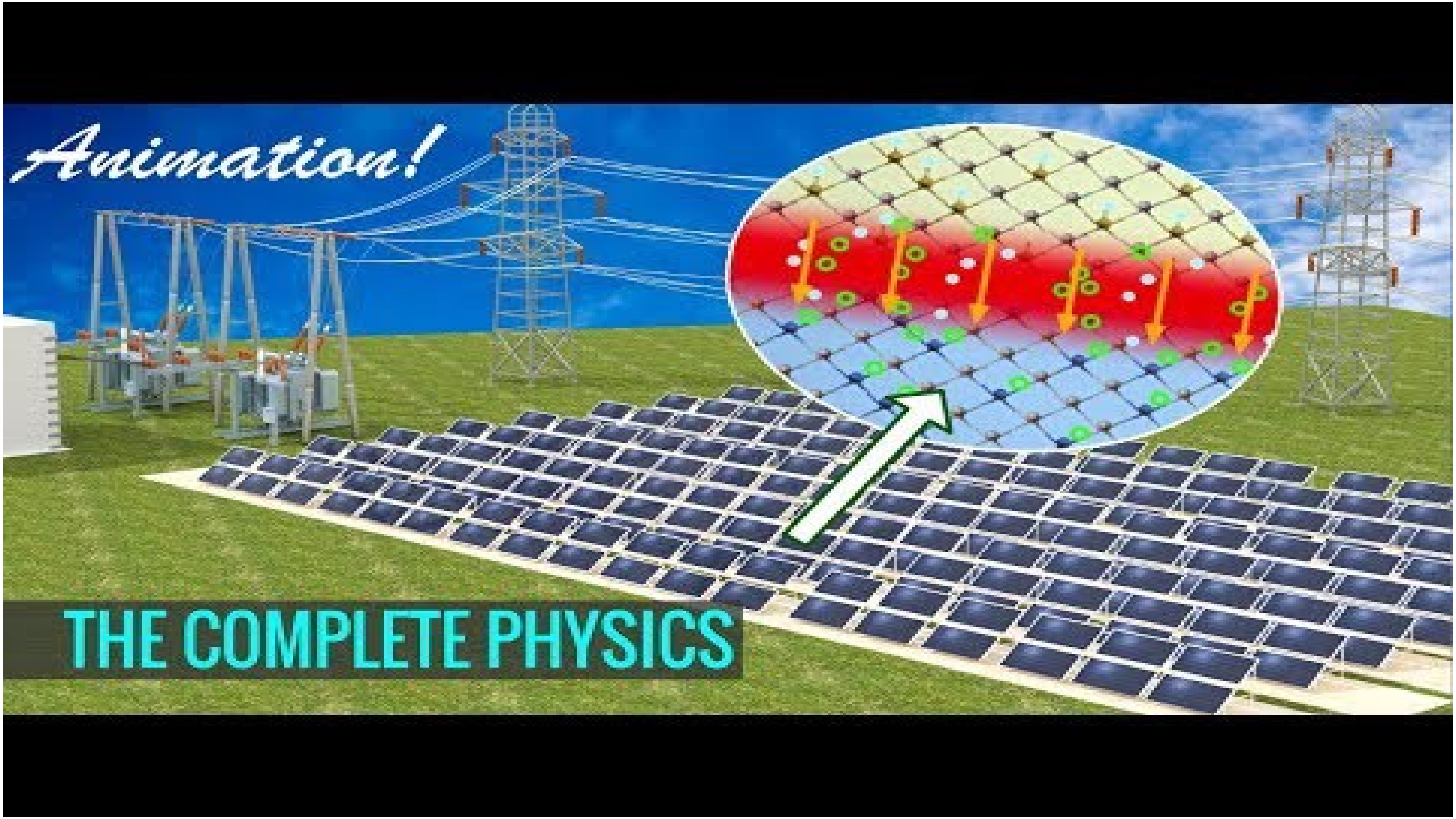


Solar cells contain layers of p-type and n-type silicon placed in direct contact.

When light hits the n-type silicon, electrons are freed from the crystal structure and moved through the external circuit, eventually returning to the p-type side.

