ENERGY CONSERVATION FOR ENVIRONMENTAL PROTECTION



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Energy Conservation for Environmental Protection (Pisupati)

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1: ENERGY AND SOCIETY

1.1: Forms of energy
1.2: Energy conversion
1.3: Measurement of energy
1.4: Sources of Energy
1.5: Power
1.6: Energy Use of Home Appliances

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1.1: Forms of energy

Six Basic Forms of Energy

There are 6 basic forms of energy:

1. Mechanical energy
2. Chemical energy
3. Thermal or heat energy
4. Electrical energy
5. Nuclear energy
6. Radiation

1. Mechanical Energy

There are two types of mechanical energy: kinetic and potential energy.

Kinetic energy is the energy that a body possesses due to its motion. Bodies that contain kinetic energy include a baseball traveling through the air after being thrown or a hammer pounding nails. In the United States, about 1/3 of the total energy produced is used for transportation or movement of people and goods.

Potential energy is the energy that a body possesses due to its position relative to a reference point. Bodies that contain potential energy include a pendulum at the top of its oscillation or a compressed spring.

Additional Information

A book sitting on a shelf in the library is said to have **potential energy** because if it is nudged off the shelf, gravity will accelerate the book, giving the book **kinetic energy**. Because the Earth's gravity is necessary to create this kinetic energy, and because this gravity depends on the Earth being present, we say that the **Earth-book system** is what really possesses this potential energy, and that this energy is converted into kinetic energy as the book falls.

2. Chemical Energy

Chemical energy is the potential energy contained in molecular bonds, which exists due to electric and magnetic forces of attraction that different parts of molecules exert. It is also referred to as "microscopic potential energy". This attractive force is the same force involved in thermal vibrations. When chemical reactions occur and the molecule is rearranged, the chemical energy can increase or decrease. Examples of bodies with chemical energy include batteries and glucose in the human body.

About 85% of the energy used in the U.S. is from fossil fuels like natural gas, coal, and oil, which all store chemical energy. Burning these fossil fuels releases thermal or heat energy which is then used to power various processes.

Additional Information

The glucose (blood sugar) in your body is said to have "chemical energy" because the glucose releases energy when chemically reacted (combusted) with oxygen. Your muscles use this energy to generate mechanical force (work) and also heat.

3. Thermal or Heat Energy

Thermal energy is a combination of the microscopic, kinetic, and potential energy of molecules. Examples of bodies with thermal

energy include boiling water and a hot beverage.

Temperature is a measure of how much thermal energy a body has. At higher temperatures, molecules are moving faster and/or vibrating, thus having more kinetic and potential energy. Movements contribute kinetic energy while vibrations contribute potential energy for molecules.

Additional Information

A hot cup of coffee is said to possess "thermal energy," or "heat energy," because it has a combination of **kinetic energy** (its molecules are moving and vibrating) and **potential energy** (the molecules have a mutual attraction for one another) - much the same way that the book on the bookshelf and the Earth have potential energy because they attract each other.

4. Electrical Energy

Electrical energy is created from the movements of electrons in matter. It is commonly converted into other forms of energy. For example, toasters convert electricity to thermal energy, and speakers convert electricity to sound. Because of the numerous applications, electricity is in high demand. In the U.S. alone, about 40% of the total primary energy used is converted into electricity.

Important Point

All matter is made up of atoms, and atoms are made up of smaller particles called protons (which have positive charge), neutrons (which have neutral charge), and electrons (which are negatively charged).

- The electrons orbit around the nucleus (which contains protons and neutrons), just like the planets orbit the sun.
- Certain metals have electrons that are only loosely attached to their atoms, so they can be easily made to move from one atom to another if an electric field is applied to them.
- When those electrons move among the atoms of matter, a current of electricity is created.

5. Nuclear Energy

Nuclear energy is produced when reactions in an atom cause a structural change in the nucleus. There are two main types of nuclear reactions: fusion and fission.

Fusion is when two nuclei join together to form one larger nucleus or particle. This releases energy in the form of light and heat. Fusion occurs in the Sun, where hydrogen nuclei fuse together to make helium nuclei, releasing energy.

Fission is when the nucleus of one atom splits into two smaller atoms. Like fusion, this also releases energy as light and heat. Nuclear reactors and the Earth's interior depend on fission, usually involving uranium as the atom being split.

Additional Information

In both fusion and fission, some of the matter making up the nuclei is converted into energy, represented by the famous equation

$$E = mc^2$$

where E is energy, m is mass, and c is the speed of light.

- This formula indicates that energy intrinsically stored in matter at rest equals its mass times the speed of light squared. When matter is destroyed, the energy stored is released.
- This equation suggests that an incredibly huge amount of energy is released when a small amount of matter is converted to energy.

6. Radiation

Radiation is energy transmitted in the form of rays, waves, or particles. Examples of radiation include ultraviolet (UV) and microwave radiation. Electromagnetic radiation is a type of energy that oscillates and is comprised of electric and magnetic fields that travel freely through space. Electromagnetic radiation is comprised of photons, which can be thought of as discrete "packets" of energy with properties of waves. Photons are created when electrons transition from higher to lower energy levels in atoms and absorbed when electrons transition from lower to higher energy levels. Photons are also created when a charged particle, like an electron, is accelerated. This occurs in radio transmitter antennae, which generate radio waves.

The electromagnetic spectrum represents the various types of electromagnetic radiation that occur at different wavelengths and frequencies, which are inversely related.

The following video explains the electromagnetic spectrum.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

As shown in the video, the lower the energy, the longer the wavelength and lower the frequency, and vice versa.

Staring directly at the Sun hurts our eyes because it contains UV light, which contains high-energy (i.e., high frequency and low wavelength) photons, and this energy can cause physical damage to cells. Humans can only see visible light, because other forms of electromagnetic radiation outside of the visible light spectrum have wavelengths/frequencies that are outside of what the human eye can perceive. A great discovery of the 19^{th} century was that radio waves, X-rays, and gamma rays (types of electromagnetic radiation) are just forms of light, and that light is just electromagnetic waves.

About 20% of electricity used in the U.S. is used to produce visible light.

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1.2: Energy conversion

Energy is often converted from one form to another to be used for various applications. Examples include:

- Using gasoline (chemical energy) and batteries (electrical energy) to cause cars to move (kinetic energy)
- Using electricity to power TVs and provide light and sound
- Using food (chemical energy) to allow a person to run (do work)

Figure 1.2.1 depicts the above examples and provides more examples of energy conversions.

Figure 1.2.1. Energy conversions in our everyday lives

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1.3: Measurement of energy

Units of Measurement

Energy is measured differently in different industries and parts of the world. The SI unit for energy is the Joule (J). Table 1.3.1. provides some units of energy that are used.

Table 1.3.1. Different measurements of energy

Unit	Definition	Used In	Unit Conversions
British thermal unit (BTU)	Amount of energy needed to raise temperature of 1 pound of water by 1 degF, equivalent to energy found in the tip of a match stick	Heating/ cooling industries	1 BTU = 1055 J
Small calorie (cal)	Amount of energy needed to raise temperature of 1 gram of water by 1 degC	Science and engineering	1 cal = 0.003969 BTUs
Food calorie or kilocalorie (Cal, kcal, Calorie)	Amount of energy needed to raise temperature of 1 kilogram of water by 1 degC, often for measuring energy content of food	Nutrition	1 Cal = 1000 cal, 4.187 J, 3.969 BTUs
Joule (J)	Amount of energy smaller than a calorie and BTU, SI unit of energy	Science and engineering	1 J = 0.2388 cal, 0.0009481 BTUs
Kilowatt hour (kWh)	Amount of energy from the steady production or consumption of 1 kilowatt of power over 1 hour	Electrical fields	1 kWh = 3.413 BTUs, 3,600,000 J
Therm	Amount of energy in natural gas	Home heating appliances	1 therm = 100,000 BTUs

Additional Information

When writing BTUs, one uses a base of “10” raised to a particular exponent.

For example:

- 10,000 BTUs = 10^4 BTUs
- 100,000 BTUs = 10^5 BTUs
- 1,000,000 BTUs = 10^6 BTUs

More specific notation involves the following:

- 10,000 BTUs = 10^4 BTUs
- 100,000 BTUs = 10^5 BTUs
- 1,000,000 BTUs =10^6 BTUs

To express measurements greater than those with a base of 10, you would do the following:

- 50,000 BTUs = 5 * 10^4 BTUs
- 700,000 BTUs = 7 * 10^5 BTUs
- 9,000,000 BTUs = 9 * 10^6 BTUs

Energy Scale

The video below shows the energy used by various countries or processes on a logarithmic scale measured in BTUs.

YouTube Video

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View this YouTube Video online

It is interesting to note that the earth received 24,330 times more energy than the entire world used in 2001. Then one might ask, “Why should anybody worry about energy shortage?" Whether energy is there or not is actually a secondary concern. The real issue is the form in which the energy is available and whether it can be easily converted to the form that we need.

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1.4: Sources of Energy

Energy is stored and available in different forms and sources. These sources are divided into two main groups: renewable and nonrenewable.

1. Renewable Energy Sources

Renewable energy sources can be replenished repeatedly. Examples include hydropower, solar, and wind energy from the Earth, biomass from plants, and nuclear fusion. These sources are commonly converted into electricity or thermal energy.

2. Nonrenewable Energy Sources

Nonrenewable energy sources cannot be replenished repeatedly. Examples include fossil fuels (natural gas, petroleum oil, coal), tar sands, and uranium (which is used for nuclear fission). These sources are commonly converted into electricity and mechanical (kinetic and potential) energy.

Our world mostly relies on nonrenewable energy sources.

Fossil Fuel Distribution

Fossil fuels are formed over millions of years by the combination of thermal energy from the Earth's core and pressure from rock and soil on the remains (fossils) of dead plants and animals. Fossil fuels are not distributed uniformly over the Earth's surface, as certain parts of the land millions of years ago had more favorable conditions for organisms to grow. Thus, certain parts of the world are richer in fossil fuels than others. Figure 1.4.1 shows a rough distribution of fossil fuels on Earth.

Figure 1.4.1. Fossil fuel distribution across different parts of the world, and quantities of fossil fuels remaining.

Credit: Roke [CC BY-SA 3.0], via Wikimedia Commons

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1.5: Power

What Is Power?

The video below is a short demonstration of power.

YouTube Video

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View this YouTube Video online

While both cyclists did the same amount of work (since they both pedaled for 10 miles) and used the same amount of energy (218 calories), the blue cyclist used the most power, because he did the same amount of work over a shorter period of time.

Important Point

Power is the rate at which we do work.

Energy is the capacity to do work.

Work is the amount done.

Measuring Power

Power is measured in units of energy per time. Examples of units with conversions include:

- Watt (W) = 1 Joule per second (J/s)
- BTU per hour (BTUs/h) = 1055 J/s
- Horsepower (hp) = 550 foot-pounds per second (ft-lb/s)
- Calories per second (Cal/s)
- Kilowatt (kW) = 1000 Watts (W)

Important Point

Units of power are *not* the same as units of energy (i.e., BTUs, calories, etc.). Units of power are measured in terms of **units of energy** used per some **unit of time**.

Calculating Power

Power can be determined by the formula

$$Power = \frac{Energy}{Time} \tag{1.5.1}$$

where $Time$ refers to the duration of usage.

Example 1

On a winter day, a home needs 1,000,000 BTUs of fuel energy every 24 hours to maintain the interior at 65°F. At what rate is the energy being consumed in Watts?

Answer available at the end of this section.

Power and Cost of Energy

Determining the cost of energy uses the formula

$$Energy\,Use = Power * (Time\,of\,Power\,Use) \tag{1.5.2}$$

$$Cost\,of\,Energy = (Energy\,Used) * (Cost\,of\,the\,Unit\,of\,Energy) \tag{1.5.3}$$

Example 2

If a 100 W light bulb is accidentally left on overnight (8 hours), how much energy does it consume? How much energy does this cost, if electricity costs 10 cents per Kilowatt?

Answer available at the end of this section.

Answers

Example 1

$$Power = \frac{1,000,000\,BTUs}{24\,hr} * \frac{1055\,W}{BTU} * \frac{hr}{3600\,s} = \mathbf{12,200\,W}$$

Example 2

Using equation 1.5.2,

$$Energy\,Use = (100\,W) * (8hr) = 800\,Wh = \mathbf{0.8\,kWh}$$

Using equation 1.5.3,

$$Cost\,of\,Energy = (0.8\,kWh) * (\$0.10) = \mathbf{\$0.08}$$

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1.6: Energy Use of Home Appliances

Calculating Energy Use

The previous section introduced the formula to calculate power as

$$Power = \frac{Energy}{Time} \tag{1.6.1}$$

and therefore

$$Energy = Power * Time \tag{1.6.2}$$

where time is the duration of usage. This formula can be slightly modified to give a formula for energy consumption per day, i.e.,

$$\frac{Energy\,Consumption}{day} = (Power\,Consumption) * \frac{Hours\,Used}{day} \tag{1.6.3}$$

where

- Energy consumption has units of kWh (like on utility bills)
- Power consumption has units of W
- Hours used per day is the number of hours that the appliance is used

Since we want to measure energy consumption in kWh, we must change the way power consumption is measured from watts to kilowatts. We know that $1kWh = 1,000Wh$, so we can adjust equation 1.6.3 to

$$\frac{Energy\,Consumption\,(kWh)}{day} = Power\,Consumption\,(W) * \frac{kW}{1000\,W} * \frac{Hours\,Used}{day} \tag{1.6.4}$$

Example 1

If you use a ceiling fan (200 watts) for four hours per day, and for 120 days per year, what would be the annual energy consumption?

Answer available at the end of this section.

Example 2

Using the results from Example 1, if the price per kWh for electricity is $.0845, what is the annual cost to operate the ceiling fan?

Answer available at the end of this section.

Example 3

If you use a personal computer (120 Watts) and monitor (150 Watts) for four hours per day, and for 365 days per year, what would be the annual energy consumption and cost?

Answer available at the end of this section.

Locating Wattage

Most appliances will have their wattage stamped on the bottom or back or on the "nameplate". This wattage denotes the maximum power drawn by the appliance. Since many appliances have a range of settings (for example, the volume on speakers), the actual amount of power consumed depends on the setting used at any one time.

A refrigerator, although turned "on" the entire time while being used, actually cycles on and off at a rate that depends on numerous factors, such as how well it is insulated, what the ambient and freezer temperatures are, how often the door is opened, if the coils are clean, if it is defrosted regularly, and how well the door seals function.

Table 1.6.1 shows the power consumption of some typical home appliances.

Table 1.6.1. Power consumption

Appliance	Wattage (range)
Clock radio	10
Coffee maker	900 - 1200
Clothes dryer	350 - 500
Dishwasher	1200 - 2400
Hair dryer	1200 - 1875
Microwave oven	750 - 1100
Laptop	50
Refrigerator	725
36" TV	133
Toaster	800 - 1400
Water heater	4500 - 5500

Amperes and Voltage

If the current instead of the wattage is listed on an appliance, one can estimate the wattage by multiplying the current (in amperes) drawn by the voltage used by the appliance. Most appliances in the U.S. use 120 volts. Larger appliances, including clothes dryers and electric cooktops, use 240 volts.

If neither the current nor wattage is listed, an ammeter can be used to find the current flowing through the appliance. Stores that sell electronics usually have ammeters. Use the ammeter while the appliance is running to obtain the current in that instance.

Phantom Loads

Many appliances will continue to draw a small amount of power even when they are switched "off" and increase the appliance's energy consumption by a few watts per hour. This occurs in most appliances that use electricity, such as TVs, VCRs, stereos, computers, and kitchen appliances.

Phantom loads can be avoided by unplugging the appliance or plugging the appliance into a power strip and cutting off all power to the appliance with the power strip switch.

Answers

Example 1

Using equation 1.6.4,

$$\frac{Energy\,Consumption}{day} = \frac{200}{1000} * \frac{4\,hrs}{day} = \frac{0.8\,kWh}{day}$$

The energy used for 120 days is

$$Energy\,Consumption = \frac{0.8\,kWh}{day} * 120\,days = \mathbf{96\,kWh}$$

Example 2

$$Annual\,Cost = 96\,kWh * \frac{\$0.0845}{kWh} = \mathbf{\$8.12}$$

Example 3

$$\frac{Energy\,Consumption}{day} = \frac{120 + 150}{1000} * \frac{4\,hr}{day} = 1.08\frac{kWh}{day}$$

$$Annual\,Energy\,Consumption = 1.08\frac{kWh}{day} * 365\,days = \mathbf{394.2\,kWh}$$

$$Cost = 394.2\,kWh * \frac{\$0.0845}{kWh} = \mathbf{\$33.30}$$

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2: ENERGY SUPPLY AND DEMAND

2.1: Global Energy Consumption
2.2: World Energy Outlook
2.3: Current and Future Energy Sources of the World
2.4: Growth in Energy Demand
2.5: Energy Reserves
2.6: Current and Future Energy Sources of the U.S.

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2.1: Global Energy Consumption

In 2015, the world used a total of 570.4 quadrillion BTUs. Table 2.1.1 shows the energy consumption in different parts of the world.

Table 2.1.1. World's total primary energy consumption (in quadrillion BTUs)

Region	1980	1985	1990	1995	2000	2005	2010	2015
North America	91.6	91.0	100	109	118	121	118	119.9
Central and South America	11.5	12.3	14.5	17.6	20.8	23.2	26.9	29.7
Europe	71.8	72.9	76.3	76.7	81.5	85.8	83.8	81.2
Eurasia	46.7	55.7	61.0	42.2	39.2	43	42.8	44.8
Africa	6.8	8.5	9.5	10.7	12.0	14.5	16.3	19.3
Asia and Oceania	48.9	58.1	73.4	93.5	111	149	194	239.9
World Total	**283**	**307**	**346**	**363**	**400**	**459**	**511**	**570.4**

From Table 2.1.1, it can be seen that the energy consumption is high for the Far East and Oceania. The amount of energy used depends on the economic prosperity of the nation and the population of the country. The North American region includes Canada, the United States, and Mexico. The Far East and Oceania include developed nations such as Japan and Australia, and densely populated developing nations such as China and India. Obviously, due to highly populated countries like China and India, total energy consumption does not reflect the quality of life of the people in those countries. Figure 2.1 shows the energy per capita consumption over the last 30 years. As can be seen from the graph that Far East and Oceania used a lot of energy as a region, but per capita energy consumption is relatively low implying that if each person in that region would consume as much as in North America, that Region's energy consumption would skyrocket.

The amount of energy consumed depends on numerous factors, including economic prosperity and population of the location. Table 2.1.1 shows that energy consumption is high in Asia and Oceania, since these areas include densely populated regions like China and India.

Figure 2.1.1 shows the energy consumption per capita.

Figure 2.1.1. Energy consumption per capita (MMBTU per person) in 1980 - 2010

Credit: Sarma Pisupati

Although Table 2.1.1 shows high energy consumption in Asia and Oceania, Figure 2.1.1 shows low energy consumption *per capita* in Asia and Oceania, implying that if each person in those regions consumed as much energy as in places like North America with high energy per capita, the overall energy consumption (i.e., values in Table 2.1.1) of Asia and Oceania would drastically increase. This difference also implies that overall energy consumption is not an indicator of quality of life.

The productivity of a country is measured by the total value (in dollars) of goods and services, called **Gross Domestic Product (GDP)**, produced by its people. Thus, the average value of goods and services produced by each person, i.e., the **GDP per capita** of a country, is an indicator of quality of life.

Energy intensity is the relationship between energy consumption and economic growth and is an important factor that affects energy consumption over time. In industrialized countries, history has shown that the link between energy consumption and economic growth to be relatively weak, as growth in energy demand lags behind economic growth. In contrast, in developing countries, this link has been strong, as energy demand has grown parallel to economic growth. Figures 2.1.2 and 2.1.3 show the correlations.

Figure 2.1.2. Energy consumption as a function of quality of life in industrialized countries. Energy demand is constantly lower than economic growth.

Credit: Sarma Pisupati

Figure 2.1.3. Energy consumption as a function of quality of life in developing countries. Energy demand is relatively close in value to economic growth.