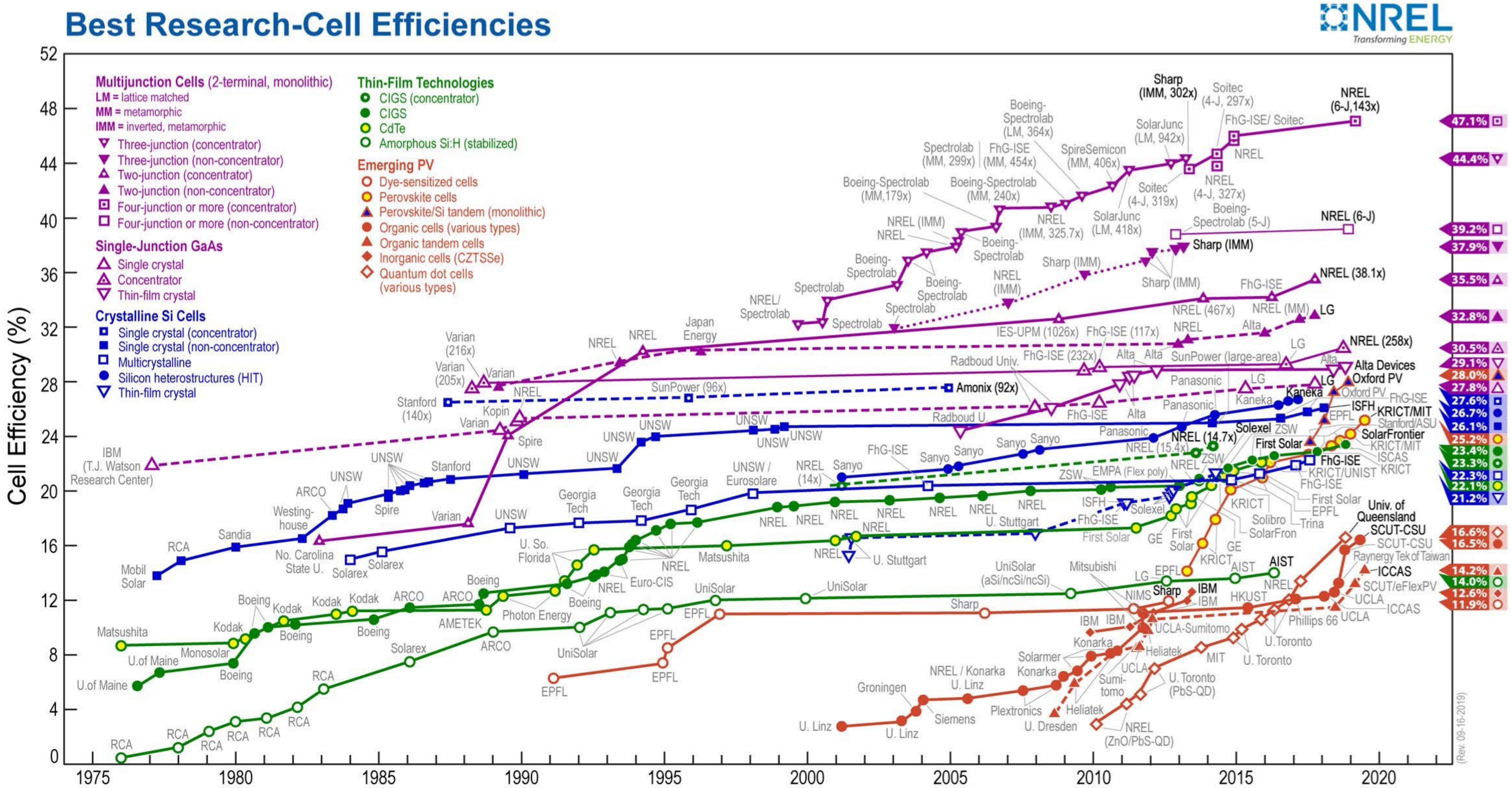
When electrons are released by sunlight, “holes” are also generated in the p-type material. These electron-hole pairs move in opposite directions and are the carriers responsible for electrical current.

How do Solar cells work?



How do Solar cells work?

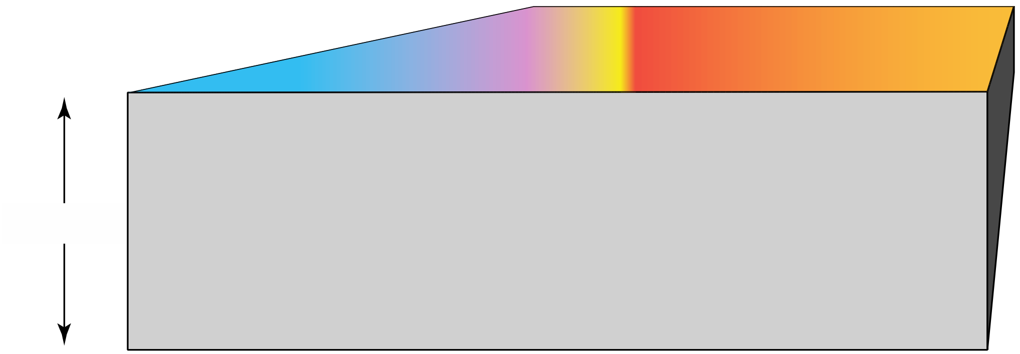
Efficiency of Solar Cells [1]

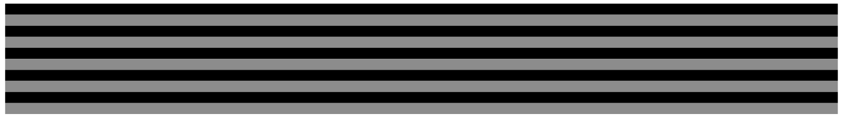


[Cell efficiency](#)

Source: National Renewable Energy laboratory (NREL) for the U.S. Department of Energy, 2018.

Efficiency of Solar Cells 2





Only photons with enough energy can knock electrons free from the doped silicon lattice.

As of 2019, silicon-based solar cells have efficiencies of only 27.6%.