Global Energy Consumption and GDP per person

In general, as the GDP per person (i.e., per capita) of a country increases, the energy consumption is also expected to increase. This correlation is much stronger in developing nations compared to developed ones. Figure 2.1.4 shows this correlation.

Figure 2.1.4. Energy consumption as a function of quality of life in developing and developed nations

As shown in Figure 2.1.4, Iceland, Finland, the U.S., and the Netherlands, all with similar GDP per capita, have significant differences in energy consumption per capita. To produce one dollar's worth of goods and services, the U.S. consumes twice the amount of energy as that of the Netherlands, while Iceland consumes four times the energy as that of the Netherlands.

Energy Consumption Differences

The differences in energy consumption are caused by various factors, including:

- Efficiency of industrial, transportation, commercial, and residential energy
- Climactic and geographical areas of a country
- Lifestyles (for example, use of more gas-guzzling cars or bigger houses)
- The nature of products produced by the nation's industries

Figures 2.1.5 and 2.1.6 illustrate the differences in energy usage between two different areas.

Figure 2.1.5. New York City

Credit: Superheros and Villains by Andreas Komodromo is licensed under CC BY-NC 2.0

Figure 2.1.6. Bangladesh

Credit: Signs on the river bank by abrinsky is licensed under BY-NC-SA-2.0

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2.2: World Energy Outlook

The world energy requirements are projected by several energy companies, including British Petroleum and Exxon Mobil, as well as international agencies like the International Energy Agency (IEA) and the U.S. Energy Information Administration (EIA). The U.S. Department of Energy projects strong growth for worldwide energy demand over the 28-year projection period from 2012 to 2040. Although these projections are based on the same principles, they differ slightly. Further details on each organization can be found in the links below.

- International Energy Agency
- British Petroleum
- Exxon Mobil
- US Energy Information Administration (EIA)

According to the International Energy Outlook 2019,

- Manufacturing centers are shifting towards Africa and South Asia, especially India, resulting in increased energy consumption. Most economic growth occurs in non-OECD (Organisation for Economic Co-operation and Development) countries, where the GDP per person nearly triples from 2018 to 2050.
- The total world energy consumption is likely to increase from 591 quadrillion BTUs in 2016 to 910 quadrillion BTUs in 2040 (a 54% increase).
- The most energy-intensive manufacturing have shifted to non-OECD Asia and, increasingly, to India.

The world's GDP (expressed in purchasing power parity terms) is projected to rise by 2.4% per year from 2018 to 2040, with the fastest growth rates occurring in emerging, non-OECD countries where combined GDP is predicted to increase by 3.5% per year. In OECD countries, GDP is set to grow at a much slower rate of 1.5% per year from 2018 to 2040.

Fun Fact

Asia is heavily populated and continues to grow at a rapid pace. As a result, industrial growth has also increased, requiring a need for more energy.

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2.3: Current and Future Energy Sources of the World

The World's Energy Supply Sources

Figures 2.3.1 and 2.3.2 show the world's energy supply sources in 2013 and 1973, respectively.

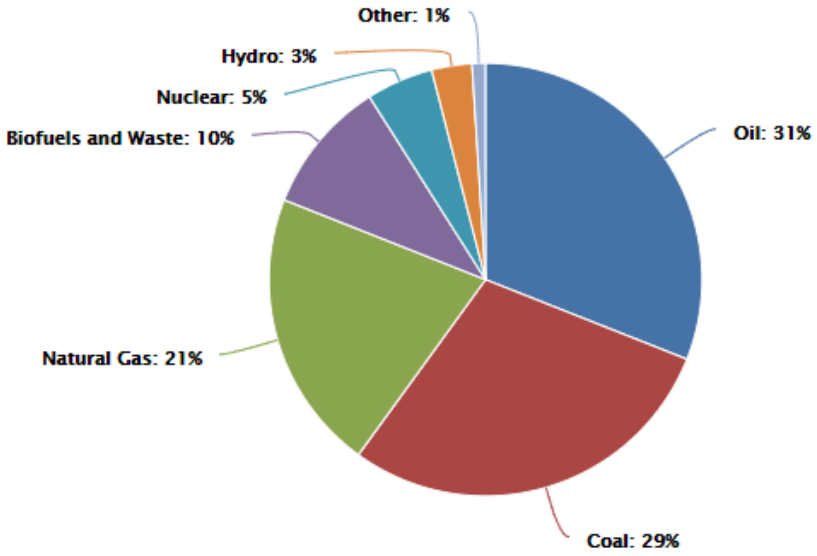


Figure 2.3.1. World's energy consumption in 2013 by fuel source (537 quads)

Data source: International Energy Agency, 2015

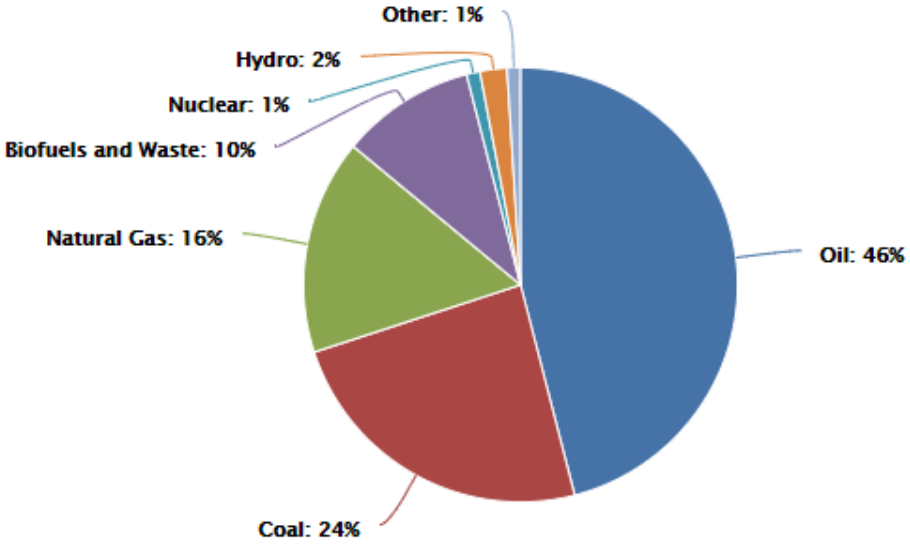


Figure 2.3.2. World's energy consumption in 1973 by fuel source (242 quads)

Data source: International Energy Agency, 2015

Figure 2.3.3 shows the projected world energy consumption in 2040.

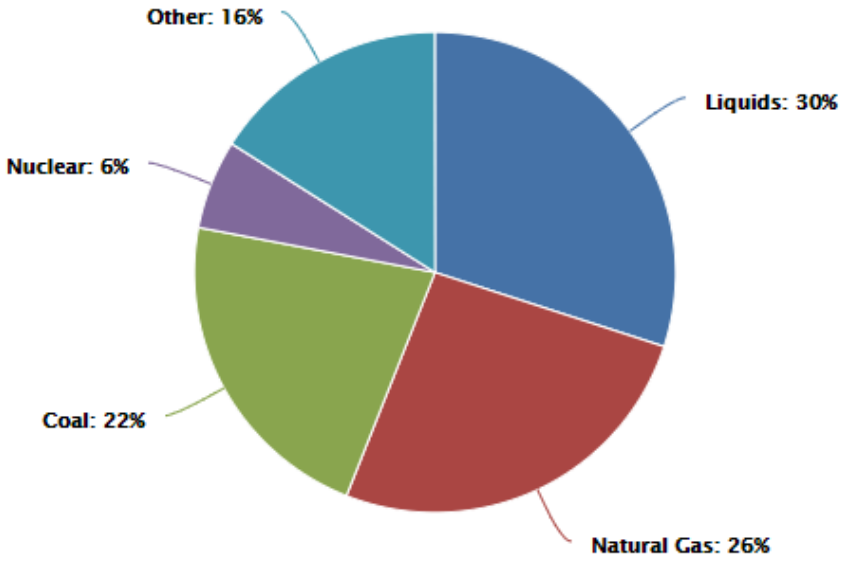


Figure 2.3.3. Projected world energy consumption in 2040 (815 quads)

Credit: Sarma Pisupati, Data source: Energy Information Administration, International Energy Outlook, 2016

Three of the World's Largest Energy Sources

Currently, the three largest energy sources are oil, natural gas, and coal (all fossil fuels). Table 2.3.1 provides further information on each source.

Table 2.3.1. Projections and comparisons of the largest energy sources

Source	Future Outlook	Advantages/Disadvantages
Oil	Over the past four decades, oil has been the world's foremost source of primary energy consumption, and it is expected to remain in that position throughout the projected time frame. Liquids (primarily oil and other petroleum products) are expected to continue to provide the largest share of world's energy consumption over the projected period.	In the transportation sector, in particular, liquid fuels continue to provide most of the energy consumed. Although advances in nonliquid-based transportation technologies are anticipated, they are not enough to offset the rising demand for transportation services worldwide. Thus, oil is projected to retain its predominance in the global energy mix and meet 30% of the total primary energy consumption in 2040.
Natural gas	Worldwide natural gas consumption is projected to increase from 120 trillion cubic feet (Tcf) in 2012 to 203 Tcf in 2040. By energy source, natural gas accounts for the largest increase in world primary energy consumption. Abundant natural gas resources from shale resources and robust production contribute to the strong competitive position of natural gas among other resources. Natural gas remains a key fuel in the electric power sector and in the industrial sector.	Natural is seen as the desired option for electric power, given its relative efficiency and environmental advantages in comparison with other fossil energy sources. Natural gas burns more cleanly than either coal or oil, making it a more attractive choice for countries seeking to reduce greenhouse gas emissions.

Source	Future Outlook	Advantages/Disadvantages
Coal	Coal is the world's slowest-growing energy source, rising by an average 0.6% per year, from 153 quadrillion BTUs in 2012 to 180 quadrillion BTUs in 2040. Throughout the projection, the top three coal-consuming countries are China, the United States, and India, which together account for more than 70% of world coal use. Coal use will continue to increase in developing countries, but in developed or industrialized countries, it may slightly decrease.	Global coal production is projected to increase from 9 billion short tons in 2012 to 10 billion short tons in 2040. Most of the projected growth in world coal production occurs in India, China, and Australia. Coal remains a vital fuel for the world's electricity markets and is expected to continue to dominate energy markets in developing parts of Asia.

Electricity

According to International Energy Outlook 2016, the strongest growth in electricity generation is projected to occur among the developing, non-OECD nations. Increases in non-OECD electricity generation average 2.5% per year from 2012 to 2040, as rising living standards increase demand for home appliances and electronic devices, as well as for commercial services, including hospitals, schools, office buildings, and shopping malls. In the OECD nations, where infrastructures are more mature and population growth is relatively slow or declining, electric power generation increases by an average of 1.2% per year from 2012 to 2040.

Figure 2.3.4 shows the energy generation of various sources.

Figure 2.3.4. World net electricity generation by fuel type

Credit: World net electricity generation by fuel type by www.EIA.gov

Nuclear Power

Worldwide, electricity generation from nuclear power is projected to increase from 2.6 trillion kWh in 2015 to 4.5 trillion kWh in 2040.

According to International Energy Outlook 2016 projections by US Department of Energy (US DOE), there is still considerable uncertainty about the future of nuclear power, and a number of issues could slow the development of new nuclear power plants. Issues related to plant safety, radioactive waste disposal, and proliferation of nuclear materials continue to raise public concerns in many countries and may hinder plans for new installations.

Although the long-term implications of the disaster at Japan's Fukushima Daiichi nuclear power plant for world nuclear power development are unknown, Germany, Switzerland, and Italy have already announced plans to phase out or cancel all their existing and future reactors. In contrast, developing Asia is poised for a robust expansion of nuclear generation. Most of the increase is by China's addition of 139 gigawatts (GW) of nuclear capacity from 2012 to 2040.

Fun Fact

In a nuclear plant, heat is produced by nuclear fission (splitting of an atom's nucleus into many new atoms) inside uranium fuel. As a result of fission, heat energy is released and the steam spins a turbine generator to produce electricity.

Hydroelectricity

Moderate growth in the world's consumption of hydroelectricity and other renewable energy resources is projected over the next 25 years, averaging 1.9% per year. Much of the projected growth in renewable generation is expected to result from the completion of large hydroelectric facilities in developing countries, particularly in developing Asia. China, India, and other

developing Asian countries are constructing or planning new, large-scale hydroelectric facilities.

Among the industrialized nations, only Canada has plans to construct any sizable hydroelectric projects over the forecast period. Much of the expected increment in renewable energy consumption in the industrialized world is projected to be non-hydropower renewable energy sources, including particularly wind energy in Western Europe and the U.S. In addition, biomass and geothermal energy sources are expected to grow rapidly in the U.S.

Fun Fact

In hydroelectricity, mechanical energy from the water being pulled downward by gravity is converted to electrical energy. More specifically, a hydroelectric generator directs the flow of water through a turbine, which extracts the kinetic energy from the movement of the water and turns it into electricity through the rotation of electrical generators. **Hydropower** is the largest single renewable electricity source today, providing 16% of world electricity at competitive prices. It dominates the electricity mix in several countries, developed, emerging, or developing.

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2.4: Growth in Energy Demand

Growth in the world and the U. S. energy consumption as a function of time, follow what is known as exponential function. The exponential increase is characterized using

$$\frac{\Delta N}{\Delta t} \propto N \tag{2.4.1}$$

or

$$\frac{\Delta N}{\Delta t} = \lambda N \tag{2.4.2}$$

where Δ (the Greek letter delta) is the change or increment of the variable and λ (lambda) is the growth rate. After some mathematical methods, it can be shown that the equation changes to the form

$$N = N_0 e^{\lambda t} \tag{2.4.3}$$

where e is a constant that equals 2.71.

We can determine how long it takes for N_0 to become $2N_0$ (twice its original number or double). That time period is called **doubling time**. After some mathematical steps it can be written as

$$Doubling\,Time = \frac{70}{\%\,Growth\,Rate\,per\,Year} \tag{2.4.4}$$

Example

Use of coal is projected to increase at the rate of 1.7% per year in the U.S. How long will it take to double its usage?

Answer available at the end of this section.

Answers

Example

Using equation 2.4.4,

$$Doubling\,Time\,(years) = \frac{70}{1.7} = 41.17 years$$

Thus, in **41.17 years**, the consumption of coal will be twice as much as it is today.

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2.5: Energy Reserves

It is clear so far that the energy requirement is going to increase in the future and also that the U.S. and the rest of the world will depend on fossil fuels. These fossil fuels are non-renewable fuels with a finite lifetime. So, the question is: Will we have enough supply for future energy requirements?

The answer to this question depends on the quantity of fossil fuels we have in the ground. Energy sources that have been discovered but not produced cannot be easily measured. Trapped several feet below the surface, they cannot be measured with precision. There are several terms used to report the estimates of the energy resources. Most commonly used terms are “reserves” and “resources.”

- "Reserves" represent that portion of demonstrated resources that can be recovered economically with the application of extraction technology available currently or in the foreseeable future. Reserves include only recoverable energy.
- “Resources” represent that portion of the energy that is known to exist or even suspected to exist irrespective of technical or economic viability. So reserves are a subset of resources.

Table 2.5.1 shows the consumption of the different types of fossil fuels.

Table 2.5.1. Annual consumption and available reserves of different non-renewable energy sources for the U.S. and the world.

	U.S. Reserves	U.S. Annual Consumption	World Reserves	World Annual Consumption
Petroleum (billions of barrels) as of Dec. 31, 2016	35	7.21	1707	35
Natural gas, wet (trillion cubic ft) as of Dec. 31, 2016	324	32.1	6588	124
Coal (billions of short tons) as of Dec. 31, 2016	260	0.73	948	8.28

As of December 31, 2016, total world proved recoverable reserves of coal were estimated at 948 billion short tons.

Five countries have nearly 73% of the world's coal reserves:

- United States—28%
- Russia—18%
- China—13%
- Australia—9%
- India—7%

Based on data from OPEC (Oil Producing and Exporting Countries) at the beginning of 2013 the highest proved oil reserves including non-conventional oil deposits are in

- Venezuela (20% of global reserves)
- Saudi Arabia (18% of global reserves)
- Canada (13% of global reserves)
- Iran (9%)
- Iraq (8%)

Based on data from BP (British Petroleum), at the end of 2016 proved gas reserves were dominated by three countries: Iran, Russia, and Qatar, which together held nearly half the world's proven reserves. According to the US CIA The World Factbook, the US has the 5th largest reserves of natural gas. Due to constant updates about the shale gas estimates, these are difficult to say with certainty.

How Long Will the Reserves Last?

How long these reserves do last depends on the rate at which we consume these reserves. For example, let's assume that we have $100,000 in the bank (reserves) and it we draw $10,000 every year (consumption) the reserve will last for 10 years. However, in this case, we are assuming that we do not add any money to our deposit and we do not increase our withdrawal.

This is generally not true in the case of life of an energy reserve. We may find new reserves and our energy consumption or production can also increase. In the case of energy reserve, although we know that we might find new resources, we do not know how much we could find. But the consumption can be predicted with some accuracy based on the past rates.

Lifetime of Current Reserves at Constant Consumption

We can calculate the life of current petroleum reserves by dividing the current reserves by current consumption.

- At the current rate of consumption, the approximate lifetime of the world's petroleum, natural gas, and coal reserves is 50 years, 52.8 years, and 153 years, respectively. (BP Statistical Review of World Energy)
- At the current rate of consumption, the current U. S. petroleum, natural gas, and coal reserves will last approximately for 4.88 years, 12.2 years, and 258 years, respectively.

It is important to note that the entire U.S. petroleum consumption is not coming from the U.S. reserves because we import more than one half of the consumption. Because we import more than one half of the consumption, the petroleum reserves at the current rate will last about 11 years. If the consumption increases in the future, the life will be less. However, there is also a chance of adding more reserves with more exploration and discoveries. The increase in consumption can change depending on the price of petroleum and other alternative fuels.

Therefore, these lifetimes are not carved in stone. It can be debated whether the U.S. reserves will last for 6 years or 10 years or even 20 years, but there is increasing consensus that we must change our lifestyle.

The R/P ratio can change from year to year similar to our bank balance. We can add more if we make more or consume more. That changes the time we can draw on the balance.

Figures 2.5.1, 2.5.2, and 2.5.3 illustrate that these ratios changed for coal, oil, and natural gas.

Figure 2.5.1. Variation of R/P ratio over time for coal. *Credit: Data from British Petroleum*

R/P for oil shows supply rates staying about the same.

Figure 2.5.2. Variation of R/P ratio over time for oil

R/P for Natural Gas shows a decline in rates in the Middle East, rates in other regions stay about the same.

Figure 2.5.3. Variation of R/P ratio over time for natural gas

Therefore, we must conserve, innovate (get more with less), or learn to live without these resources.

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2.6: Current and Future Energy Sources of the U.S.

Figure 2.6.1 shows the distribution of energy consumption in the U.S.

Figure 2.6.1. The 2019 energy flow chart released by the Lawrence Livermore National Laboratory details the sources of energy production, how Americans are using energy, and how much waste exists.

Figure 2.6.2 shows the quantities of fossil fuels imported by the U.S.

Figure 2.6.2. U.S. energy imports between 1950 and 2019

Credit: EIA Energy Explained

It can be observed from Figure 2.6.2 that the U.S. Crude oil imports have significantly reduced between 2005 and 2019 from a peak of 25 quadrillion BTUs. Another significant change that can be noted is that the U.S. is now exporting natural gas (below zero on the vertical axis) instead of importing it. Although crude oil is imported, US exports finished petroleum products resulting in less net imports. As a matter of fact, U.S. total energy exports exceeded the imports in 2019 since 1950.

The top five countries (sources) of U.S. total petroleum in 2019 were Canada (49%), Mexico (7%), Saudi Arabia (6%), Russia (6%) and Columbia (4%).

The U.S. also ranks:

- first in worldwide reserves of coal;
- sixth in worldwide reserves of natural gas;
- eleventh in worldwide reserves of oil.

Figure 2.6.3 shows the worldwide energy flow.

Figure 2.6.3. Total energy flow (quadrillion BTUs) in 2019

Credit: Monthly Energy Review, May 2020

US Energy Consumption by Source and the chart of the U.S. Energy consumption by source and user sector shows each energy source and the amount of energy it supplies in British thermal units (BTU). Petroleum is the leading source of energy in the U.S. in 2019 with 36.72 quadrillion BTUs. Next is natural gas with 32.10 quadrillion BTUs. Coal supplies 11.31 quadrillion BTUs of energy. Renewable energy and nuclear power are responsible for 11.46 and 8.46 quadrillion BTUs respectively. Of the total petroleum consumption, 72% is used for transportation and another 23% is used by the industrial sector. Similarly, 35% of the natural gas (largest fraction) is used for power generation. On the other hand, 76% of the residential and commercial energy needs are met by natural gas.

U.S. Energy Consumption by Source and Sector

The graph shows how dependent the U.S. is on our petroleum supply, as it accounts for almost 37% of our energy. Our next two highest sources of energy, like petroleum, are non-renewable and include natural gas and coal. Only about 11% of our energy comes from renewable energy sources such as wood and water (hydroelectricity). According to Energy Information Administration, U.S. renewable energy consumption surpassed coal for the first time in over 130 years in 2019. Of the 4.12 trillion kWh of electricity generated in the US, 38% was from natural gas, coal accounted for about 23% and nuclear adding another 20%. Renewable sources contributed to 17% of the total electricity generated.

Figure 2.6.4 shows the distribution of energy consumption in the U.S. by sector.

Figure 2.6.4. Graph of U.S. energy consumption by source and use by end sectors

Credit: Energy Review Monthly, May 2020 by EIA

U.S. Energy Consumption over Time

Figure 2.6.5 shows U.S. energy consumption over time.

Figure 2.6.5. U.S. primary energy consumption history (quadrillion BTUs)

Credit: US EIA, Energy Monthly Review June 2016

Figure 2.6.6 focuses on renewable energy sources in the U.S.

Figure 2.6.6. U.S. renewable energy consumption history

Credit: US EIA Energy Review Monthly, June 2016

In 2019, fossil fuels made up 81% of total U.S. energy consumption, the lowest fossil fuel share in the past century. According to EIA projections, the percentage declines to 76.6% by 2040. Policy changes or technology breakthroughs that go beyond the trend improvements could significantly change that projection. In 2019, the renewable share of energy consumption in the United States was its largest since the 1930s at nearly 11.7%. The greatest growth in renewable energy sources over the past decade has been in solar and wind electricity generation. Liquid biofuels have also increased in recent years, contributing to the growing renewable share of total energy consumption.

The most significant decline in recent years has been coal: U.S. coal consumption fell by 41% since 2009 in a decade, from 997 million tons to 587 million tons. Biomass, which includes wood as well as liquid biofuels like ethanol and biodiesel, remain relatively flat, as wood use declines and biofuel use increases slightly. In contrast, wind and solar are among the fastest-growing energy sources in the projection, ultimately surpassing biomass and nuclear, and nearly exceeding coal consumption by 2040.

Figure 2.6.7 compares the energy consumption in 2012 with what is projected in 2035.

Figure 2.6.7. U.S. energy consumption history

Credit: US EIA Energy Review Monthly, June 2016

Energy Sources in the U.S. and Their Future Outlook

Table 2.6.1 summarizes the U.S.'s energy sources and their future outlook.

Table 2.6.1. Comparisons of the different types of fossil fuels (the primary energy sources, currently) in the U.S.

Source	Future Outlook	Advantages/Disadvantages
Oil	Petroleum demand is projected to grow from 19.17 million barrels per day in 2010 to 19.9 million barrels per day in 2035.	Approximately 72.1% of the petroleum in the U.S. is used for transportation, and about 22.5% is used by the industrial sector.

Source	Future Outlook	Advantages/Disadvantages
Natural gas	Total dry natural gas production in the U.S. increased by 35% from 2005 to 2013, with the natural gas share of total U.S. energy consumption rising from 23% to 28%. Production growth resulted largely from the development of shale gas resources. In 2009, production stood at 20.65 trillion cubic feet (Tcf), net imports at 2.68 Tcf, and consumption at 22.85 Tcf. The projections for domestic natural gas consumption in 2030 is 26.1 trillion cubic feet per year, as compared with 24.13 trillion cubic feet in 2010. In the reference case, natural gas consumption in the electric power sector is projected to increase from 7.38 trillion cubic feet in 2010 to a peak of 8.08 trillion cubic feet in 2015. Natural gas use in the electric power sector declines after 2020, to 7.87 trillion cubic feet in 2025, as new coal-fired generating capacity displaces natural-gas-fired generation. Continued growth in residential, commercial, and industrial consumption of natural gas is roughly offset by the projected decline in natural gas demand for electricity generation. As a result, overall natural gas consumption is almost flat between 2020 and 2025.	The EIA forecasts greater dependence on more costly supplies of natural gas, such as imports of Liquefied Natural gas (LNG), and remote resources from Alaska and the Mackenzie Delta in Canada. LNG imports, Alaskan production, and production in the 48 States from nonconventional sources are not expected to increase enough to offset the impacts of resource depletion and increased demand. The industrial sector was the largest consuming sector of natural gas. Production of gas from shale (such as Marcelleus) is likely to change the natural gas usage very quickly. Gas can be converted to oil. New gas to liquid fuel plants in the U.S. are likely to change the oil imports scenario in the next two decades.
Coal	Between 2008 and 2013, U.S. coal production fell by 187 million short tons (16%), as declining natural gas prices made coal less competitive as a fuel for generating electricity. U.S. coal production increases at an average rate of 0.7%/year from 2013 to 2030, from 985 million short tons (19.9 quadrillion BTUs) to 1,118 million short tons (22.4 quadrillion BTUs). Over the same period, rising natural gas prices, particularly after 2017, contribute to increases in electricity generation from existing coal-fired power plants as coal prices increase more slowly. After 2030, coal consumption for electricity generation levels off through 2040.	Compliance with the Mercury and Air Toxics Standards (MATS), coupled with low natural gas prices and competition from renewables, leads to the projected retirement of 31 gigawatts (GW) of coal-fired generating capacity and the conversion of 4 GW of coal-fired generating capacity to natural gas between 2014 and 2016. However, coal consumption in the U.S. electric power sector is supported by an increase in output from the remaining coal-fired power plants, with the projected capacity factor for the U.S. coal fleet increasing from 60% in 2013 to 67% in 2016. In the absence of any significant additions of coal-fired electricity generating capacity, coal production after 2030 levels off as many existing coal-fired generating units reach maximum capacity factors and coal exports grow slowly. Total U.S. coal production remains below its 2008 level through 2040.

In 2010, domestic supply was 14.72 million barrels per day, and net imports were 9.17 million barrels per day. The trend of increasing U.S. dependence on imported oil in the past decade is expected to continue.

In 2015, the United States imported approximately 9.4 million barrels per day (MMb/d) of petroleum from about 82 countries. Petroleum includes crude oil, natural gas plant liquids, liquefied refinery gases, refined petroleum products such as gasoline and diesel fuel, and biofuels including ethanol and biodiesel. About 78% of gross petroleum imports were crude oil. In 2015, the United States exported about 4.8 MMb/d of petroleum to 136 countries. Most of the exports were petroleum products. The resulting net imports (imports minus exports) of petroleum were about 4.6 MMb/d.

Net U.S. imports of energy declined from 30% of total energy consumption in 2005 to 13% in 2013 and down to 7.6 % in 2017, as a result of strong growth in domestic oil and dry natural gas production from tight formations and slow growth of total energy consumption.

US Energy Consumption History

A pie chart of US energy consumption in 2012 shows the percentage of each type of energy that was consumed for that year. Renewables 8%, nuclear 9%, coal 21%, natural gas 25%, and oil 37%. A second pie chart of the US energy consumption in 2035 shows the prediction of the percentage of each type of energy that will be consumed for that year. Renewables 16%, nuclear 9%, coal 20%, natural gas 26%, and oil 32%. The history of the energy consumption profile of the United States indicates that petroleum makes the largest part of the energy demand over the past seven decades. Natural gas has taken the second over the past decade with the production of gas from shale. Coal is slowly being replaced by natural gas for power generation over the past decade. Renewable energy is growing at a much faster rate. Among the renewable energy sources, biomass has the larger share followed by hydroelectric energy. Wind energy and solar energy are the fastest growing energy sources.

US Vehicle Fuel Consumption

Table 2.6.2 below shows vehicle fuel consumption and travel.

Table 2.6.2. U.S. vehicle fuel consumption and travel from 1960 to 2018 (unless otherwise indicated)

	1960	1970	1980	1990	2000	2010	2018
Vehicles registered (thousands)[a]	73,858	111,242	161,490	193,057	225,821	250,070	273,602
Vehicle-miles traveled (millions)	718,762	1,109,724	1,527,295	2,144,362	[R]2,746,925	2,967,266	3,269,088
Fuel consumed (million gallons)	57,880	92,329	114,960	130,755	[R]162,554	169,679	176,444 (2016)
Average miles traveled per vehicle (thousands)	9.7	10.0	9.5	11.1	12.2	11.8	11.9
Average miles traveled per gallon	12.4	12.0	14.9	18.8	20.0	21.5	22.3
Average fuel consumed per vehicle (gallons)	784	830	712	677	[R]720	678	644

[R] = revised, [a] = includes personal passenger vehicles, buses, and trucks.

Sources:

- *1960-94: U.S. Department of Transportation, Federal Highway Administration, Highway Statistics Summary to 1995, FHWA-PL-97-009 (Washington, DC: July 1997), table VM-201A.*
- *1995-2005: Ibid., Highway Statistics (Washington, DC: Annual issues), table VM-1*
- *U.S. Department of Transportation, Federal Highway Administration, Highway Statistics 2010*

Electricity

U.S. electricity generation is expected to grow from 3.7 trillion kWh in 2015 to 4558 kWh in 2035. The webpage US electricity explained - Sources and profiles has more details. Notice, in this webpage,

- Sources of U.S. electricity generation
- Notable changes in the major sources for electricity generation between 1950 and 2019
- Role of renewable energy in the electricity generation

Growth in electricity use for computers, office equipment, and electrical appliances in the residential and commercial sectors is partially offset by improved efficiency in these and other, more traditional electrical applications, by the effects of demand-side management programs, and by slower growth in electricity demand for some applications, such as air conditioning.

Most capacity additions over the next 10 years are natural-gas-fired plants, increasing the natural gas share to 26% and lowering the coal share to 20% in 2035. Nuclear and renewable generation increase as new plants are built stimulated by Federal tax

incentives and rising fossil fuel prices. The nuclear generation (about 9 percent of total electricity supply in 2012) is projected to remain at about 9% in 2035. Generation from renewable resources is expected to rise from 8% in 2012 to 16% in 2035.

Additional Information

Demand-side management programs address efficiency. By being more efficient, we can do more with less, and then reduce the demand for energy.

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3: ENERGY EFFICIENCY

3.1: Energy Conversion Devices
3.2: Efficiency of Energy Conversion Devices
3.3: Measuring Thermal Energy
3.4: Kelvin Scale
3.5: Heat Engines
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3.1: Energy Conversion Devices

In Chapter 1, we saw that energy can be transformed from one form to another, and during this conversion, all the energy that we put into a device comes out. However, all the energy that we put in may not come out in the desired form.

For example, as depicted in Figure 3.1.1, we put electrical energy into a bulb and the bulb produces light (which is the desired form of output from a bulb), but we also get heat from the bulb (undesired form of energy from an electric bulb).

Figure 3.1.1. Electrical energy conversion to light and heat

Therefore, energy flow into and out of any energy conversion device can be summarized in Figure 3.1.2 below.

Figure 3.1.2: Energy flow diagram for an energy conversion device

When all forms of energy coming out of an energy conversion device are added up, it will be equal to the energy that is put into a device. Energy output must be equal to the input. This means that energy can not be destroyed or created. It can only change its form.

In the case of an electric bulb, the amount of electrical energy put into a bulb equals the amount of light energy (desirable form) plus the heat energy that comes out of the bulb (undesirable form).

Additional Information

Say you go to the mall with $100 and you come back with only $10. You need to account for the $90 that was spent. After thinking about it, you come up with the following list:

Gas ($15); Sandwich, fries, and a drink ($8); Lost ($5); New clothes ($62)

So you spent $62 on something useful - the clothes - but you spent additional money for other things that were necessary for your trip to the mall.

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3.2: Efficiency of Energy Conversion Devices

Efficiency is the useful output of energy and is calculated using

$$Efficiency = \frac{Useful\ Energy\ Output}{Total\ Energy\ Output} \tag{3.2.1}$$

Example 1

An electric motor consumes 100 watts (a joule per second (J/s)) of power to obtain 90 watts of mechanical power. Determine its efficiency.

Answer available at the end of this section.

For extra practice similar to Example 1, use this link to generate random practice problems.

Example 2

The United States' power plants consumed 39.5 quadrillion Btus of energy and produced 3.675 trillion kWh of electricity. What is the average efficiency of the power plants in the U.S.?

Answer available at the end of this section.

For extra practice similar to Example 2, use this link to generate random practice problems.

Energy Efficiencies

Energy efficiencies are not 100% and sometimes they are pretty low. Table 3.2.1 shows typical efficiencies of some of the devices that are used in everyday life.

Table 3.2.1. Typical efficiencies of day to day devices

Device	Efficiency
Electric motor	90%
Home gas furnace	95%
Home oil furnace	80%
Home coal stove	75%
Steam boiler in a power plant	90%
Overall power plant	36%
Automobile engine	25%
Electric bulb (incandescent)	5%
Electric bulb (fluorescent)	20%

From our discussion on national and global energy usage patterns in Chapter 2, we have seen that

- About 40% of the US energy is used in power generation
- About 27% of the US energy is used for transportation

Yet the energy efficiency of a power plant is about 35%, and the efficiency of automobiles is about 25%. Thus, over 62% of the total primary energy in the U.S. is used in relatively inefficient conversion processes.

Why are power plant and automobile design engineers allowing this? Can they do better?

It turns out that there are some natural limitations when converting energy from heat to work.

Answers

Example 1

Input to the electric motor is in the form of electrical energy and the output is mechanical energy.

Using equation 3.2.1,

$$Efficiency = \frac{Mechanical\ Power}{Electrical\ Power} = \frac{90\,W}{100\,W} = 0.9$$

Therefore, the efficiency is **90%**.

Caution: if the two variables were measured differently, you would need to convert them to equivalent forms before performing the calculation.

Example 2

Assume that the total energy input equals the total energy output.

$$Total\ Energy\ Input = 39.5 * 10^15\ BTUs$$

$$Useful\ Energy\ Output = 3.675 * 10^12\ kWh$$

We are given that 1 kWh = 3412 BTUs. Therefore, to convert all units to BTUs,

$$Useful\ Energy\ Output = 3.675 * 10^12\ kWh * \frac{3412\ BTUs}{kWh} = 1.254 * 10^16\ BTUs$$

Then, use equation 3.2.1 to obtain

\[Efficiency = \dfrac{1.254 * 10^16 \, BTUs}{39.5 * 10^15 \, BTUs} = 0.3174

Therefore, the power plants have an average efficiency of **31.74%**.

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3.3: Measuring Thermal Energy

Thermal energy is energy associated with random motion of molecules. It is indicated by temperature which is the measure of the relative warmth or coolness of an object.

A temperature scale is determined by choosing two reference temperatures and dividing the temperature difference between these two points into a certain number of degrees.

The two reference temperatures used for most common scales are the melting point of ice and the boiling point of water.

- On the **Celsius** temperature scale, or centigrade scale, the melting point is taken as 0°C and the boiling point as 100°C, with the difference between them being equal to 100 degrees.
- On the **Fahrenheit** temperature scale, the melting point is taken as 32°F and the boiling point as 212°F, with the difference between them being equal to 180 degrees.

It is important to realize, however, that the temperature of a substance is not a measure of its heat content, but rather, the **average kinetic energy of its molecules resulting from their motions.**

The following video compares the heat content and amount of energy in a 6-ounce vs. a 12-ounce cup of hot water at the same temperature. Some questions to consider are

1. Do they have the same heat content?
2. Do they have the same amount of energy?

YouTube Video

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View this YouTube Video online

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3.4: Kelvin Scale

When water molecules freeze at 0°C, the molecules still have some energy compared to ice at -50°C. In both cases, the molecules are not moving, so there is no heat energy.

So what is the temperature at which all the molecules have absolutely zero energy? A temperature scale can be defined theoretically for which zero degree corresponds to zero average kinetic energy. Such a point is called **absolute zero**, and such a scale is known as an **absolute temperature scale**. At absolute zero, the molecules do not have any energy.

The Kelvin temperature scale is an absolute scale having degrees the same size as those of the Celsius temperature scale. Therefore, all the temperature measurements related to energy measurements must be made on Kelvin scale.

You can convert a temperature in Celsius (c) to Kelvin (k) using the formula

$$k = c + 273.15 \tag{3.4.1}$$

You can also change a temperature in Kelvin to Celsius using the formula

$$c = k - 273.15 \tag{3.4.2}$$

To make calculations easier, you may round off and use just 273 in your conversions.

The following video shows what happens to an ice cube at different temperatures.

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3.5: Heat Engines

Figure 3.5.1 illustrates energy conversions in an automobile.

Figure 3.5.1. Energy conversions that occur in an automobile

Any device that converts thermal energy into mechanical energy—such as an automobile or a power plant—is called a heat engine. In these devices, high temperature heat (thermal energy) produced by burning a fuel is partly converted to mechanical energy to do work and the rest is rejected into the atmosphere, typically as a low temperature exhaust. Figure 3.5.2 shows an example of a heat engine.

Figure 3.5.2. Heat engine

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3.6: Carnot Efficiency

A general expression for the efficiency of a heat engine can be written as

$$Efficiency = \frac{Work}{Heat\ Energy\,(hot)} \tag{3.6.1}$$

We know that all the energy that is put into the engine has to come out either as work or waste heat. So work is equal to Heat at High temperature minus Heat rejected at Low temperature. Therefore, this expression becomes

$$Efficiency = \frac{Q_{hot} - Q_{cold}}{Q_hot} \tag{3.6.2}$$

where Q_{hot} is the heat input at high temperature and Q_{cold} is the heat rejected at low temperature. The symbol η (Greek letter eta) is often used for efficiency this expression can be rewritten as:

$$\eta'\,(\%) = 1 - \frac{Q_{cold}}{Q_{hot}} * 100\% \tag{3.6.3}$$

The above equation is multiplied by 100 to express the efficiency as percent.

French Engineer Sadi Carnot showed that the ratio of Q_{hot} to Q_{cold} must be the same as the ratio of temperatures of high temperature heat and the rejected low temperature heat. So this equation, also called **Carnot Efficiency**, can be simplified as:

$$\eta'\,(\%) = 1 - \frac{T_{cold}}{T_{hot}} * 100\% \tag{3.6.4}$$

Note

Unlike the earlier equations, the positions of T_{cold} and T_{hot} are reversed.

The Carnot Efficiency is the theoretical maximum efficiency one can get when the heat engine is operating between two temperatures:

- The temperature at which the high temperature reservoir operates (T_{hot}).
- The temperature at which the low temperature reservoir operates (T_{cold}).

In the case of an automobile, the two temperatures are:

- The temperature of the combustion gases inside the engine (T_{hot}).
- The temperature at which the gases are exhausted from the engine (Tcold).

The following video explains how automobile engines work.

YouTube Video

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Then, why should we operate the automobiles at low efficiencies?

It is not that we cannot achieve high temperatures, but we do not have the **engine materials** that can withstand the high temperature. As a matter of fact, we do not let the engine gases go the maximum that they can go even now and instead try to keep the engine cool by circulating the coolant.

So we are taking the heat out of the gases (thus lowering the T_{hot}) and making the engine operate at cooler temperatures so that the engine is protected - but lowering the efficiency of an automobile.

Additional Information

An analogy is taxes. The more money you earn (heat), the more money is taxed (cold), leaving you with less money to take home (efficiency). However, if you could earn more money (heat) and find a way to have less taxes taken out (better engine material), you would have more money to take home (efficiency).

Figure 3.6.1 shows two temperature scales. The scale labeled "HOT," shows the range of temperatures for the combustion of gases in a car engine. The scale labeled "COLD," shows the range of temperatures at which gases are exhausted from the car engine.