Multilayer solar cells increase the efficiency to almost 50%, but are very expensive to produce. These designs feature many layers with thicknesses on the order of tens of micrometers

Distributed Generation

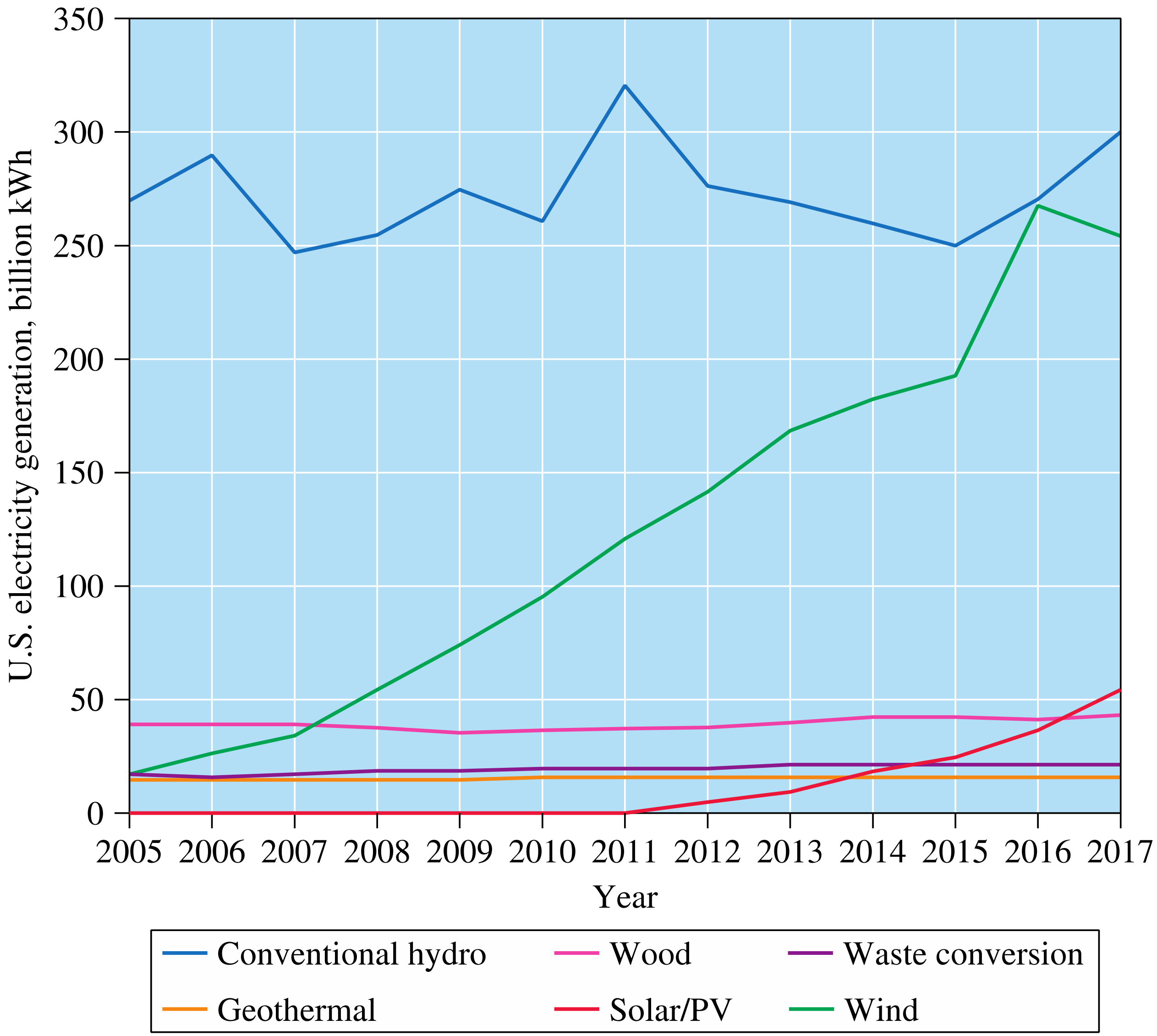
Source: NREL/U.S. Dept. of Energy3.

More than ⅓ of Earth's population is not connected to an electric network.

Photovoltaic (solar) power is being used to bring electricity to isolated villages in economically disadvantaged countries.

Source: NREL/U.S. Dept. of Energy.

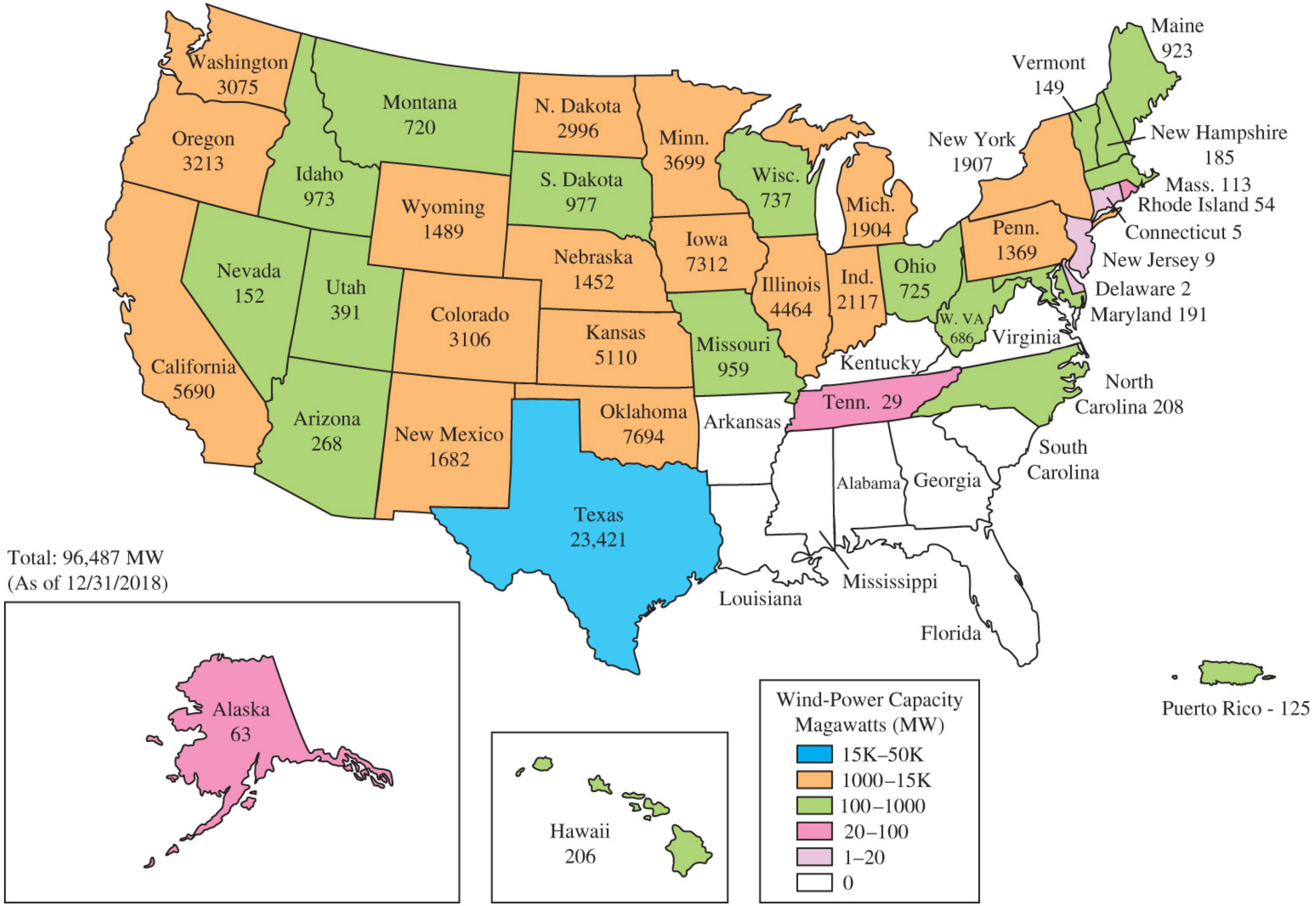
Renewable Energy Sources



Among the possible alternative sources of energy, wind power has seen the largest growth over the last decade.

Hydroelectric power has consistently generated the most electricity since 1990. However, the average generation of hydroelectric (300 billion kWh) is much less than the combustion of fossil fuels (3 trillion kWh).

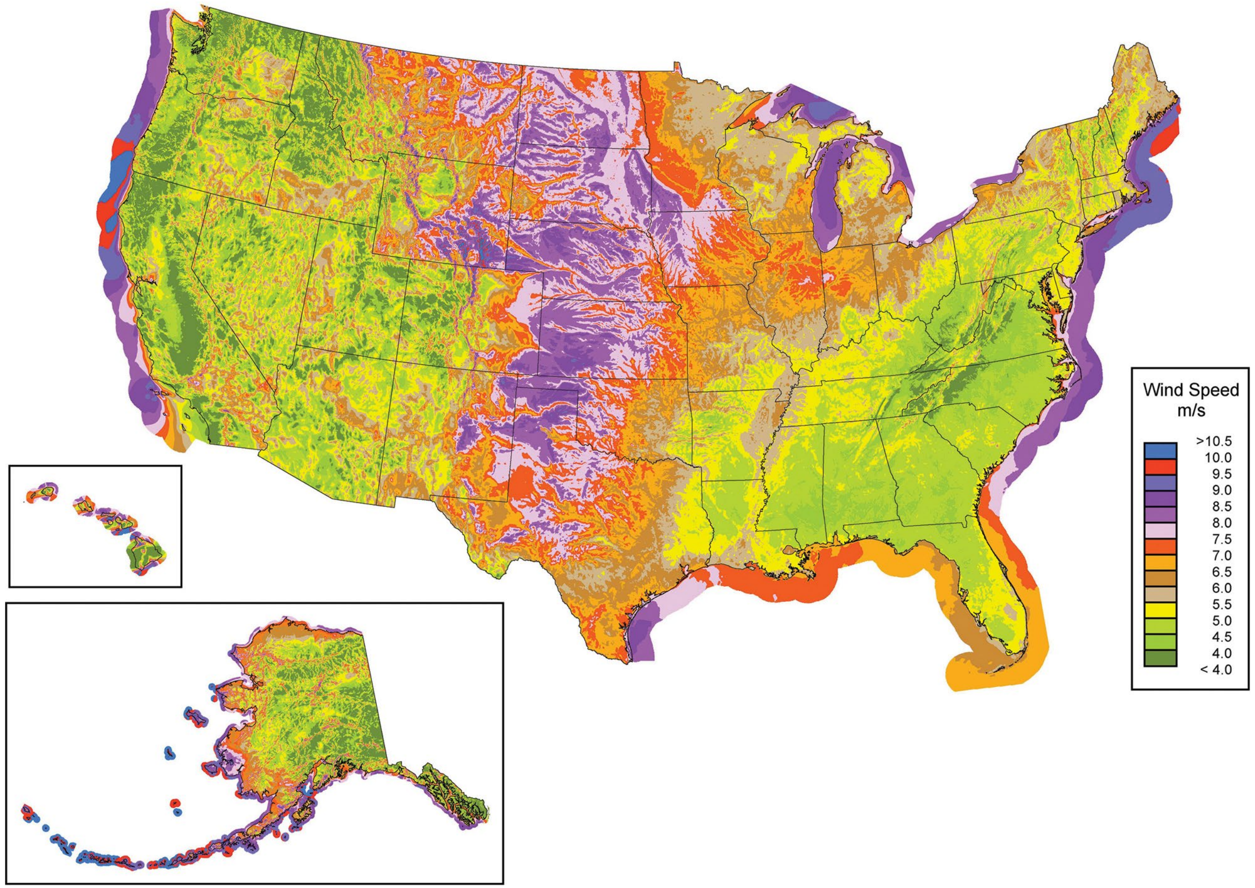
Wind Power Capacity in the U.S.