Figure 3.6.1. Hot and cold temperature scales in a typical car engine

Table 3.6.1 lists efficiencies as a function of hot and cold temperatures.

Table 3.6.1. Car engine efficiency (in %)

	Hot 500°C	Hot 600°C	Hot 700°C	Hot 800°C	Hot 900°C	Hot 1000°C	Hot 1500°C	Hot 2000°C
Cold 150°C	45	52	57	61	64	67	76	81
Cold 125°C	49	54	59	63	66	69	78	82
Cold 100°C	52	57	62	65	68	71	79	84
Cold 75°C	55	60	64	68	70	73	80	85
Cold 50°C	58	63	67	70	72	75	82	86
Cold 25°C	61	66	69	72	75	77	83	87

Example Problems

Example 1

For a coal-fired utility boiler, the temperature of high pressure steam (T_{hot})would be about 540°C and T_{cold}, the cooling tower water temperature, would be about 20°C. Calculate the Carnot efficiency of the power plant.

Answer available at the end of this section.

For extra practice problems, refer to this link.

Answers

Example 1

Carnot efficiency depends on high temperature and low temperatures between which the heat engine operates. We are given both temperatures. However, the temperatures need to be converted to Kelvin first.

$$T_{hot} = 540 + 273 = 813K$$

$$T_{cold} = 20 + 273 = 293K$$

Using equation 3.6.4,

$$\eta = (1 - \frac{293}{813}) * 100\% = 64\%$$

From the Carnot Efficiency formula, it can be inferred that a maximum of **64%** of the fuel energy can go to generation. To make the Carnot efficiency as high as possible, either T_{hot} should be increased or T_{cold} (temperature of heat rejection) should be decreased.

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3.7: Entropy and Quality of Energy

The following video shows energy conversions that occur in a power plant.

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The following video shows a demonstration of a small-scale power plant.

YouTube Video

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View this YouTube Video online

The following video quantitatively shows the basic energy conversions in the three main components of a power plant.

YouTube Video

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View this YouTube Video online

Figure 3.7.1 shows two temperature scales. The scale labeled "HOT," shows the range of temperatures for the combustion of gases in a power plant. The scale, "COLD," shows the range of temperatures at which gases are exhausted from the power plant.

Figure 3.7.1. Power plant temperatures. Red indicates power plant combustion temperatures while blue indicates exhausted gas temperatures.

Table 3.7.1 shows the power plant efficiencies at varying temperatures.

Table 3.7.1. Power plant efficiencies (in %) as a function of the hot and cold temperatures

	Hot 350°C	Hot 400°C	Hot 500°C	Hot 600°C	Hot 700°C	Hot 800°C	Hot 900°C	Hot 1000°C
Cold 300°C	8	15	26	34	41	47	51	55
Cold 250°C	16	22	32	40	46	51	55	59
Cold 200°C	24	30	39	46	51	56	60	63
Cold 150°C	32	37	45	52	57	61	64	67
Cold 100°C	40	45	52	57	62	65	68	71

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3.8: Overall Efficiency

Calculating Overall Efficiency

Using the energy efficiency concept, we can calculate the component and overall efficiency:

$$Overall\ Efficiency = \frac{Electrical\ Energy\ Output}{Chemical\ Energy\ Input} \tag{3.8.1}$$

Here the electrical energy is given in Wh and Chemical Energy in BTUs. So Wh can be converted to BTUs knowing that there are 3.412 Wh in a BTU.

This overall efficiency can also be expressed in steps as follows:

$$Overall\ Efficiency = \underbrace{\left[\frac{Thermal\ Energy}{Chemical\ Energy}\right]}_{Boiler\ Efficiency} * \underbrace{\left[\frac{Mechanical\ Energy}{Thermal\ Energy}\right]}_{Turbine\ Efficiency} * \underbrace{\left[\frac{Electrical\ Energy}{Mechanical\ Energy}\right]}_{Generator\ Efficiency} \tag{3.8.2}$$

$$Overall Efficiency = \eta_{boiler} * \eta_{turbine} * \eta_{generator} \tag{3.8.3}$$

Steps of Overall Efficiency

We have been looking at the efficiencies of an automobile or a power plant individually. But when the entire chain of energy transformations is considered—from the moment the coal is brought out to the surface to the moment the electricity turns into its final form—true overall efficiency of the energy utilization will be revealed. The final form at home could be light from a bulb or sound from a stereo. The series of steps are:

1. Production of coal (mining)
2. Transportation to power plant
3. Electricity generation
4. Transmission of electricity
5. Conversion of electricity into light (use)

The following video discusses overall power plant efficiency.

YouTube Video

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View this YouTube Video online

Efficiency of a Light Bulb

If efficiency of each step is known, we can calculate the overall efficiency of production of light from coal in the ground. Table 3.8.1 illustrates the calculation of overall efficiency of a light bulb.

Table 3.8.1. Calculation of overall efficiency of a light bulb

Step	Step Efficiency	Cumulative (Overall) Efficiency
Extraction of coal	96%	96%
Transportation	98%	94% = (0.96 * 0.98) * 100%
Electricity generation	35%	33% = (0.94 * 0.35) * 100%
Transmission of electricity	95%	31% = (0.33 * 0.95) * 100%
Lighting: incandescent bulb	5%	1.56% = (0.31 * 0.05) * 100%
Lighting: fluorescent bulb	20%	6.2% = (0.31 * 0.20) * 100%

Efficiency of an Automobile

A similar analysis on automobile efficiency is shown in Figure 3.8.1.

Figure 3.8.1. Overall automobile efficiency

Table 3.8.2 shows that only about 10% of the energy in the crude oil in the ground is in fact turned into mechanical energy moving people.

Table 3.8.2. Automobile efficiency

Step	Step Efficiency	Cumulative/Overall Efficiency
Extraction of crude oil	96%	96%
Refining	87%	84%
Transportation	97%	81%
Engine	25%	20%
Transmission	50%	10%

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4: ENERGY AND THE ENVIRONMENT

4.1: Fossil Fuels and Products of Combustion

4.2: Global and Regional Effects of Secondary Pollutants (I)

4.3: Global and Regional Effects of Secondary Pollutants (II)

4.4: Acid Rain and Ozone (I)

4.5: Acid Rain and Ozone (II)

4.6: Acid Rain and Ozone (III)

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4.1: Fossil Fuels and Products of Combustion

Fossil Fuel Elements

Fossil fuels are hydrocarbons comprised primarily of the following elements: carbon and hydrogen and some sulfur, nitrogen, oxygen, and mineral matter. Mineral matter turns into ash when burnt.

The composition and the amounts of these elements change for different fossil fuels (coal, petroleum, and natural gas), but the elements are the same, as shown in Figure 4.1.1. For example, there is more hydrogen in liquid fuels than in coal per unit mass.

Figure 4.1.1. Fossil fuel composition

Combustion is rapid oxidation of the fossil fuel's elements resulting in the generation of heat. When these elements oxidize (or combine with oxygen), products of combustion are formed.

Products of Combustion

Some of the fuel (hydrocarbon) may not completely burn during combustion and therefore is released into the atmosphere along with the products. The products that are formed during combustion of fossil fuels are shown in Figure 4.1.2.

Figure 4.1.2. Products formed during combustion of fossil fuels

We will now look at six products of combustion:

1. Carbon Dioxide
2. Carbon Monoxide
3. Sulfur Dioxide
4. Nitrogen Oxides
5. Lead
6. Particulate Matter

Carbon dioxide (CO_2)

Carbon dioxide is the principal product of combustion of fossil fuels since carbon accounts for 60–90 percent of the mass of fuels that we burn.

China has emerged as the largest single emitter of energy-related CO_2 emissions, reaching an all-time high of 8320 million metric tons of carbon dioxide in 2010. The United States emitted about 5610 million metric tons in 2010. Figure 4.1.3 shows the trend in carbon dioxide emissions from 1980. For Asia and Oceania, and particularly for China and India, emissions can be seen to have increased significantly in the past two decades.

Figure 4.1.3. Graph of CO_2 emission trends

Each of the end sectors (users) and their contribution (%) to the overall CO_2 emissions is shown in Table 4.1.1.

Table 4.1.1. Energy-related CO_2 emissions (million metric tons) by source and sector for the U.S. in 2011

Sources	Residential	Commercial	Industrial	Transportation	Electric Power	Source Total
Coal	1	5	151	0	1,718	1,874
Natural gas	256	171	419	39	411	1,296
Petroleum	78	49	345	1,802	25	2,299
Other					11	11
Electricity	827	767	567	4		
Sector total	1,162	992	1,482	1,845	2,166	5,481

Credit: US Energy Information Administration

Additional Information

In 2010, 41.9% of U.S. fossil-fuel emissions came from the consumption of petroleum products, and coal usage accounted for 35.4% of U.S. fossil-fuel CO_2 emissions. About 22.5% of the CO_2 emissions were a result of natural gas use.

Carbon Monoxide (CO)

Carbon monoxide, or CO, is a colorless, odorless gas that is formed when carbon in fuel is not burned completely. Figure 4.1.4 shows the contribution of various sources to the emissions of CO.

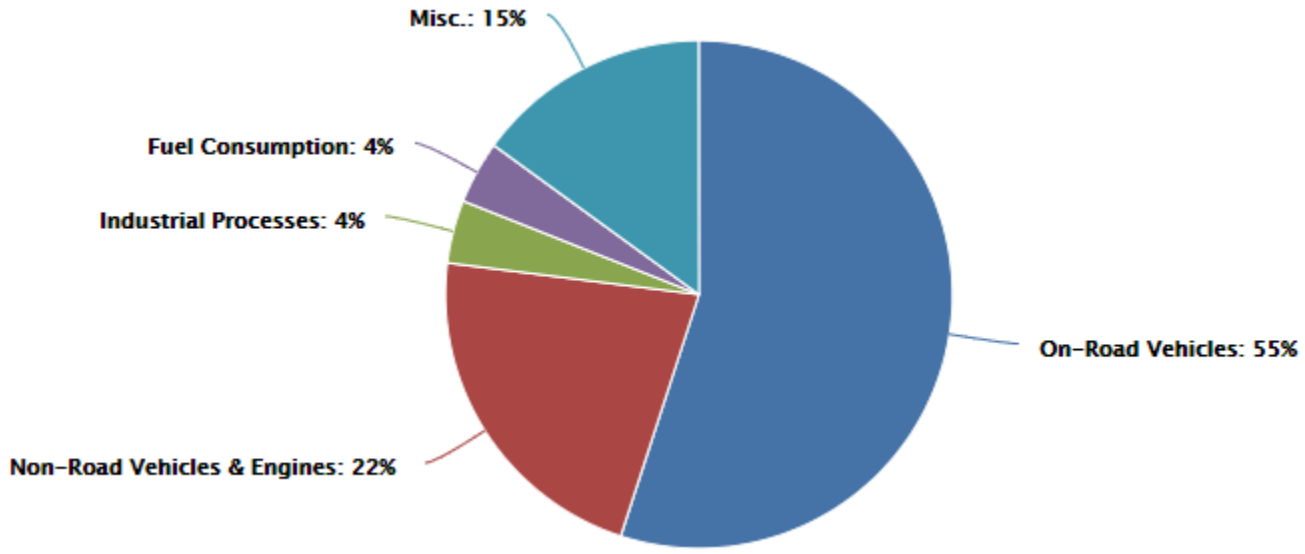


Figure 4.1.4. Sources of CO emissions

Carbon monoxide is a component of motor vehicle exhaust, which contributes about 55 percent of all CO emissions nationwide. Other non-road engines and vehicles (such as construction equipment and boats) contribute about 22 percent of all CO emissions nationwide. Higher levels of CO generally occur in areas with heavy traffic congestion. In cities, 85 to 95 percent of all CO emissions may come from motor vehicle exhaust.

Other sources of CO emissions include industrial processes (such as metals processing and chemical manufacturing), residential wood burning, as well as natural sources such as forest fires. Woodstoves, gas stoves, cigarette smoke, and unvented gas and kerosene space heaters are sources of CO indoors.

The highest levels of CO in the outside air typically occur during the colder months of the year when inversion conditions are more frequent. An inversion is an atmospheric condition that occurs when the air pollutants are trapped near the ground beneath

a layer of warm air.

Sulfur Dioxide (SO_2)

Sulfur dioxide, or SO_2, belongs to the family of sulfur oxide gases (SO_x). These gases dissolve easily in water. Sulfur is prevalent in all raw materials, including crude oil, coal, and ores that contain common metals, such as aluminum, copper, zinc, lead, and iron.

SO_x gases are formed when fuel containing sulfur, such as coal and oil, is burned, and when gasoline is extracted from oil, or metals are extracted from ore. A distribution of the emissions is shown in Figure 4.1.5. SO_2 dissolves in water vapor to form acid and interacts with other gases and particles in the air to form sulfates and other products that can be harmful to people and their environment.

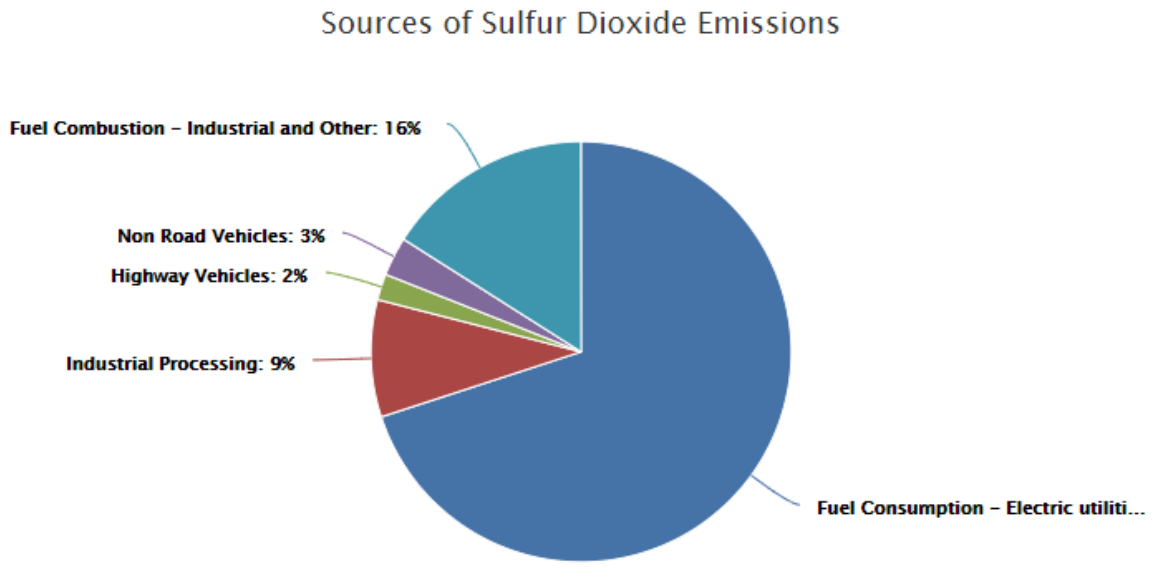


Figure 4.1.5. Sources of SO_2 emissions

Nitrogen Oxides (NO_x)

Nitrogen oxides, or NO_x, is the generic term for a group of highly reactive gases, all of which contain nitrogen and oxygen in varying amounts. Many of the nitrogen oxides are colorless and odorless.

Nitrogen oxides form when fuel is burned at high temperatures, as in a combustion process. The primary sources of NO_x are motor vehicles, electric utilities, and other industrial, commercial, and residential sources that burn fuels as shown in Figure 4.1.6.

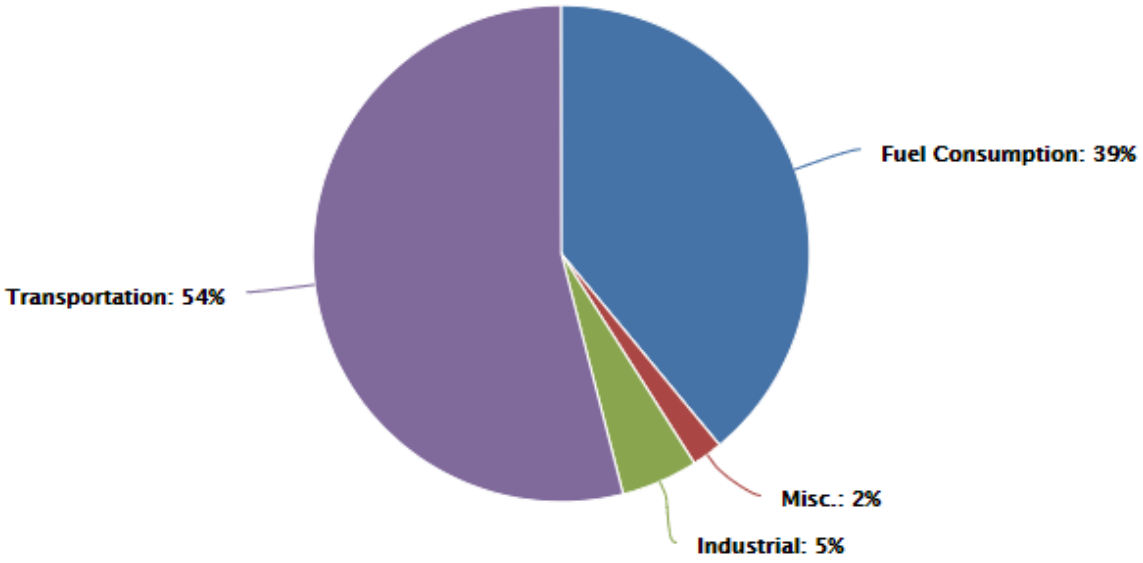


Figure 4.1.6. Sources of NO_x emissions

Although many of the nitrogen oxides are colorless and odorless, one common pollutant, nitrogen dioxide (NO_2) along with particles in the air can often be seen as a reddish-brown layer over many urban areas, as shown in Figure 4.1.7.

Figure 4.1.7. Smog over Los Angeles

Lead (Pb)

The major sources of lead emissions have historically been motor vehicles (such as cars and trucks) and industrial sources.

Due to the phase-out of leaded gasoline, metals processing is the major source of lead emissions to the air today. The highest levels of lead in air are generally found near lead smelters (devices that process lead ores). Other stationary sources are waste incinerators, utilities, and lead-acid battery manufacturers. Figure 4.1.8 shows numerous boxes of lead.

Figure 4.1.8. Lead is a metal found naturally in the environment as well as in manufactured products

Fun Fact

Lead is used in the manufacturing of many items, including glass, rubber, paint, batteries, insecticides, plumbing and protective shielding for X-rays.

Particulate Matter (PM)

Particulate matter (PM) is the general term used to describe a mixture of solid particles and liquid droplets found in the air. Some particles are large enough to be seen as dust or dirt. Others are so small they can be detected only with an electron microscope.

Different sizes of particles include:

- PM 2.5 describes the “fine” particles that are less than or equal to 2.5 µm (micro meter) in diameter.
- “Coarse fraction” particles are greater than 2.5 µm, but less than or equal to 10 µm in diameter.
- PM 10 refers to all particles less than or equal to 10 µm in diameter (about one-seventh the diameter of a human hair). PM

can be emitted directly or formed in the atmosphere.

Different sources of particles include:

- "**Primary**" particles are formed from combustion sources and are emitted directly into the atmosphere. Examples of primary particles are dust from roads or black carbon (soot).
- "**Secondary**" particles are formed in the atmosphere from primary gaseous emissions. Examples of secondary particles are sulfates formed from SO_2 emissions from power plants and industrial facilities; nitrates formed from NO_x emissions from power plants, automobiles, and other combustion sources; and carbon formed from organic gas emissions from automobiles and industrial facilities.

Additional Information

The chemical composition of PM depends on location, time of year, and weather. Generally, primary particles make up coarse PM and secondary particles make up most of fine PM.

Health and Environmental Effects of Primary Pollutants

The pollutants that are emitted directly from a combustion process – or the products of combustion - are called “primary pollutants.” We just described these products earlier in the lesson, now we will look at their impact on the environment and human health.

Carbon dioxide (CO_2)

Carbon dioxide (CO_2) is not a pollutant that would harm our health but it is a proven greenhouse gas. It has an ability to absorb infrared radiation that is escaping from the surface of the earth causing the atmosphere to warm up. Excessive emission of CO_2 along with other greenhouse gases is thought to contribute to the undesirable climate change.

Carbon Monoxide (CO)

As we learned earlier, Carbon monoxide, or CO, is a colorless, odorless and tasteless gas that is formed when carbon in fuel is not burned completely.

At much higher levels of exposure not commonly found in ambient air, CO can be poisonous, and even healthy individuals can be affected. Exposure to elevated levels of CO may result in:

- Visual impairment
- Reduced work capacity
- Reduced manual dexterity
- Poor learning ability
- Difficulty in performing complex tasks

The health threat from levels of CO sometimes found in the ambient air is most serious for those who suffer from cardiovascular disease such as angina pectoris.

Additional Information

In the human body, hemoglobin (an iron compound) in the blood carries the oxygen (O_2) from the lungs to various tissues and transports back carbon dioxide (CO_2) to the lungs. Hemoglobin has 240 times more affinity toward CO than it does for O_2. Therefore, when the hemoglobin reacts with CO, it reduces the hemoglobin that is available for the transport of O_2. This in turn reduces oxygen supply to the body's organs and tissues.

Sulfur Dioxide (SO_2)

High concentrations of SO_2 can result in the following health problems:

- Short term exposure
  - Adults and children with asthma who are active outdoors will experience temporary breathing impairment.
  - Individuals with asthma may experience breathing difficulties with moderate activity and may exhibit symptoms such as wheezing, chest tightness, or shortness of breath.
- Long term exposure
  - Aggravation of existing cardiovascular disease
  - Respiratory illness
  - Alterations in the lungs' defenses
- The subgroups of the population that may be affected under these conditions include individuals with heart or lung disease, as well as the elderly and children.

The following video describes how the body reacts to different types of air.

YouTube Video

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Together, SO_2 and NO_x (discussed on the following section) are the major precursors to acidic deposition (acid rain), which is associated with the acidification of soils, lakes, and streams and accelerated corrosion of buildings and monuments. We will talk more about this in the next section. SO_2 also is a major precursor to PM 2.5, which is a significant health concern, and a main contributor to poor visibility.

Nitrogen Oxides (NO_x)

Nitric oxide (NO) and nitrogen dioxide (NO_2) together are represented by NO_x. Most of the emissions from combustion devices (approximately 90%) are in the form of NO.

NO_x react in the air to form ground-level ozone and fine particulates, which are associated with adverse health effects.

- Short-term exposures (e.g., less than 3 hours) to low levels of NO_2 may lead to changes in airway responsiveness and lung function in individuals with preexisting respiratory illnesses. These exposures may also increase respiratory illnesses in children.
- Long-term exposures to NO_2 may lead to increased susceptibility to respiratory infection and may cause irreversible alterations in lung structure.

NO_x contributes to a wide range of environmental effects directly and when combined with other precursors in acid rain and ozone.

- Increased nitrogen inputs to terrestrial and wetland systems can lead to changes in plant species composition and diversity.
- Direct nitrogen inputs to aquatic ecosystems such as those found in estuarine and coastal waters (e.g., Chesapeake Bay) can lead to eutrophication (a condition that promotes excessive algae growth, which can lead to a severe depletion of dissolved oxygen and increased levels of toxins harmful to aquatic life).
- Nitrogen, alone or in acid rain, also can acidify soils and surface waters.

Additional Information

Acidification of soils causes the loss of essential plant nutrients and increased levels of soluble aluminum that are toxic to plants. Acidification of surface waters creates conditions of low pH and levels of aluminum that are toxic to fish and other aquatic organisms. NOx also contributes to visibility impairment.

Particulate Matter (PM)

Particles smaller than or equal to 10 µm (micro meter or millionth of a meter) in diameter can get into the lungs and can cause numerous health problems. Inhalation of these tiny particles has been linked with illness and death from heart and lung disease. Various health problems have been associated with long-term (e.g., multi-year) exposures to these particles. Shorter-term daily and potentially even shorter term peak (e.g., 1-hour) exposures to these particles can also be associated with health problems.

Particles can aggravate respiratory conditions, such as asthma and bronchitis, and have been associated with cardiac arrhythmias (heartbeat irregularities) and heart attacks. People with heart or lung disease, the elderly, and children are at highest risk from exposure to particles.

Particles of concern can include both fine and coarse-fraction particles, although fine particles have been more clearly linked to the most serious health effects.

- Particles larger than 2 micro meters (µm) do not penetrate beyond the nasal cavity or trachea.
- Particles smaller than 0.1 µm tend to deposit in tracheobronchia tree and are removed when exhaling.
- Particles between 0.1 and 2.0 µm penetrate deep into the lungs and settle in respiratory bronchioles or alveolar sacs.

Additional Information

In addition to health problems, PM is the major cause of reduced visibility in many parts of the United States by scattering and absorbing some of the light emitted or reflected by the body reducing the contrast. Airborne particles can also impact vegetation and ecosystems, and can cause damage to paints and building materials.

The following video describes how the body reacts to different sizes of PM.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Lead (Pb)

Exposure to lead occurs mainly through inhalation of air and ingestion of lead in food, water, soil, or dust. It accumulates in the blood, bones, and soft tissues and can adversely affect the kidneys, liver, nervous system, and other organs.

- Excessive exposure to lead may cause neurological impairments such as seizures, mental retardation, and behavioral disorders.
- Even at low doses, lead exposure is associated with damage to the nervous systems of fetuses and young children, resulting in learning deficits and lowered IQ.
- Recent studies indicated that lead may be a factor in high blood pressure and subsequent heart disease.
- Lead can also be deposited on the leaves of plants, presenting a hazard to grazing animals and to humans through ingestion.

The following video details the impact of using unleaded rather than leaded gasoline.

YouTube Video

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View this YouTube Video online

Secondary Pollutants

The pollutants that are emitted directly from a combustion process are called “primary pollutants.” When emitted into the atmosphere, these primary pollutants combine with other reactants and form “secondary” pollutants.

An example of a secondary pollutant would be ozone. When hydrocarbons are emitted and they react with NO_x in presence of sunlight, they form ozone. Health and environmental effects of secondary pollutants are discussed in the next section.

Fun Fact

Ozone is a form of oxygen and also a poisonous gas. However, when in the earth's atmosphere, ozone acts as a protective shield against ultraviolet radiation in space.

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4.2: Global and Regional Effects of Secondary Pollutants (I)

The Earth is continuously receiving energy from the sun. Energy also leaves the Earth in the nighttime (of course in the form of invisible infrared energy!). Otherwise, the Earth would be continuously warming up. This delicate balance between the energy coming in and leaving due to natural greenhouse effect is what keeps the planet warm enough for us to live on.

It is very obvious that if more energy comes in than the energy that leaves, the planet will become warm. Similarly, if the energy that leaves is more than the energy that comes in, the planet will become cool. The atmospheric temperature fluctuates over centuries due to certain natural causes.

Greenhouse Effect

In an earlier chapter, we saw that energy can be transformed from one form to another, and during this conversion, all the energy that we put into a device comes out. However, all the energy that we put in may not come out in the desired form. An example of this is the greenhouse effect, which the following video discusses.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

This Excel Sheet gives the current levels of CO_2 in the atmosphere - 392 ppm in 2011.

Greenhouse Gases

The concentration of greenhouse gases in the atmosphere has been changing over the past 150 years. Since pre-industrial times atmospheric concentrations of the gases have increased:

- CO_2 has climbed over 31 percent.
- CH_4 has climbed over 151 percent.
- N_2O has climbed 17 percent.

Scientists have confirmed that this is primarily due to human activities, which include burning coal, oil, and gas, and cutting down forests, depicted in Figure 4.2.1.

Figure 4.2.1: Lumberjack climbing a tree

Figure 4.2.2 gives the percentages of various gases found in greenhouse emissions.

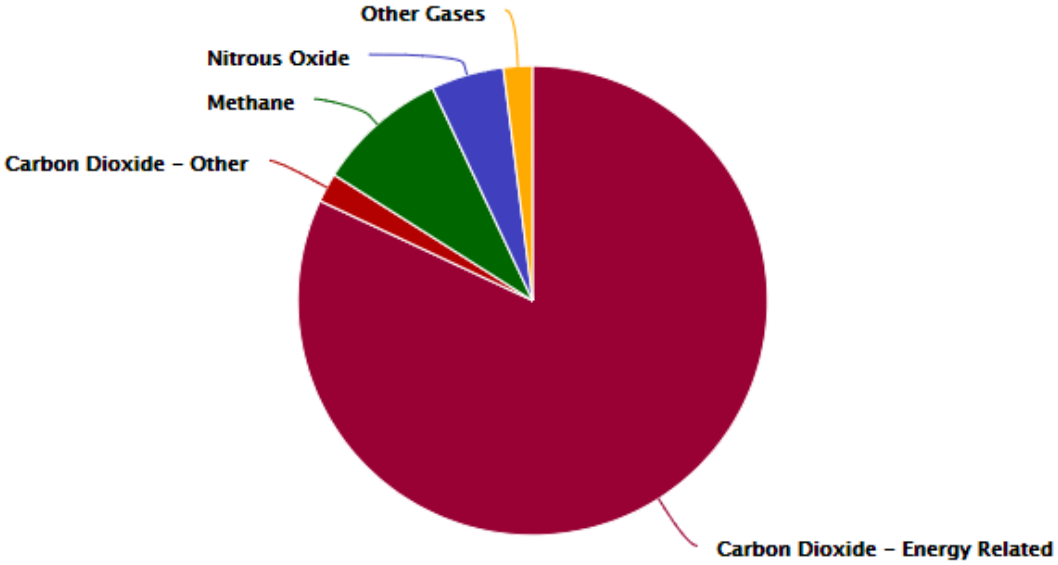


Figure 4.2.2: Distribution of emissions by greenhouse gases

The following list shows the greenhouse gasses and the source of emission:

- **Carbon dioxide (CO2): Energy related CO2: 82% and Other CO2: 2%.**
  Produced by combustion of solid waste, fossil fuels, and wood and wood products.
- **Methane (CH4): 9%.**
  Source is the production and transport of coal, natural gas, and oil. Methane emissions also result from the decomposition of organic wastes in municipal solid waste landfills, and the raising of livestock.
- **Nitrous Oxide (N2O): 5%.**
  Produced by agricultural and industrial activities, as well as during combustion of solid waste and fossil fuels.
- **Other gases (CFC-12, HCFC-22, Perfluoromethane [CF4], and Sulfur Hexaflouride [SF6]): 2%.**
  Produced by industrial processes.

As you can see, energy related CO_2 and CH_4 accounts for 90 percent of the total greenhouse gas emissions in the United States. This highlights the impact of energy use on the environment.

How Has CO_2 Concentration Changed?

Table 4.2.1 shows the change in greenhouse gas concentration between Pre-Industrial times and 2010, as well as the Atmospheric Lifetime and Global Warming Potential.

Table 4.2.1. Change in greenhouse gas concentration between pre-industrial times and 2010

Greenhouse Gases	Pre-Industrial Concentration (PPBV)	2010 Concentration (PPBV)	Atmospheric Lifetime (years)	Global Warming Potential (GWP)
CO_2	278,000	390,000*	Variable	1
CH_4 (methane)	715	1810.5	12	25
N_2O (nitrous oxide)	270	322.5	114	298
CFC-12	0	0.533	100	10,900
HCFC-22	0	0.208	12	1810
CF_4 (perfluoromethane)**	0	0.007	50,000	6,500

Greenhouse Gases	Pre-Industrial Concentration (PPBV)	2010 Concentration (PPBV)	Atmospheric Lifetime (years)	Global Warming Potential (GWP)
SF_6 (sulfur hexafluoride)	0	0.007	3,200	22,800

**Recent CO_2 concentration (390.5 ppm) is the 2011 average taken from globally averaged marine surface data given by the National Oceanic and Atmospheric Administration Earth System Research Laboratory.*

***2005 data*

Source: CDIAC.org

Additional Information

Atmospheric lifetime is the period of time during which a gas changes and is either transformed or removed from the atmosphere.

GWP is an index defined as the cumulative radiative forcing (infrared radiation absorption) between the present and some chosen time horizon caused by a unit mass of gas emitted now, expressed relative to a reference gas such as CO_2, as is used here. GWP is an attempt to provide a simple measure of the relative radiative effects of different greenhouse gases.

Figure 4.2.3 shows how the amounts of greenhouse gases in the atmosphere have changed over time. The increase in the greenhouse gases between 1950 and 2010 is believed to have caused an increase in the global temperature. The mean increase in the global temperature over the past one century is about 1 degree Fahrenheit.

Figure 4.2.3: Greenhouse gas emissions from 1950 to 2010

Additional Information

Data from the graph above was obtained from ice core samples of trapped air. More specifically, ice in the Polar Regions traps air from that particular time period, and then new ice is deposited over the previously deposited ice, trapping more air from the past. Thus, the analysis of ice core samples provides the composition of past air, which can be used to determine the past temperatures.

The increase in the greenhouse gases between 1950 and 2010 is believed to have caused an increase in the global temperature, as depicted in Figure 4.2.4. The mean increase in the global temperature over the past one century is about 1°F.

Figure 4.2.4: Global annual surface temperature from 1950 to 2010

Additional Information

Since 1880, about when the industrial age first started, the average increase in global temperature has been 1°F.

Not only has there been an increase in temperatures with the increase of greenhouse gasses, there has also been an increase in CO_2 emissions from fossil fuels – this has been apparent over the last 150 years (since about 1850).

The graph below depicts data from ice core samples showing temperature and CO_2 concentrations in the atmosphere from 400,000 years ago to about the year 2000.

Figure 4.2.5: Global temperature and CO_2 concentration changes over the past 400,000 years

Important Point

Based on the graph above, it can be determined that during periods of time where there was no human activity:

- The average global temperature increase was 2°C or 4°F.
- The average temperature decrease was 8°C or 17°F.

CO_2 and Temperature Fluctuations

Unanswered Question

We have seen that there have been fluctuations in both temperature and CO_2 emissions in the past 400,000 years. This leads to an important question:

- Did the atmospheric CO_2 concentrations and temperatures change prior to the pre-industrial period or only after it?

Or more specifically:

- If we attribute the mean global temperature increase of 1°F over the past century to human activities, how do we explain the mean global temperature fluctuations between +4°F to -17°F that occurred thousands of years ago, when there was no human activity?

Possible Answer

Some argue that temperature change is natural and cyclical. Thus, since it is cyclical, we, the humans, might not be influencing the current change in the climate.

The most important difference between now and then that we have to keep in mind is the human species. More than six billion people live on this planet now, who were not there during those earlier natural temperature cycles, and any chances that jeopardize the existence of this humankind must be taken seriously. The reasons for concern are discussed next.

Important Point

More than 6 billion people live on this planet now who were not here during the earlier natural temperature cycles, and any chances that jeopardize the existence (land and food supply) of this humankind must be taken seriously.

The significant temperature fluctuations shown in the earlier graph of the ice core samples led to the glacial and inter-glacial ice ages. The temperature increase over the last 150 years, however, is not significant compared to the changes in the past known history. Figure 4.2.6 shows the CO_2 profile.

Figure 4.2.6: CO_2 concentration over time

From Figure 4.2.6, we know that CO_2 concentration did not rise above 310 ppmv at any time from 400,000 years ago to the year 1950, even though the temperatures continued to increase. Based on this information, we can conclude that this increase is something that the atmosphere did not experience earlier, which means that the increase is the result of human activity.

Now let's look at how CO_2 concentration and temperature have changed in the last 50 years, since 1960, as shown in Figure 4.2.7.

Figure 4.2.7: CO_2 concentration vs. temperature change graph

Based on your observations of the above graph, reflect on the questions discussed below:

1. In the past, 310 ppm of CO_2 increased the temperature by about 4 degrees F, so how do you think the current CO_2 concentration of 370 ppm is impacting the temperature?
2. How long will it take for the temperature to come to a level that corresponds to the CO_2 concentration of 370 ppm? Or are we already there?
3. What will the consequences be if the concentration of CO_2 increases to 550 ppm (double the pre-industrial concentration), or even to 70 ppm (both of which are proposed to be likely scenarios with the increased fossil fuel consumption?)

If the temperature already reached the maximum temperature corresponding to 370 ppm, then some other factors are cooling the planet that were absent in the previous cycles.

Now, let's examine the reasons or causes for the natural fluctuations.

Global Warming

The sun is the main source of energy and, as we discussed earlier, it is the net balance between the incoming solar energy and the outgoing energy that causes the temperature changes.

The Earth is continuously moving around the sun. Based on its position, the incoming energy changes. The Earth's axis of rotation is tilted at an angle of 23.5°, and this tilt goes from one side to the other and back over in 40,000-year cycles. Earth's axis of rotation takes about 21,000 years to complete a cycle.

The following video shows the earth's movement around the sun.

YouTube Video

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View this YouTube Video online

The Earth's orbit around the sun changes from a circular path to an elliptical path and back to a circular path over 100,000 years. These are long-term changes. On a much shorter term, the radiation from the sun can be affected by the activity on the surface of the sun. Sun spots (intense flares on the surface) can increase the radiation from the sun. The increase in the solar activity occurs over an 11-year cycle.

Like many fields of scientific study, there are uncertainties associated with the science of global warming. This does not imply that all things are equally uncertain. Some aspects of the science are based on well-known physical laws and documented trends, while other aspects range from 'near certainty' to 'big unknowns.'

In the following sections, we will discuss the following:

- What is known for certain? Human activities change the Earth's Atmosphere.
- What is likely? Greenhouse gases contribute to global warming. Several factors impact temperature (clouds, fine particles, oceans). Global Warming affects health, water resources, polar regions, coastal zones and forests.
- What is uncertain? The long term effects of global warming, especially for smaller areas.

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4.3: Global and Regional Effects of Secondary Pollutants (II)

What is Known for Certain

Human Activities Change the Earth's Atmosphere

Scientists know for certain that human activities are changing the composition of Earth's atmosphere. Increasing levels of greenhouse gases in the atmosphere, like carbon dioxide (CO_2), have been well documented since pre-industrial times. There is no doubt this atmospheric buildup of carbon dioxide and other greenhouse gases is largely the result of human activities.

It's well accepted by scientists that greenhouse gases trap heat in the Earth's atmosphere and tend to warm the planet. By increasing the levels of greenhouse gases in the atmosphere, human activities are strengthening Earth's natural greenhouse effect. The key greenhouse gases emitted by human activities remain in the atmosphere for periods ranging from decades to centuries.

Additional Information

A warming trend of about $1^{o}F$ has been recorded since the late 19^{th} century. Warming has occurred in both the northern and southern hemispheres, and over the oceans. Confirmation of twentieth-century global warming is further substantiated by melting glaciers, decreased snow cover in the northern hemisphere, and even warming below ground.

What is Likely but Uncertain

Greenhouse Gases Contribute to Global Warming

Determining to what extent the human-induced accumulation of greenhouse gases since pre-industrial times is responsible for the global warming trend is not easy. This is because other factors, both natural and human, affect our planet's temperature. Scientific understanding of these other factors—most notably natural climatic variations, changes in the sun's energy, and the cooling effects of pollutant aerosols—remains incomplete or uncertain; however...

- The Intergovernmental Panel on Climate Change (IPCC) stated there was a "discernible" human influence on climate; and that the observed warming trend is "unlikely to be entirely natural in origin."
- In the most recent Third Assessment Report (2001), IPCC wrote "There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities."

In short, scientists think rising levels of greenhouse gases in the atmosphere are contributing to global warming, as would be expected; but to what extent is difficult to determine at the present time.

Additional Information

As atmospheric levels of greenhouse gases continue to rise, scientists estimate average global temperatures will continue to rise as a result. By how much and how fast remain uncertain. IPCC projects further global warming of 2.2 - $10^{o}F$ (1.4 - $5.8^{o}C$) by the year 2100.

Factors Affecting Temperature

Some factors that affect the Earth's temperatures include clouds, fine particles, and oceans.