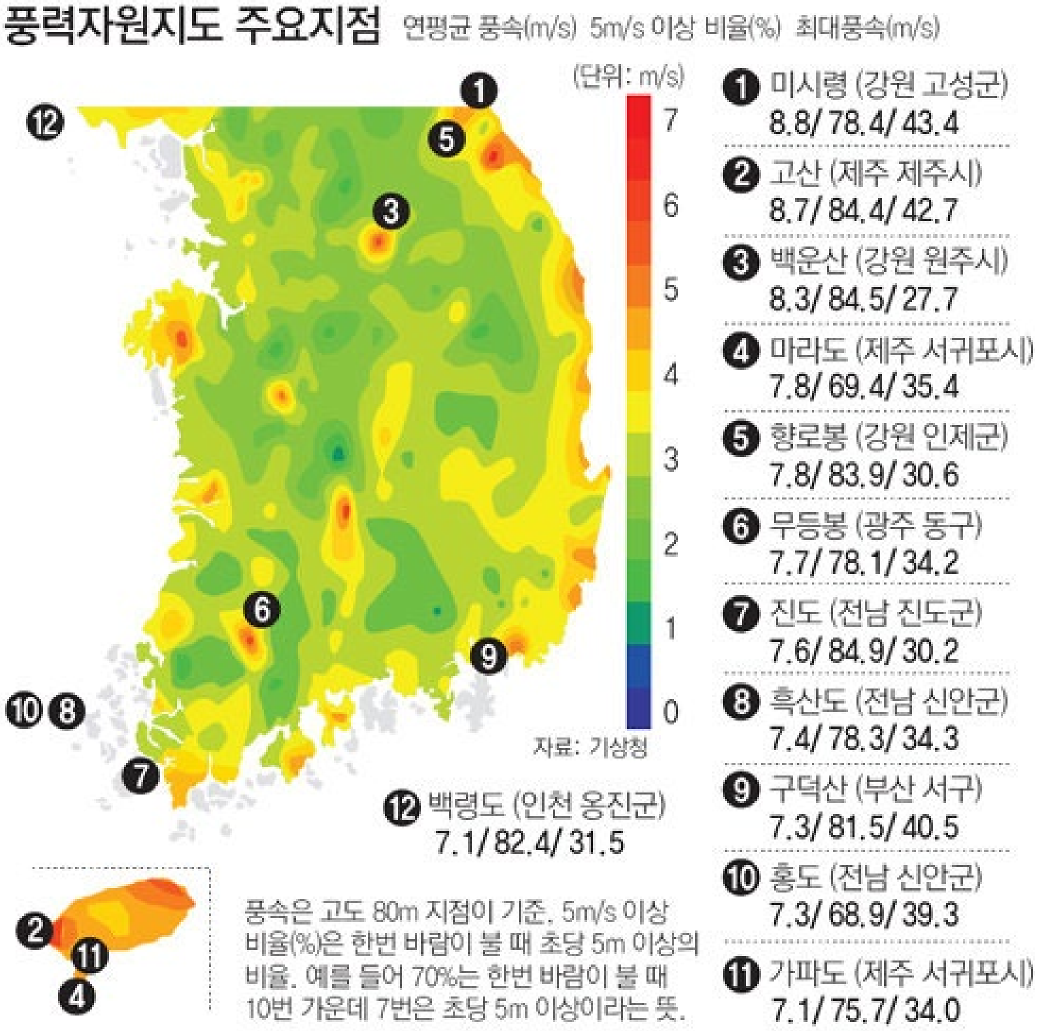


Wind power capacity in the US (2017)