Clouds

- Low, thick clouds primarily reflect solar radiation and cool the surface of the Earth.
- High, thin clouds primarily transmit incoming solar radiation; at the same time, they trap some of the outgoing infrared radiation emitted by the Earth and radiate it back downward, thereby warming the surface of the Earth.
- Whether a given cloud will heat or cool the surface depends on several factors, including the cloud's height, its size, and the make-up of the particles that form the cloud.
- The balance between the cooling and warming actions of clouds is very close - although, overall, cooling predominates.

Fine Particles (Aerosols) in the Atmosphere

The amount of fine particles or aerosols in the air has a direct effect on the amount of solar radiation hitting the Earth's surface. Aerosols may have significant local or regional impact on temperature.

Atmospheric factors shown in the image below include natural factors such as clouds, volcanic eruptions, natural biomass (forest) burning, and dust from storms. In addition, human-induced factors such as biomass burning (forest and agricultural fires) and sulfate aerosols from burning coal add tiny particles that contribute to cooling, as detailed in the following video.

YouTube Video

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View this YouTube Video online

When Mount Pinatubo erupted in the Philippines in 1991, an estimated 20 million tons of sulfur dioxide and ash particles blasted more than 12 miles high into the atmosphere. The eruption caused widespread destruction and human causalities. Gases and solids injected into the stratosphere circled the globe for three weeks.

Volcanic eruptions of this magnitude can impact global climate, reducing the amount of solar radiation reaching the Earth's surface, lowering temperatures in the troposphere, and changing atmospheric circulation patterns. The extent to which this occurs is an uncertainty.

Figure 4.3.1 shows a picture of Mount Pinatubo next to a map of its location and how far the ash from its eruption spread.

Figure 4.3.1. Mount Pinatubo erupting (left) and a map of its location and how far the ash from its eruption spread (right)

Additional Information

Water vapor is a greenhouse gas, but at the same time, the upper white surface of clouds reflects solar radiation back into space. Albedo—reflections of solar radiation from surfaces on the Earth—creates difficulties in exact calculations. If, for example, the polar icecap melts, the albedo will be significantly reduced. Open water absorbs heat, while white ice and snow reflect it.

Oceans

Oceans play a vital role in the energy balance of the Earth. It is known that the top 10 feet of the oceans can hold as much of the heat as the entire atmosphere above the surface. However, most of the incoming energy is incident on the equatorial region.

The water in the oceans in the equatorial regions is warmer and needs to be transported to the northern latitudes. This is done

due to natural variations in the temperatures of the water and prevailing winds that cause the disturbances in the surface waters.

The Intergovernmental Panel on Climate Change (IPCC) states that even the low end of this warming projection "would probably be greater than any seen in the last 10,000 years, but the actual annual to decadal changes would include considerable natural variability."

The following video explains the ocean conveyor belt.

YouTube Video

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View this YouTube Video online

Impact of Global Warming

Impact of Global Warming on such things as health, water resources, polar regions, coastal zones, and forests is likely but it is uncertain to what extent.

Health

The most direct effect of climate change would be the impacts of the hotter temperatures, themselves. Extremely hot temperatures increase the number of people who die on a given day for many reasons:

- People with heart problems are vulnerable because one's cardiovascular system must work harder to keep the body cool during hot weather.
- Heat exhaustion and some respiratory problems increase.
- Higher air temperatures also increase the concentration of ozone at ground level.
- Diseases that are spread by mosquitoes and other insects could become more prevalent if warmer temperatures enabled those insects to become established farther north; such "vector-borne" diseases include malaria, dengue fever, yellow fever, and encephalitis.

Water Resources

Changing climate is expected to increase both evaporation and precipitation in most areas of the United States. In those areas where evaporation increases more than precipitation, soil will become drier, lake levels will drop, and rivers will carry less water. Lower river flows and lower lake levels could impair navigation, hydroelectric power generation, and water quality, and reduce the supplies of water available for agricultural, residential, and industrial uses. Some areas may experience increased flooding during winter and spring, as well as lower supplies during summer.

Polar Regions

Climate models indicate that global warming will be felt most acutely at high latitudes, especially in the Arctic where reductions in sea ice and snow cover are expected to lead to the greatest relative temperature increases. Ice and snow cool the climate by reflecting solar energy back to space, so a reduction in their extent would lead to greater warming in the region.

Coastal Zones

Sea level is rising more rapidly along the U.S. coast than worldwide. Studies by EPA and others have estimated that along the Gulf and Atlantic coasts, a one-foot (30 cm) rise in sea level is likely by 2050.

In the next century, a two-foot rise is most likely, but a four-foot rise is possible. Rising sea level inundates wetlands and other low-lying lands, erodes beaches, intensifies flooding, and increases the salinity of rivers, bays, and groundwater tables. Low-lying countries like Maldives located in the Indian Ocean and Bangladesh may be severely affected. The world may see global warming refugees from these impacts.

Forests

The projected 2°C (3.6°F) warming could shift the ideal range for many North American forest species by about 300 km (200 mi.) to the north.

- If the climate changes slowly enough, warmer temperatures may enable the trees to colonize north into areas that are currently too cold, at about the same rate as southern areas became too hot and dry for the species to survive. If the Earth warms 2°C (3.6°F) in 100 years, however, the species would have to migrate about 2 miles every year.
- Poor soils may also limit the rate at which tree species can spread north.
- Several other impacts associated with changing climate further complicate the picture:
  - On the positive side, CO_2 has a beneficial fertilization effect on plants, and also enables plants to use water more efficiently. These effects might enable some species to resist the adverse effects of warmer temperatures or drier soils.
  - On the negative side, forest fires are likely to become more frequent and severe if soils become drier.

What is Uncertain

The Long Term Effects of Global Warming

Scientists have identified that our health, agriculture, water resources, forests, wildlife, and coastal areas are vulnerable to the changes that global warming may bring. But projecting what the exact impacts will be over the twenty-first century remains very difficult. This is especially true when one asks how a local region will be affected.

Scientists are more confident about their projections for large-scale areas (e.g., global temperature and precipitation change, average sea level rise) and less confident about the ones for small-scale areas (e.g., local temperature and precipitation changes, altered weather patterns, soil moisture changes). This is largely because the computer models used to forecast global climate change are still ill-equipped to simulate how things may change at smaller scales.

Some of the largest uncertainties are associated with events that pose the greatest risk to human societies. IPCC cautions, "Complex systems, such as the climate system, can respond in non-linear ways and produce surprises." There is the possibility that a warmer world could lead to more frequent and intense storms, including hurricanes. Preliminary evidence suggests that, once hurricanes do form, they will be stronger if the oceans are warmer due to global warming. However, the jury is still out whether or not hurricanes and other storms will become more frequent.

Fun Fact

IPCC stands for Intergovernmental Panel on Climate change. Its role is to assess scientific, technical and socio-economic information to determine the risk of human-induced climate change and the options available for adapting to these changes.

Solutions for Global Warming

Today, there is no single solution that is agreed upon, because scientists are still debating whether the problem is a real one or a perceived one. The main question is whether we want to wait to see the effects for sure and then act, or whether we want to start to do something now?

Like many pioneer fields of research, the current state of global warming science can't always provide definitive answers to our questions. There is certainty that human activities are rapidly adding greenhouse gases to the atmosphere, and that these gases tend to warm our planet. This is the basis for concern about global warming.

The fundamental scientific uncertainties are these: How much more warming will occur? How fast will this warming occur? And

what are the potential adverse and beneficial effects? These uncertainties will be with us for some time, perhaps decades.

Global warming poses real risks. The exact nature of these risks remains uncertain. Ultimately, this is why we have to use our best judgment—guided by the current state of science—to determine what the most appropriate response to global warming should be.

What Difference Can I Make?

When faced with this question, individuals should recognize that, collectively, they can make a difference. In some cases, it only takes a little change in lifestyle and behavior to make some big changes in greenhouse gas reductions. For other types of actions, the changes are more significant.

When that action is multiplied by the 270 million people in the U.S. or the 6 billion people worldwide, the savings are significant. The actions include being energy efficient in the house, in the yard, in the car, and in the store.

Everyone's contribution counts, so why not do your share?

Note

Energy efficiency means doing the same (or more) with less energy. When individual action is multiplied by the 270 million people in the U.S., or the 6 billion people worldwide, the savings can be significant.

How Can I Save the Environment?

You can help save the environment by making changes from the top to the bottom of your home.

These are the things you can do in your home – from top to bottom - to protect from the environment:

1. Purchase "Green Power" - electricity that is generated from renewable sources such as solar, wind, geothermal, or biomass - for your home's electricity, if available from your utility company. Although the cost may be slightly higher, you'll know that you are buying power from an environmentally friendly energy source.
2. Insulate your home – you'll learn more about this in Home Activity Three.
3. Use low-flow faucets in your showers and sinks.
4. Replace toilets with water-saving lavatories.
5. Purchase home products—appliances, new home computers, copiers, fax machines, that display the ENERGY STAR® label - You can reduce your energy consumption by up to 30 percent and lower your utility bills! Remember, the average house is responsible for more air pollution and carbon dioxide emissions than is the average car.
6. When your lights burn out, replace them with energy-efficient compact fluorescent lights.
7. Lower the temperature on your hot water tank to 120 degrees.
8. Tune up your furnace.
9. Insulate your water heater and all water pipes to reduce heat loss.

When you remodel, build, or buy a new home, incorporate all of these energy efficiency measures—and others.

Important Point

Each of us, in the U.S., contributes about 22 tons of carbon dioxide emissions per year, whereas the world average per capita is about 6 tons.

The good news is that there are many ways you and your family can help reduce carbon dioxide pollution and improve the environment for you and your children

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4.4: Acid Rain and Ozone (I)

Acid rain is a serious environmental problem around the world, particularly affecting Asia, Europe, and large parts of the U.S. and Canada. The acidic pollutants such as SO_2 and NO_x are emitted into the environment by combustion of fossil fuels.

Most of the sulfur in any fuel combines with oxygen and forms SO_2 in the combustion chamber. This SO_2 when emitted into the atmosphere slowly oxidizes to SO_3. SO_3 is readily soluble in water in the clouds and forms H_2SO_4 (sulfuric acid).

$$\mathrm{S + O_2 \longrightarrow SO_2 + \frac{1}{2}O_2 \quad (in \quad the \quad atmosphere)}$$

$$\mathrm{SO_2 + \frac{1}{2}\ O_2 \quad (in \quad the \quad atmosphere) \longrightarrow SO_3 + H_2O}$$

$$\mathrm{SO_3 + H_2O \longrightarrow H_2SO_4 \quad (sulfuric \quad acid)}$$

Most of the NO_x that is emitted is in the form of NO. This NO is oxidized in the atmosphere to NO_2. NO_2 is soluble in water and forms HNO_3 (nitric acid).

$$\mathrm{NO + \frac{1}{2}\ O_2 \quad (in \quad the \quad atmosphere) \longrightarrow NO_2 + H_2O}$$

$$\mathrm{NO_2 + H_2O \longrightarrow HNO_3 \quad (nitric \quad acid)}$$

Acid Deposition

Sunlight increases the rate of most of the SO_2 and NO reactions. The result is a mild solution of sulfuric acid and nitric acid. "**Acid rain**" is a broad term used to describe several ways that acids fall out of the atmosphere. A more precise term is **acid deposition**, which has two parts: wet and dry.

- **Wet deposition** - refers to acidic rain, fog, and snow. As this acidic water flows over and through the ground, it affects a variety of plants and animals. The strength of the effects depend on many factors, including:
  - the acidity of the water;
  - the chemistry and buffering capacity of the soils involved;
  - the types of fish, trees, and other living things that rely on the water.

- **Dry deposition** - refers to acidic gases and particles. About half of the acidity in the atmosphere falls back to earth through dry deposition.
  - Acidic particles and gases are blown by the wind onto buildings, cars, homes, and trees.
  - Dry deposited gases and particles can also be washed from trees and other surfaces by rainstorms. When that happens, the runoff water adds those acids to the acid rain, making the combination more acidic than the falling rain alone

Process of Acid Deposition

Prevailing winds blow the compounds that cause both wet and dry acid deposition across state and national borders, and sometimes over hundreds of miles. The video goes into more detail about the process of acid deposition.

YouTube Video

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pH Scale

Acid rain is measured using a pH scale.

pH is a measure of hydrogen ion concentration, which is measured as a negative logarithm. In other words, acids produce hydrogen ions and alkalis produce hydroxyl ions, so pH is the power of a solution to yield hydrogen ions [H+].

The pH scale ranges from 0 to 14 and indicates how acidic or basic a substance is.

- A pH of 7 is neutral.
- A pH less than 7 is acidic.
- A pH greater than 7 is basic.

The *lower* a substance's pH, the *more acidic* it is. Each whole pH value below 7 (the neutral point) is ten times more acidic than the next higher value.

- For example, a pH of 4 is ten times more acidic than a pH of 5 and 100 times (10 times 10) more acidic than a pH of 6.

The *higher* a substance's pH, the *more basic* or *alkaline* it is.

- Each whole pH value above 7 is ten times more alkaline (another way to say basic) than the next lower whole value.
- For example, a pH of 10 is ten times more alkaline than a pH of 9.

Figure 4.4.1 gives a visual of the pH scale.

Figure 4.4.1. pH scale

Effects of Acid Rain

Overview

Pure water has a pH of 7.0. Normal rain is slightly acidic because carbon dioxide dissolves into it, so it has a pH of about 5.5. As of the year 2000, the most acidic rain falling in the US has a pH of about 4.3.

Below is a video demonstration that replicates the effect of acid rain on plant life. In the video, beans are placed in: a) water, b) slightly acidic water and c) acidic water, and their growth is observed over a period of three days.

YouTube Video

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Effects of Acid Rain on Forests and Aquatic Life

Forests

Acid rain does not usually kill trees directly. Instead, it is more likely to weaken trees by:

- damaging their leaves;
- limiting the nutrients available to them;
- exposing them to toxic substances slowly released from the soil.

Quite often, injury or death of trees is a result of these effects of acid rain in combination with one or more additional threats.

Aquatic Life

Acid rain causes acidification of lakes and streams and contributes to damage of trees at high elevations (for example, red spruce trees above 2,000 feet) and many sensitive forest soils. Several regions in the U.S. were identified as containing many of the surface waters sensitive to acidification, as shown in Figure 4.4.2. They include the:

- Adirondacks and Catskill Mountains in New York State;
- Mid-Appalachian Highlands along the east coast;
- Upper Midwest;
- Mountainous areas of the Western United States.

Figure 4.4.2. Map of the U.S. showing high elevation areas

Some types of plants and animals can handle acidic waters. Others, however, are acid-sensitive and will be lost as the pH declines. Figure 4.4.3 shows the pH levels that fish, shellfish, and insects can tolerate.

Figure 4.4.3. pH tolerances of various organisms

Effects of Acid Rain on Materials, Visibility, and Human Health

Materials

Acid rain and the dry deposition of acidic particles contribute to the corrosion of metals (such as bronze) and the deterioration of paint and stone (such as marble and limestone). These effects seriously reduce the value to society of buildings, bridges, cultural objects (such as statues, monuments, and tombstones), and cars. Figure 4.4.4 shows an example of a statue affected by acid rain.

Figure 4.4.4. Acid rain erosion to a statue

Visibility

Sulfates and nitrates that form in the atmosphere from sulfur dioxide (SO_2) and nitrogen oxides (NO_x) emissions contribute to visibility impairment, meaning we can't see as far or as clearly through the air.

Eastern U.S.

Sulfate particles account for 50 to 70 percent of the visibility reduction in the eastern part of the United States, affecting our enjoyment of national parks, such as the Shenandoah and the Great Smoky Mountains.

Through the Acid Rain Program, SO_2 reductions will be completed to improve visual range at national parks located in the eastern United States, such as the Great Smoky Mountains, shown in Figure 4.4.5. Based on a study of the value national park visitors place on visibility, these reductions are expected to be worth over a billion dollars annually by the year 2010.

Figure 4.4.5. Great Smoky Mountains

Western U.S.

In the western part of the United States, nitrates and carbon also play roles, but sulfates have been implicated as an important source of visibility impairment in many of the Colorado River Plateau national parks, including the Grand Canyon (shown in Figure 4.4.6), Canyonlands, and Bryce Canyon.

Figure 4.4.6. Grand Canyon

Human Health

Acid rain looks, feels, and tastes just like clean rain. The harm to people from acid rain is not direct. Walking in acid rain, or even swimming in an acid lake, is no more dangerous than walking or swimming in clean water. However, the pollutants that cause acid rain also damage human health.

- **Effects of Sulfur Dioxide (SO_2)**: These gases interact in the atmosphere to form fine sulfate and nitrate particles that can be transported long distances by winds and inhaled deep into people's lungs. Fine particles can also penetrate indoors. Many scientific studies have identified a relationship between elevated levels of fine particles and increased illness and premature death from heart and lung disorders, such as asthma and bronchitis.
- **Effects of Nitrogen Oxide (NO_x)**: Decrease in nitrogen oxide emissions are also expected to have a beneficial impact on human health by reducing the nitrogen oxides available to react with volatile organic compounds and form ozone. Ozone impacts on human health include a number of morbidity and mortality risks associated with lung inflammation, including asthma and emphysema.

Protecting the Environment from Acid Rain

You can do the following to protect the environment from acid rain:

- Turn off lights, computers, and other appliances when you're not using them.
- Use energy efficient appliances: lighting, air conditioners, heaters, refrigerators, washing machines, etc.
- Only use electric appliances when you need them.
- Keep your thermostat at 68°F in the winter and 72°F in the summer. You can turn it even lower in the winter and higher in the summer when you are away from home.
- Insulate your home as best you can.
- Carpool, use public transportation, or better yet, walk or bicycle whenever possible.
- Buy vehicles with low NO_x emissions, and maintain all vehicles well.

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4.5: Acid Rain and Ozone (II)

Introduction to Ozone

Ozone (O_3) is a triatomic oxygen molecule gas that occurs both in the Earth's upper atmosphere and at ground level. Ozone can be good or bad, depending on where it is found: It is a bluish gas that is harmful to breathe. Therefore, it is bad at the ground level. Figure 4.5.1 has more information on ozone.

Figure 4.5.1. Ozone in the Earth's atmosphere

The Ozone Cycle

The video below shows the process of ozone depletion. Ozone depletion is caused by chlorofluorocarbons (CFCs) and other ozone-depleting substances.

YouTube Video

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Production and Destruction of Ozone

Ozone is constantly produced and destroyed in a natural cycle, as shown in the figure below. However, the overall amount of ozone is essentially stable. This balance can be thought of as a stream's depth at a particular location. Although individual water molecules are moving past the observer, the total depth remains constant. Similarly, while ozone production and destruction are balanced, ozone levels remain stable. This was the situation until the past several decades. The following video talks more about ozone destruction.

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Large increases in stratospheric chlorine and bromine, however, have upset the balance of the Ozone. In effect, they have added a siphon downstream, removing ozone faster than natural ozone creation reactions can keep up. Therefore, ozone levels fall.

Since ozone filters out harmful UVB radiation, less ozone means higher UVB levels at the surface. The more the ozone is depleted, the larger will be the increase in incoming UVB radiation. UVB has been linked to:

- skin cancer;

- cataracts;
- damage to materials like plastics;
- harm to certain crops and marine organisms.

Although some UVB reaches the surface even without ozone depletion, its harmful effects will increase as a result of this problem.

Additional Information

Ozone-Depleting Substance(s) (ODS) are:

- CFCs;
- HCFCs (used in the energy related to refrigeration and air conditioning in homes, commercial buildings, and cars, and manufacture of foam products);
- Halons (used in fire extinguishers);
- Methyl bromide, carbon tetrachloride;
- Methyl chloroform (used as solvents in chemical industries).

The Ozone Hole

Recent studies by NASA and others have indicated that about 40 percent of the ozone in the Antarctica has been destroyed and that about 7 percent of ozone is destroyed from the Arctic Circle. The destruction of ozone is also called “Ozone Hole."

Ozone hole does not mean that there is no ozone in the region. The ozone hole is defined as the area having less than 220 **dobson units** (DU) of ozone (concentration) in the overhead column (i.e., between the ground and space).

Figure 4.5.2 and 4.5.3 show the reduction in ozone concentration over Antarctica. This hole in the Antarctica is unfortunately allowing more Australians to be exposed to UV radiation. However, if this kind of ozone destruction ever takes place in the Arctic zone, more humans (in the Northern hemisphere) would be exposed to higher levels of UVB radiation.

Figure 4.5.2. Ozone concentrations in the Antarctic

Credit: Ozone Concentrations in the Antarctic by NASA Ozone Watch, available for public use.

Figure 4.5.3. Map of Antarctica showing total ozone (DU) / ozone total (UD) as of Sept. 12, 2011

Credit: Antarctica Ozone by NASA Ozone Watch, available for public use.

Fun Fact

A Dobson Unit is the measure of the amount or thickness of ozone in the atmosphere. It is based on a measurement taken directly above a specific point on the Earth's surface. One Dobson unit refers to a layer of ozone that would be 0.001 cm thick under conditions of standard temperature (0 degree C) and pressure (the average pressure at the surface of the Earth). The Dobson unit was named after G.M.B. Dobson, who was a researcher at Oxford University in the 1920s. He built the first instrument (now called the Dobson meter) to measure total ozone from the ground.

The size of the Southern Hemisphere ozone hole as a function of the year is shown in the figure below. Figure 4.5.4 compares the size of the hole over a twenty year period, from 1980 to 2010. It can be seen that the size increased each year. Each year in the spring, the ozone hole is at its largest.

Figure 4.5.4. Southern hemisphere ozone hole area

Effects of Ozone Depletion on Skin

Effects of ozone depletion can result in 1) increased cases of skin cancer, 2) skin damage, 3) cataracts and other eye damage, and 4) immune suppression.

Skin Cancer

The incidence of skin cancer in the United States has reached epidemic proportions. One in five Americans will develop skin cancer in their lifetime, and one American dies every hour from this devastating disease.

Medical research is helping us understand the causes and effects of skin cancer. Many health and education groups are working to reduce the incidence of this disease, of which 1.3 million cases have been predicted for 2000 alone, according to The American Cancer Society. Figure 4.3.11 shows the sources of ozone depleting substances.

Figure 4.5.5. Various sources that produce ODS

Melanoma

Melanoma, the most serious form of skin cancer, is also one of the fastest growing types of cancer in the United States. Many dermatologists believe there may be a link between childhood sunburns and melanoma later in life. Melanoma cases in this country have more than doubled in the past 2 decades, and the rise is expected to continue.

Non-melanoma Skin Cancers

Nonmelanoma skin cancers are less deadly than melanomas. Nevertheless, left untreated, they can spread, causing disfigurement and more serious health problems. More than 1.2 million Americans will develop nonmelanoma skin cancer in 2000 while more than 1,900 will die from the disease. There are two primary types of nonmelanoma skin cancers.

- **Basal Cell Carcinomas** are the most common type of skin cancer tumors. They usually appear as small, fleshy bumps or nodules on the head and neck, but can occur on other skin areas. Basal cell carcinoma grows slowly, and rarely spreads to other parts of the body. It can, however, penetrate to the bone and cause considerable damage.
- **Squamous Cell Carcinomas** are tumors that may appear as nodules or as red, scaly patches. This cancer can develop into large masses, and unlike basal cell carcinoma, it can spread to other parts of the body.

These two cancers have a cure rate as high as 95 percent if detected and treated early. The key is to watch for signs and seek medical treatment.

Other Skin Damage

Other UV-related skin disorders include actinic keratoses and premature aging of the skin.

- **Actinic keratoses** are skin growths that occur on body areas exposed to the sun. The face, hands, forearms, and the "V" of the neck are especially susceptible to this type of lesion. Although premalignant, actinic keratoses are a risk factor for squamous cell carcinoma. Look for raised, reddish, rough-textured growths and seek prompt medical attention if you discover them.
- Chronic exposure to the sun also causes **premature aging**, which over time can make the skin become thick, wrinkled, and leathery. Since it occurs gradually, often manifesting itself many years after the majority of a person's sun exposure, premature aging is often regarded as an unavoidable, normal part of growing older. With proper protection from UV radiation, however, most premature aging of the skin can be avoided.

Note

Protect yourself against sunburn. Minimize sun exposure during midday hours (10 am to 4 pm). Wear sunglasses, a hat with a wide brim, and protective clothing with a tight weave. Use a broad spectrum sunscreen with a sun protection factor (SPF) of at least 15. To be safer, 30 is better.

Effects of Ozone Depletion on Eyes and Immune System

Cataracts and Other Eye Damage

Cataracts are a form of eye damage in which a loss of transparency in the lens of the eye clouds vision. If left untreated, cataracts can lead to blindness. Research has shown that UV radiation increases the likelihood of certain cataracts. Although curable with modern eye surgery, cataracts diminish the eyesight of millions of Americans and cost billions of dollars in medical care each year. The following video provides more information on cataracts.

YouTube Video

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Other kinds of eye damage include **pterygium** (i.e., tissue growth that can block vision), skin cancer around the eyes, and degeneration of the macula (i.e., the part of the retina where visual perception is most acute). All of these problems can be lessened with proper eye protection from UV radiation.

Immune Suppression

Scientists have found that overexposure to UV radiation may suppress proper functioning of the body's immune system and the skin's natural defenses. All people, regardless of skin color, might be vulnerable to effects including impaired response to immunizations, increased sensitivity to sunlight, and reactions to certain medications.

Protecting the Environment - Ozone Depletion

Your "power" in protecting the environment from ozone depletion includes:

- Making sure that technicians working on your car air conditioner, home air conditioner, or refrigerator are certified by an EPA-approved program to recover the refrigerant (this is required by law).
- Having your car and home air conditioner units and refrigerator checked for leaks. When possible, repair leaky air conditioning units before refilling them.
- Contacting local authorities to properly dispose of refrigeration or air conditioning equipment.

International Action in Protecting the Environment from Ozone Depletion

In 1987, the Montreal Protocol, an international environmental agreement, established requirements that began the worldwide phase out of ozone-depleting CFCs (chlorofluorocarbons). These requirements were later modified, leading to the phase out in 1996 of CFC production in all developed nations.

Ground Level Ozone and Photochemical Smog

Ozone is a secondary pollutant that forms from the primary pollutants such as Volatile Organic Compounds (Hydrocarbons) and nitrogen oxides (NO_X) in the presence of sunlight, as shown in Figure 4.5.6. Its formation is mainly from the automobile emissions.

Figure 4.5.6. Ozone formation

Below is a demonstration on how ozone forms at the ground level (note ground level ozone is also known as “bad” ozone).

YouTube Video

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View this YouTube Video online

As previously mentioned, the formation of ozone is mainly from automobile emission. A typical profile of pollutants in the air of major cities is well repeatable and is shown in the figure below. Note how the formation changes over the course of a day, as shown in Figure 4.5.7:

- Early in the morning - During peak traffic hours, NO and Hydrocarbons are emitted along with CO.
- Mid-morning - NO is slowly oxidized to NO_2.
- Mid-afternoon - In the presence of sunlight, NO_x react with VOCs to form ozone.

Figure 4.5.7. Typical pollutant profile and ozone formation during the day

Ozone, by itself, is damaging to health and also to the environment. Ozone triggers a variety of health problems even at very low levels and may cause permanent lung damage after long-term exposure. Ozone also leads to the formation of smog or haze, causing additional problems such as a decrease in visibility as well as damage to plants and ecosystems.

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4.6: Acid Rain and Ozone (III)

Basic Chemistry and Sources

As we have learned, volatile Organic Compounds (Hydrocarbons) combine with nitrogen oxides (NO_x) in the presence of sunlight to form ozone.

$$\mathrm{VOCs} + \mathrm{NOx} \xrightarrow{\text{sunlight}} \mathrm{Ozone} \tag{4.6.1}$$

In turn, sunlight and hot weather cause ground-level ozone to form in harmful concentrations in the air. As a result, it is known as a summertime air pollutant.

$$\mathrm{Ozone} + \mathrm{NO} \xrightarrow{\text{sunlight}} \mathrm{Photochemical} \quad \mathrm{Smog} \quad (\mathrm{Haze}) \tag{4.6.2}$$

Many urban areas tend to have high levels of "bad" ozone, but even rural areas are also subject to increased ozone levels because wind carries ozone and pollutants that form it hundreds of miles away from their original sources.

Figure 4.6.1 compares the major sources of NO_x and VOC that help to form ozone.

Figure 4.6.1. Major sources of NO_x and VOC

Health and Environmental Impact

Several groups of people are particularly sensitive to ozone—especially when they are active outdoors—because physical activity causes people to breathe faster and more deeply. In general, as concentrations of ground-level ozone increase, more and more people experience health effects, the effects become more serious, and more people are admitted to the hospital for respiratory problems. When ozone levels are very high, everyone should be concerned about ozone exposure. Figure 4.3.15 shows how ozone can affect the lungs.

Figure 4.6.2. Ozone can inflame the lung's lining. These photos show a healthy lung airway (left) and an inflamed lung airway (right).

Health Effects of Ground Level Ozone

- **Ozone can irritate your respiratory system**, causing you to start coughing, feel an irritation in your throat and/or experience an uncomfortable sensation in your chest.
- **Ozone can reduce lung function** and make it more difficult for you to breathe as deeply and vigorously as you normally would. When this happens, you may notice that breathing starts to feel uncomfortable. If you are exercising or working outdoors, you may notice that you are taking more rapid and shallow breaths than normal.
- **Ozone can aggravate asthma**. When ozone levels are high, more people with asthma have attacks that require a doctor's attention or the use of additional medication. One reason this happens is that ozone makes people more sensitive to allergens, which are the most common triggers for asthma attacks. Also, asthmatics are more severely affected by the reduced lung function and irritation that ozone causes in the respiratory system.
- **Ozone can inflame and damage cells that line your lungs**. Within a few days, the damaged cells are replaced and the old cells are shed—much in the way your skin peels after a sunburn.
- **Ozone may aggravate chronic lung diseases** such as emphysema and bronchitis and reduce the immune system's ability to fight off bacterial infections in the respiratory system.
- **Ozone may cause permanent lung damage**. Repeated short-term ozone damage to children's developing lungs may lead to reduced lung function in adulthood. In adults, ozone exposure may accelerate the natural decline in lung function that occurs as part of the normal aging process.

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5: APPLIANCES

5.1: Appliance Energy Consumption
5.2: EnergyGuide Labels
5.3: Water Heaters
5.4: Refrigerators
5.5: Clothes Washers
5.6: Clothes Dryers
5.7: Dishwashers

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5.1: Appliance Energy Consumption

Most homes have a variety of appliances with a wide range of operating costs. Typical costs of operation of basic household appliances are shown in Figure 5.1.1.

Figure 5.1.1. Typical energy costs for various appliances

Household appliances, cooking, and lighting consume 33% of the energy at home as shown in Figure 5.1.2. Water heating (not included in the appliances) is the second largest energy expense after home heating and cooling. It typically accounts for about 14% of the utility bill.

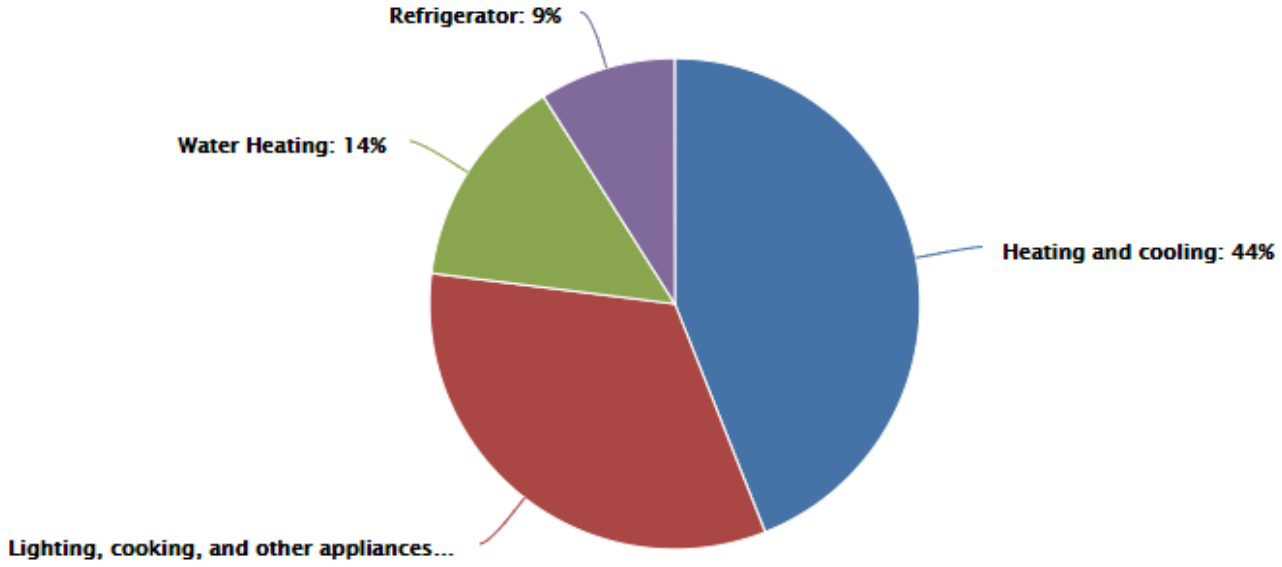


Figure 5.1.2. Typical residential energy use

Credit: *U.S. Department of Energy*

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5.2: EnergyGuide Labels

All major home appliances must meet the Appliance Standards Program set by the US Department of Energy (DOE). Manufacturers must use standard test procedures developed by DOE to prove the energy use and efficiency of their products. Test results are printed on yellow Energy Guide labels (pictured below) which manufacturers are required to display on many appliances. This label provides the necessary information to perform a Life Cycle Analysis when comparing different models.

Figure 5.2.1 provides detailed descriptions about the information found on Energy Guide labels.

Figure 5.2.1. Energy guide labels

Credit: Energy Guide Label by Federal Trade Commission

The Federal Trade Commission's Appliance Labeling Rule requires appliance manufacturers to put these labels on refrigerators, freezers, dishwashers, clothes washers, water heaters, furnaces, boilers, central air conditioners, room air conditioners, heat pumps, and pool heaters. The law requires that the labels specify:

- the capacity of the particular model—for refrigerators, freezers, dishwashers, clothes washers, and water heaters;
- the energy efficiency rating and the estimated annual energy consumption of the model—for air conditioners, heat pumps, furnaces, boilers, and pool heaters;
- the range of estimated annual energy consumption, or energy efficiency ratings, of comparable appliances.

How to Use the Labels

A worksheet on how to use the labels in choosing a cost-effective and environmentally friendly appliance is given in Table 5.2.1.

Table 5.2.1. How to use energy labels

Part A - General Information	
1. Are the appliances comparable in size and features?	Answer must be yes
2. What is the price of the more energy-efficient model?	$ _____
3. What is the price of the less energy-efficient model?	$ _____
4. What is the price of electricity in your region?	$ _____ / kWh
5. How long do you expect to keep the appliance? What is the life of the appliance?	_____
Part B - Determining Why You Should Buy an Energy-Efficient Model	
1. Calculate the price difference:	
2. Price of the more energy-efficient model	$ _____
3. Price of the less energy-efficient model	$ _____
4. Price Difference	$ _____
Determining the Annual Energy Savings	
1. Annual energy consumption of the less energy-efficient model	_____ kWh
2. Annual energy consumption of the more energy-efficient model	_____ kWh
3. Annual energy savings	_____ kWh
Determining the Savings	

1. Annual energy savings	_____ kWh
2. Annual monetary savings on energy (energy savings x price)	$ _____
3. Energy savings over the life time of the appliance	_____ kWh
(Life in years) * (Annual Energy Savings)	
1. Cost of energy savings over life time of the appliance	$ _____
Determining the Payback Period	
1. Price difference between the models	$ _____
2. Annual monetary savings on energy (energy savings x price)	$ _____
3. Pay Back Period (years to recover the additional investment)	$ _____
4. Monetary savings on energy over the lifetime	$ _____
5. Price Difference	$ _____
6. Total monetary benefit for choosing environmentally friendly appliance (4 – 5)	$ _____

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5.3: Water Heaters

Heat is continuously flowing from the tank of the water heater and the pipes to the room because the water heater is always at a higher temperature than the surroundings (basement or garage). Thermal energy flows from high temperature to low temperature. Heat is lost whether you use water or not.

Like most appliances, water heaters have improved greatly in recent years. Today's models are much more energy efficient, and you will be able to purchase a more efficient water heater that will save you money on energy each month. The average life expectancy of a water heater is 13 years. Therefore, the initial purchase price should not be an important factor in selecting a water heater.

Costs of Water Heaters

Just like other appliances, there are two costs associated with water heaters - initial purchase price and operating costs. Water heaters typically last for about 13 years, after which they need to be replaced. Also, each month, you pay for the fuel you use. An energy-efficient model could save hundreds of dollars in the long run in the energy costs and may offset the higher initial purchase price.

It can be compared to automobile mileage—some cars get 15 miles to a gallon, while other, more efficient, vehicles can go 30 miles or more on a gallon of gas. In the same way, some water heaters use energy more efficiently.

One should buy an energy-efficient water heater and spend less money each month to get the same amount of hot water.

Typical Water Use at Home

Table 5.3.1 shows typical water use for various purposes at home.

Table 5.3.1. Typical water use

Use	Gallons per use
Shower	7 to 10
Bath (standard tub)	20
Bath (whirlpool tub)	35 to 50
Clothes washer (hot water wash, warm rinse)2	32
Clothes washer (warm wash, cold rinse)	7
Automatic dishwasher	8 to 10
Food preparation and cleanup	5
Personal (hand-washing, etc.)	2

Energy costs increase with water temperature. Dishwashers require the hottest water of all household uses, typically 135°F to 140°F. However, these devices are usually equipped with booster heaters to increase the incoming water temperature by 15°F to 20°F. Setting the water heater between 120°F and 125°F and turning the dishwasher's booster on should provide sufficiently hot water while reducing the chances for scalding.

Energy Required for Water Heating

To calculate the amount of energy required for water heating, use the equation

$$Q = m * C_p * \Delta T \tag{5.3.1}$$

where

- m = mass of water heated
- C_p = the heat capacity of water (1 BTU / lb °F)
- ΔT = temperature difference

Important Point

Remember to make your units of measurements consistent. Since C_p is measured in pounds, your mass of water heated should be measured in pounds as well. Thus, if you only know the number of gallons, you must convert it into pounds. One gallon of water = about 8.3 pounds, so multiply number of gallons by 8.3 to determine the weight in pounds.

Example Problems

Example 1

It is estimated by the United States Department of Energy that a family of four each showering for 10 minutes a day consumes about 700 gal of hot water a week. Water for the showers comes into the home at 55°F and needs to be heated to 120°F. What is the cost of gas vs. electricity to power this home, and which is more expensive?

Answer available at the end of this section.

Example 2

Estimate the % energy savings of an electric water heater that heats 100 gallons of per day when the temperature is set back at 110°F instead of 120°F. The basement is heated and is at 65°F. The life of the water heater is expected to be about 10 years. Use an appropriate cost for electricity and compare the operating expenses.

Answer available at the end of this section.

Types of Water Heaters: Storage or Tank

There are several types of water heaters that are available on the market:

- Storage or tank
- On demand
- Heat pump
- Tankless coil
- Indirect
- Solar

However, most water heaters use a storage tank type.

Storage or tank-type water heaters are relatively simple devices and by far the most common type of residential water heater used in the United States. They range in size from 20 to 80 gallons, and can be fueled by electricity, natural gas, propane, or oil.

Parts of an Electric Hot Water Heater

Figure 5.3.1 breaks down the parts of an electric water heater.

Figure 5.3.1. Electric hot water heater

Parts of a Gas Hot Water Heater

Figure 5.3.2 breaks down the parts of a gas hot water heater.

Figure 5.3.2. Gas hot water heater

How a Gas Hot Water Heater Works

When you turn on a hot water faucet or use hot water in a dishwasher or clothes washer, water pipes draw hot water from the tank. To replace that hot water, cold water enters the bottom of the tank, ensuring that the tank is always full. Depending on the type of fuel that is used, either electrical heating elements or a natural gas burner is used to heat the water.

The following video shows an animation of how a gas water heater works.