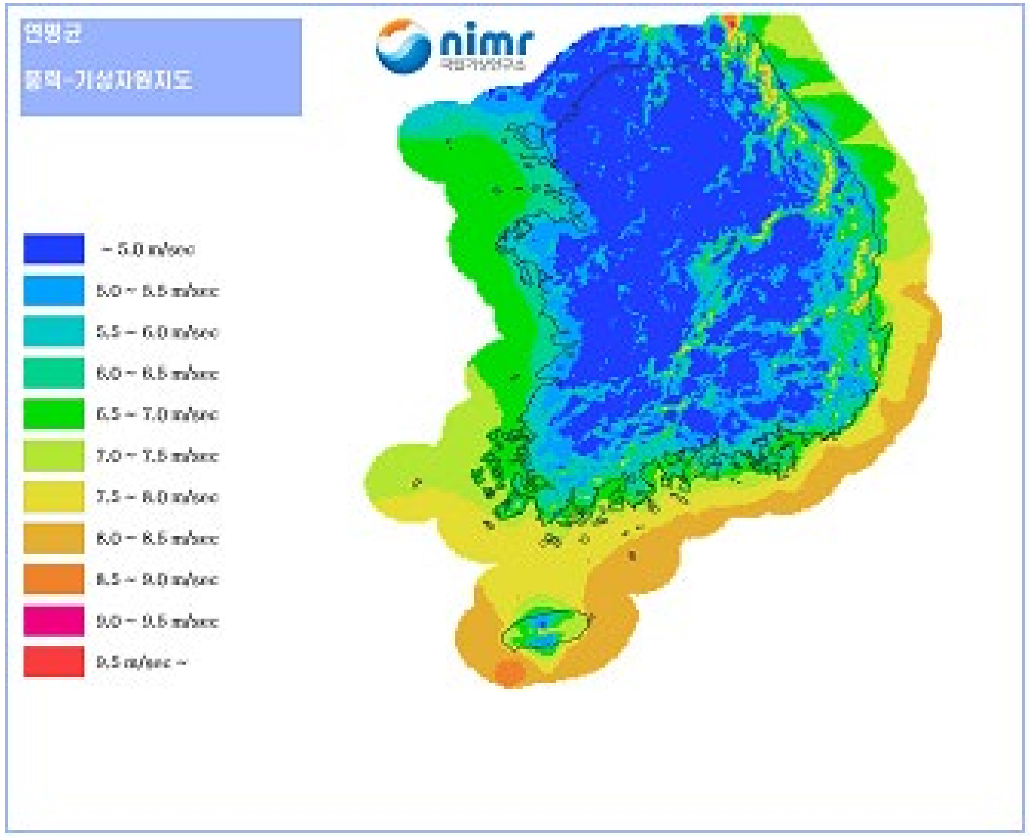
Source: National Renewable Energy Laboratory (NREL) for the U.S. Department of Energy, 2018.

Average Wind Speed

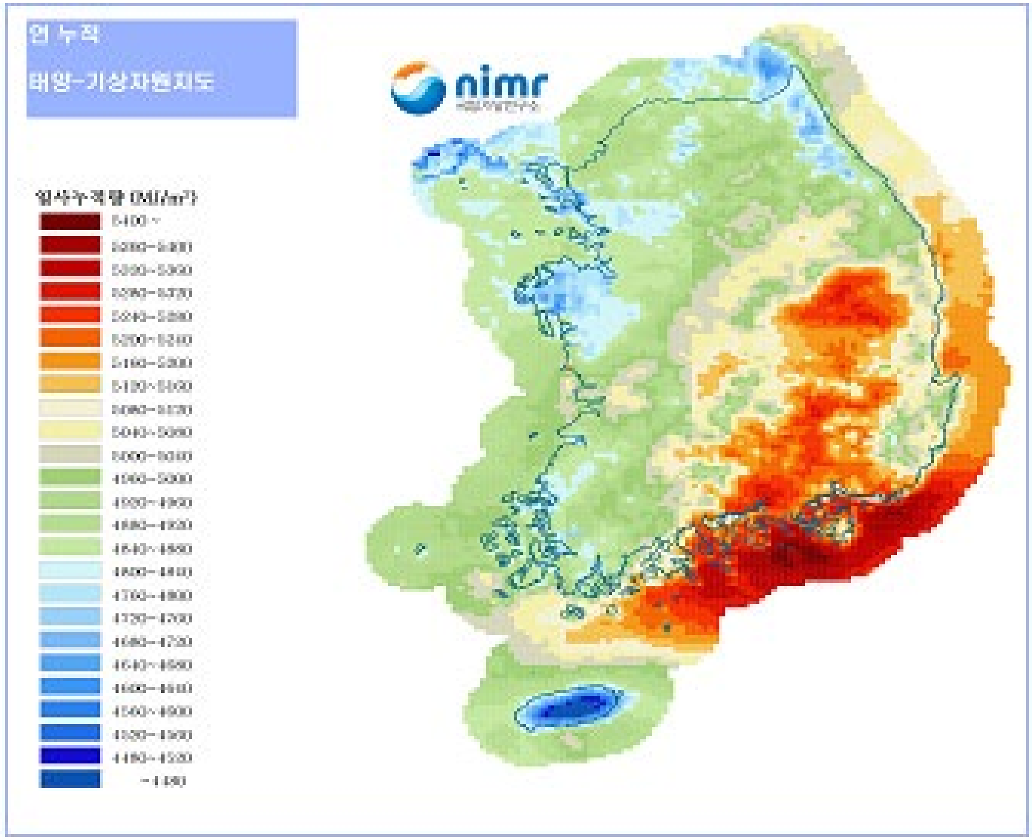




Source: National Renewable Energy Laboratory (NREL) for the U.S. Department of Energy, 2014.



[풍력-기상자원지도(2009년판)]

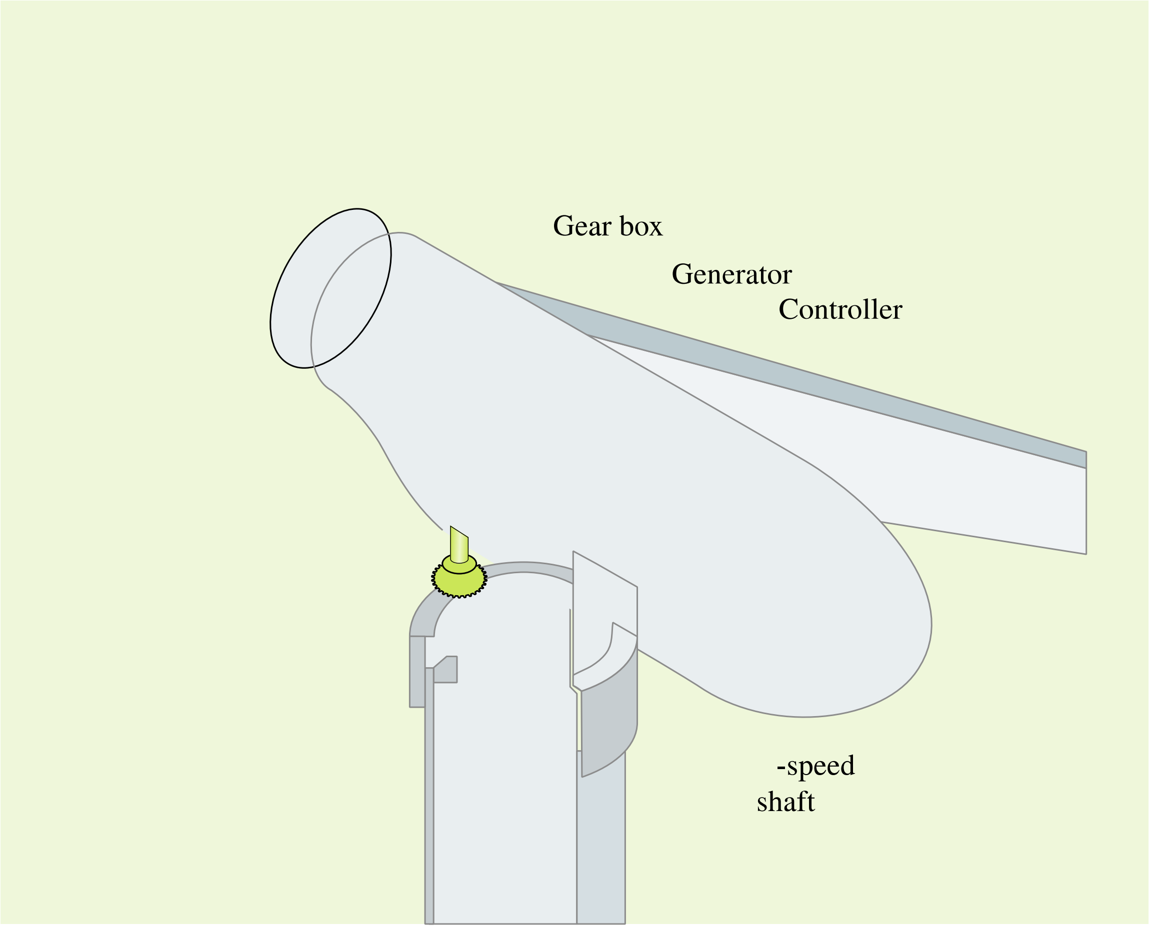


[태양-기상자원지도(시범지도)]

[녹색성장과 기상자원지도 활용 > 전문가컬럼 > 날씨이야기 > 참여와 소통 (kma.go.kr)](kma.go.kr)

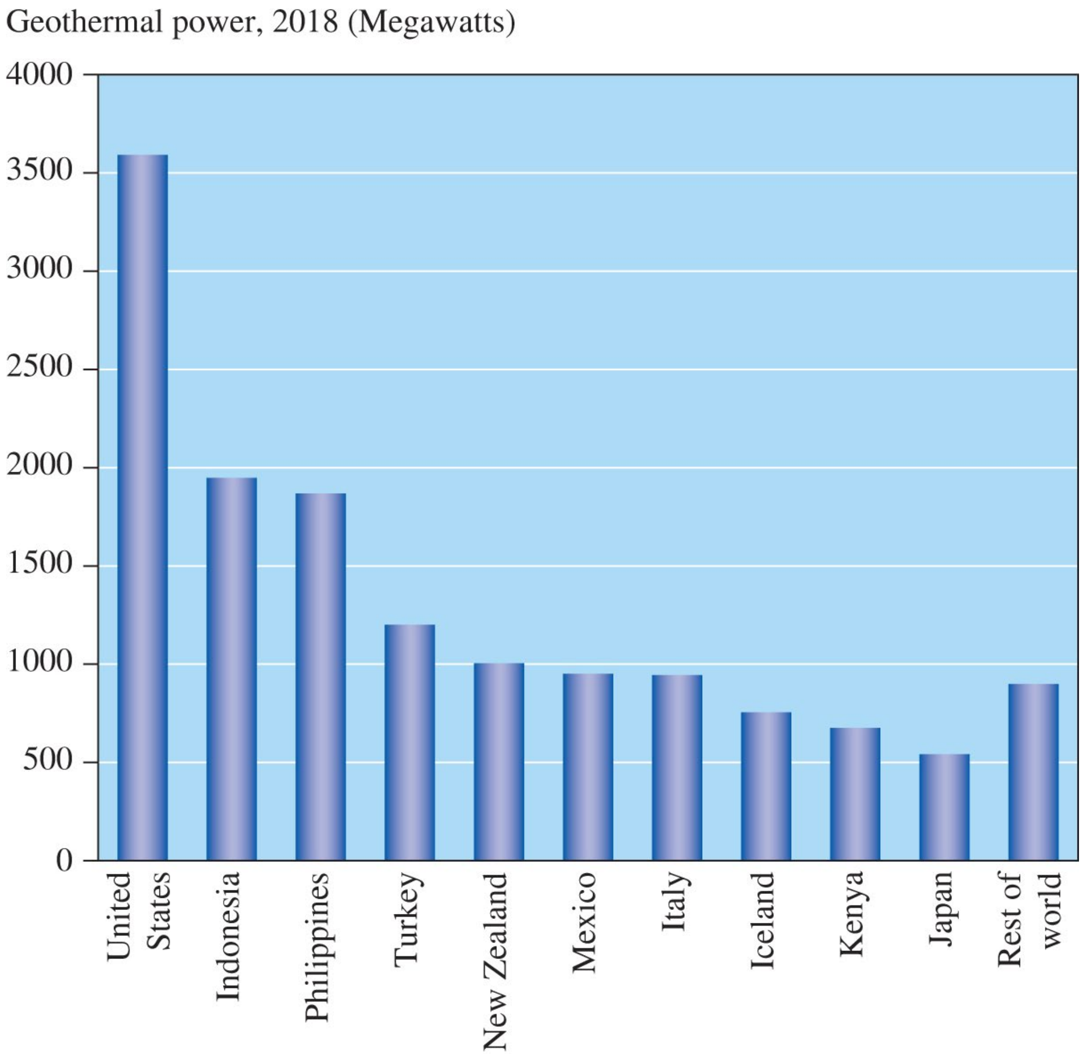
Source: National Renewable Energy Laboratory (NREL) for the U.S. Department of Energy, 2014.

Schematic of a Wind Turbine



[MidAmerican Energy Wind Farm](#)

Worldwide Geothermal Capacity



The top five countries for geothermal electric generating capacity are: the U.S. (3.6 GW), Indonesia (1.9 GW), the Philippines (1.8 GW), Turkey (1.2 GW), and New Zealand (1.0 GW).

Source: MidAmerican Energy Company.

Group Discussion

Your Turn 7.32 Our Energetic Future

Renewable energy comes from the wind, the oceans, and geothermal sources, not just from the Sun and biofuels (discussed in Chapter 6). Pick one of these renewable energy sources and learn more about the technologies available to harness it.

a. Name the geographic restrictions (if any) to its use.

b. Prepare a list of the reasons to support this technology. Prepare a similar list for the "nay-sayers."

c. Predict how this technology will affect energy production output where you live.

Your Turn 7.33 Group Activity: The World's Energy

Supporters of nuclear energy encourage its use as a source that does not emit greenhouse gases. Bill McKibben, a prominent environmentalist, says that "there is an urgent need to stop subsidizing the fossil fuel industry, dramatically reduce wasted energy, and significantly shift our power supplies from oil, coal, and natural gas to wind, solar, geothermal, and other renewable energy sources." After reading this chapter, how do you think nuclear and renewable energy fit into the world's energy portfolio?

Example topics that you can delve into further...

1. Assess whether nuclear power plants are a viable alternative energy source, supporting your argument with scientific evidence.
2. Explore the health impacts of indoor radon exposure, identify its primary sources, and suggest methods to decrease its concentration.
3. Investigate if there are any materials that can serve as substitutes for silicon in photovoltaic cells.
4. Analyze the reasons behind the significant growth in wind power and its advantages compared to other energy sources.
5. Determine the more suitable location for wind power generation: offshore (sea) or mountainous areas.