YouTube Video

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Credit: Dr. Sarma Pisupati

Electric water heaters are generally less expensive to install (purchase price) than gas-fired types because they don't require gas lines and vents to let the combustion products out of the house. In previous lessons, and in Home Activity 2, we have seen that natural gas costs about 7–12 dollars per million BTUs, whereas electrical energy is 20–25 dollars per million BTUs, making electric water heaters more expensive to operate.

Storage tank-type water heaters raise and maintain the water temperature to the temperature setting on the tank (usually between 120°–140°F). Because the water is constantly heated and kept ready for use in the tank, heat energy can be lost even when no faucet is on. This is called **standby heat loss**. These standby losses represent 10 to 20 percent of a household's annual water heating costs. Newer, more energy-efficient storage models can significantly reduce the amount of standby heat loss, making them much less expensive to operate.

Types of Water Heaters: Demand Water Heaters

Demand Water Heaters do not have storage tanks, so there is no standby heat loss from the tank, and energy consumption is reduced by 20 to 30 percent. Demand water heaters are available in propane (LP), natural gas, or electric models.

In these types of water heaters, cold water travels through a pipe into the unit, and either a gas burner or an electric element heats the water only when needed. With these systems, you never run out of hot water. However, the flow rate is limited by the outlet temperature.

The appeal of demand water heaters is the elimination of the tank standby losses, the resulting lower operating costs, and the fact that the heater delivers hot water continuously.

How a Demand Water Heater Works

The following video explains how a demand water heater works.

YouTube Video

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Typically, demand heaters provide hot water at a rate of 2 to 4 gallons per minute. This flow rate might meet the requirements of a household's hot water needs as long as the hot water is not needed in more than one location at a time (e.g., one cannot shower and do the laundry simultaneously). To meet hot water demand when multiple faucets are being used, demand heaters can be installed in parallel sequence.

Although gas-fired demand heaters tend to have higher flow rates than electric ones, they can waste energy even when no water is being heated if their pilot lights stay on. However, the amount of energy consumed by a pilot light is quite small. Thus, in most cases, gas demand water heaters will cost less to operate than electric water heaters.

Demand water heaters cost more than conventional storage tank-type units. Small point-of-use heaters that deliver 1 to 2 gallons per minute (gpm) sell for about $200. Larger gas–fired demand units that deliver 3 to 5gpm cost $550 - $1,000. The more hot water the unit produces, the higher the cost.

Advantages and Disadvantages of Demand Water Heaters

Table 5.3.2 details the advantages and disadvantages.

Table 5.3.2. Advantages and disadvantages of demand water heaters

Advantages	Disadvantages
• Compact in size • Virtually eliminates standby losses • Wastes less water because warm water is provided immediately where it is used (no need to wait for water to warm up) • Provides unlimited hot water as long as it is operated within its capacity • Equipment life is longer (20 years vs. 10-15 years for tank-type heaters) than tank-type heaters because they are less subject to corrosion	• Demand water heaters usually cannot supply enough hot water for simultaneous uses such as showers and laundry. • Unless your demand system has a feature called modulating temperature control, it may not heat water to a constant temperature at different flow rates. That means that water temperatures can fluctuate uncomfortably—particularly if the water pressure varies wildly in your own water system. • Electric units will draw more instantaneous power than tank-type water heaters. If electric rates include a demand charge, operation may be expensive. • Electric demand water heaters require a relatively high electric power draw because water must be heated quickly to the desired temperature. Make sure your wiring is up to the demand. • Demand gas water heaters require a direct vent or conventional flue. If a gas-powered unit has a pilot light, it can waste a lot of energy.

Types of Water Heaters: Solar Water Heaters

An estimated one million residential and 200,000 commercial solar water-heating systems, shown in Figure 5.3.3, have been installed in the United States. Although there are a large number of different types of solar water-heating systems, the basic technology is very simple.

Sunlight strikes and heats an "absorber" surface within a "solar collector" or an actual storage tank. These roof-mounted solar heaters supply about 80% of the hot water for the home. Either a heat-transfer fluid or the actual potable water to be used flows through tubes attached to the absorber and picks up the heat from it. (Systems with a separate heat-transfer-fluid loop include a heat exchanger that then heats the potable water.) The heated water is stored in a separate preheat tank or a conventional water heater tank until needed.

If additional heat is needed, it is provided by electricity or fossil-fuel energy by the conventional water-heating system.

Figure 5.3.3. A roof mounted solar water heater

Credit: Work found at http://en.Wikipedia.org/wiki/File:ThermodynamicPanelsInstalled.jpg

How a Solar Water Heater Works

The following video explains how a solar water heater operates.

YouTube Video

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By reducing the amount of heat that must be provided by conventional water heating, solar water-heating systems directly substitute renewable energy for conventional energy, reducing the use of electricity or fossil fuels by as much as 80%.

Today's solar water-heating systems are proven reliable when correctly matched to climate and load. The current market consists of a relatively small number of manufacturers and installers that provide reliable equipment and quality system design.

A quality assurance and performance-rating program for solar water-heating systems, instituted by a voluntary association of the solar industry and various consumer groups, makes it easier to select reliable equipment with confidence.

Building owners should investigate installing solar hot water-heating systems to reduce energy use. However, before sizing a solar system, water-use reduction strategies should be put into practice.

Types of Solar Hot Water Heaters

There are five types of solar hot water systems:

- **Thermosiphon Systems**. These systems heat water or an antifreeze fluid, such as glycol. The fluid rises by natural convection from collectors to the storage tank, which is placed at a higher level. No pumps are required. In thermosiphon systems, fluid movement, and therefore heat transfer, increases with temperature, so these systems are most efficient in areas with high levels of solar radiation.
- **Direct-Circulation Systems.** These systems pump water from storage to collectors during sunny hours. Freeze protection is obtained by recirculating hot water from the storage tank, or by flushing the collectors (drain-down). Since the recirculation system increases energy use, while flushing reduces the hours of operation, direct-circulation systems are used only in areas where freezing temperatures are infrequent.
- **Drain-Down Systems.** These systems are generally indirect water-heating systems. Treated or untreated water is circulated through a closed loop, and heat is transferred to potable water through a heat exchanger. When no solar heat is available, the collector fluid is drained by gravity to avoid freezing and convection loops in which cool collector water reduces the temperature of the stored water.
- **Indirect Water-Heating Systems.** In these systems, freeze-protected fluid is circulated through a closed loop and its heat

is transferred to potable water through a heat exchanger with 80 to 90 percent efficiency. The most commonly used fluids for freeze protection are water-ethylene glycol solutions and water-propylene glycol solutions.
- **Air Systems**. In this indirect system, the collectors heat the air, which is moved by a fan through an air-to-water heat exchanger. The water is then used for domestic or service needs. The efficiency of the heat exchanger is in the 50% range.

Direct-circulation, thermosiphon, or pump-activated systems require higher maintenance in freezing climates. For most of the United States, indirect air and water systems are the most appropriate. Air solar systems, while not as efficient as water systems, should be considered if maintenance is a primary concern since they do not leak or burst.

Types of Water Heaters: Heat Pump Water Heaters (HPWHs)

Heat pumps are a well-established technology for space heating. The same principal of transferring heat is at work in HPWHs except that they extract heat from air (indoor, exhaust, or outdoor air) and deliver it to water. Some models come as a complete package, including tank and back-up resistance heating elements, while others work as an adjunct to a conventional water heater.

The simplest HPWH is the **ambient air-source unit**, which removes heat from surrounding air, providing the additional benefit of space cooling. Exhaust air units extract heat from a continuously exhausted air stream and work better in heating-dominated climates because they do not cool ambient air. Some units can even be converted between the two modes of operation for optimum operation in either summer or winter.

In mild climates, you can place ambient air-source units in unheated but protected spaces such as garages, essentially using outdoor air as a heat source.

Important Point

Because it extracts heat from air, the HPWH delivers about twice the heat for the same electricity cost as a conventional electric resistance water heater.

Parts of a HPWH

Figure 5.3.4 shows the components of a HPWH.

Figure 5.3.4. Heat pump water heater parts

Desuperheaters

The **Desuperheater** feature is available on some central air conditioners and is a variation of the stand-alone HPWH. It provides economical supplemental water heating as a byproduct of air conditioning.

Desuperheater water heating can be part of an integrated package with a heat pump or air conditioner system. In most such systems, the heat pump water heating only occurs during normal demand for space conditioning, with resistance electric coils providing water heating the rest of the time.

During the cooling season, the Desuperheater actually improves the efficiency of the air conditioning system while heating water at no direct cost. In an average climate, a desuperheater might meet 20 to 40 percent of annual water heating demand.

Heat pump water heaters can provide up to 60 percent energy savings over conventional water heaters.

How a HPWH Works

The HPWH consists of three circuits. The HPWH consists of three circuits. The following video explains more about how a HPWH works.

YouTube Video

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View this YouTube Video online

Credit: Dr. Sarma Pisupati

Note: The concept shown in the animation is applicable to all HPWH: heat is picked up and delivered into some source – which could either be the ground, air, or water.

Most of the heat delivered to the water comes from the evaporator of the unit, not through the electrical input to the machine. Consequently, the efficiency of the HPWH is much higher than for direct-fired gas or electric storage water heaters.

The installed cost of commercial HPWH systems is typically several times that of gas or electric water heaters; yet the low operating costs can often offset the higher total installed cost, making the HPWH the economic choice for water heating.

The HPWH becomes increasingly attractive in building applications where energy costs are high, and where there is a steady demand for hot water. This attractiveness is less a function of building type than it is of water demand and utility cost.

Energy Efficiency of Water Heaters

The federal efficiency standards for water heaters took effect in 1990, assuring consumers that all new water heaters meet certain minimum-efficiency levels. New standards, which took effect in January 2004, will increase the minimum efficiency levels of these products.

Water heater efficiency is reported in terms of the **energy factor (EF)**. EF is an efficiency ratio of the energy supplied in heated water divided by the energy input to the water heater, and it is based on recovery efficiency, standby losses, and cycling losses. The higher the EF, the more efficient the water heater.

- Electric resistance water heaters have EFs ranging from 0.7 and 0.95.
- Gas water heaters from 0.5 and 0.6, with some high-efficiency models ranging around 0.8.
- Oil water heaters from 0.7 and 0.85.
- Heat-pump water heaters from 1.5 to 2.0.

Additional Information

There is little difference between the most efficient electric resistance storage water heaters and the minimum-efficiency standard that will take effect in January 2004. If you need to rely on electricity to heat your water, keep your eye out for the further development of heat-pump water heaters. This technology uses one-third to one-half as much electricity as a conventional electric resistance water heater.

Energy Efficiency Recommendations

Everything else being equal, select a water heater with the highest energy factor (EF). Table 5.3.3 energy efficiency recommendations.

Table 5.3.3. Water heater energy efficiency recommendations

Storage Type	Recommended		Best Available	
	Energy Factor	Annual Energy Use (kWh)	Energy Factor	Annual Energy Use (kWh)
Less than 60 gallons	0.93	4.721	0.95	4,622
60 gallons or more	0.91	4.825	0.92	4,773

Important Point

The higher the EF, the more efficient the water heater.

Other Considerations

In addition to EF, also look for a water heater with at least one-and-a-half inches of tank insulation and a heat trap.

In addition, capacity of a water heater is an important consideration. The water heater should provide enough hot water at the busiest time of the day. For example, a household of two adults may never use more than 30 gallons of hot water in an hour, but a family of six may use as much as 70 gallons in an hour.

The ability of a water heater to meet peak demands for hot water is indicated by its "first hour rating." This rating accounts for the effects of tank size and the speed by which cold water is heated. Water heaters must be sized properly. Over-sized water heaters not only cost more but increase energy use due to excessive cycling and higher standby losses.

Life Cycle Analysis

Figure 5.3.5. EnergyGuide labels for two different water heaters

Water Heaters: Your "Power" in Enviromental Protection

Here are some things you can do to minimize the environmental impact of your water heater.

- Do as much cleaning as possible with cold water to save the energy used to heat water.
- Check your faucets for leaks. They waste both water and energy!
- Conserve hot water by installing water-saving showerheads. A new showerhead can save as much as $10 a year in water and energy.
- Once your water is hot, insulate to help keep it that way. Wrapping exposed hot water pipes with insulation will minimize heat loss. So will installing an R-12 insulation blanket around your water heater, unless the manufacturer does not recommend it.
- Reduce your water heater's temperature to 120 degrees Fahrenheit. That will produce plenty of hot water and still save energy. For homes with a dishwasher, a setting of 140 degrees is required to clean properly, but most of the new dishwashers have a built-in water temperature booster.
- Many new water heaters have a "vacation" setting you can use to save energy if you're away for more than a few days. Turn the thermostat "down" or "off" when you're gone for more than three days.

Answers

Example 1

Determine the variables for equation 5.3.1:

- m = mass of water heated = 700 gallons = 5810 lbs
- C_p = heat capacity of water = 1 BTU/lb °F (given)
- ΔT = temperature difference = 120 - 55 = 65°F

The heat energy required to heat 700 gal can be calculated as follows:

$$Heat = 5810\,lbs * \frac{1BTU}{lb^oF} * 65^oF = 377650\,BTU/week$$

Then, the heat required for one year is

$$Heat\,(1\,year) = \frac{377650 BTU}{week} * \frac{52 weeks}{year} = 19,637,800\,BTU/year = 5755\,kWh$$

Assuming that the natural gas costs $10/MMBTU (1 MMBTU = 1,000,000 BTU) and electricity costs $0.092 per kWh, the gas costs would be **$196.37** while electric costs would be **$529.46**. Clearly, electric heat is more expensive than natural gas.

Example 2

Calculate the energy required for heating the water to 120°F by using equation 5.3.1:

$$Energy = \underbrace{\frac{100 gal}{day} * \frac{8.3 lb}{gal}}_{m} * \underbrace{\frac{1 BTU}{lb°F}}_{C_p} * \underbrace{(120-65)°F}_{\Delta T} = 45,650\,BTUs/day$$

In one year,

$$Energy\,(per\,year) = \frac{45,650\,BTUs}{day} * \frac{365\,days}{year} = 16,662,250\,BTUs/year$$

In a 10-year period,

$$Energy\,(per\,10\,years) = \frac{16,662,250\,BTUs}{year} * 10\,years = 166,622,500\,BTUs$$

This is equivalent to 48,834 kWh (since 1 kWh = 3,412 BTUs).

The operating cost over its lifetime is

$$Operating\,cost = 48,834\,kWh * \frac{\$0.09}{kWh} = \$4,395.06$$

Now, calculate the energy required for heating the water to 110°F by using equation 5.3.1:

$$Energy = \underbrace{\frac{100 gal}{day} * \frac{8.3 lb}{gal}}_{m} * \underbrace{\frac{1 BTU}{lb°F}}_{C_p} * \underbrace{(110-65)°F}_{\Delta T} = 37,350\,BTUs/day$$

In one year,

$$Energy\,(per\,year) = \frac{37,350\,BTUs}{day} * \frac{365\,days}{year} = 13,632,750\,BTUs/year$$

In a 10-year period,

$$Energy\,(per\,10\,years) = \frac{13,632,750\,BTUs}{year} * 10\,years = 136,327,500\,BTUs$$

This is equivalent to 39,995 kWh (since 1 kWh = 3,412 BTUs).

The operating cost over its lifetime is

$$Operating\,cost = 39,995 kWh * \frac{\$0.09}{kWh} = \$3,595.95$$

The estimated % energy savings are

$$Savings = \$4,395.06 - \$3,595.95 = \$799.11$$

$$\%\,Savings = \frac{\$799.11}{\$4,395.06} = \mathbf{18.2\%\ savings}$$

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5.4: Refrigerators

Refrigerators are heat movers, which move heat from a low temperature (inside the refrigerator) to high temperature (outside the refrigerator into the kitchen). Heat movers do not produce any heat but just move from one location to another.

The following video shows how a heat mover works.

YouTube Video

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How Does a Refrigerator Work?

The principle of operation of a refrigerator is similar to an air conditioner. It moves the heat energy from inside to outside. There are four basic components in a refrigerator and their functions are as follows:

- **Expansion valve** - A liquid refrigerant at high pressure flows through an expansion valve. As the refrigerant moves through the expansion valve, it moves from a high-pressure zone to a low-pressure zone. The decrease in pressure corresponds with a decrease in temperature.
- **Evaporator or heat exchanging pipes** - A set of coiled tubes carrying the low pressure, expanded refrigerant. In the evaporator, the liquid refrigerant also expands and evaporates. The evaporation of liquid takes away heat, creating cold gas in the coils. The cold refrigerant flowing through the coils absorbs heat from the refrigerator. The food gets cold. However, the refrigerant warms up because of the absorption of heat.
- **Compressor** - A device that pressurizes the warm refrigerant and makes it hot (hotter than the kitchen temperature). This hot refrigerant goes into the condenser.
- **Condenser or second heat exchanger coil** - Located at the back of the refrigerator where it gives off the heat to the air in the kitchen.

The following video explains how a refrigerator works.

YouTube Video

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Types and Features

There are four types of refrigerators: top-freezer (or top-mount), bottom-freezer (or bottom-mount), side-by-side, and built-in (as shown in Figure 5.4.1).

Refrigerators also come in four size categories: small (7 to 9.9 cubic feet), medium (10 to 13.9 cubic feet), large (14 to 19.9 cubic feet), and extra large (20 to 29 cubic feet).

Figure 5.4.1. Types of refrigerators: top mounted (left), bottom mounted (middle), side-by-side (right)

Energy Efficiency of a Refrigerator

Most of the energy used by a refrigerator is used to pump heat out of the cabinet. A small amount is used to keep the cabinet from sweating, to defrost the refrigerator, and to illuminate the interior.

The efficiency of a refrigerator is based on the energy consumed per year for a given size. The efficiency of a refrigerator is expressed in **volume cooled per unit electric energy per day**, i.e.,

$$Refrigerator\ Efficiency = \frac{Volume\ Cooled\ (ft^3)}{Unit\ Electrical\ Energy\ per\ day\ (kWh)} \tag{5.4.1}$$

The energy efficiency of refrigerators and freezers has improved dramatically over the past three decades. For example, the energy bill for a typical new refrigerator with automatic defrost and top-mounted freezer will be about $55 per year, whereas a typical model sold in 1973 will cost nearly $160 per year (almost three times the energy consumption).

The Department of Energy (DOE) standards set maximum allowable annual energy consumption for different sizes and classes of refrigerators. These Federal efficiency standards first took effect in 1993, requiring new refrigerators and freezers to be more efficient than ever before. A new set of stricter standards took effect July 1, 2001.

EnergyGuide Labels

Refrigerators now come with an EnergyGuide label, shown in Figure 5.4.2, that tells you in kilowatt-hours (kWh) how much electricity a particular model uses in a year. The smaller the number, the less energy the refrigerator uses and the less it will cost you to operate.

- Full-sized refrigerators that exceed the federal standard by 15% or more (and full-sized freezers that exceed it by 10%) qualify for the ENERGY STAR label.
- Compact refrigerators and freezers must exceed the standard by 20% to qualify for ENERGY STAR.

Figure 5.4.2. EnergyGuide label

ENERGY STAR qualified refrigerators provide energy savings without sacrificing the features you want. ENERGY STAR–qualified models have

- High-efficiency compressors
- Improved insulation
- More precise temperature
- More precise defrost mechanisms

These models also use at least 15% less energy than required by current federal standards, and 40% less energy than the conventional models sold in 2001.

Many ENERGY STAR qualified models include automatic ice-maker and through-the-door ice dispensers. Qualified models are also available with top, bottom, and side-by-side freezers.

What to Look for in a Refrigerator

When selecting a refrigerator, remember the following:

- Refrigerators with the freezer on either the bottom or top are the most efficient. Bottom freezer models use approximately 16 percent less energy than side-by-side models and top freezer models use about 13 percent less than side-by-side.
- Through-the-door ice makers and water dispensers are convenient and reduce the need to open the door, which helps

maintain a more constant temperature; however, these convenient items will increase your refrigerator's energy use by 14 to 20 percent.
- Mini-doors give you easy access to items most often used. The main door is opened less often, which saves energy.
- Too large a refrigerator may waste space and energy. One that's too small can mean extra trips to the grocery store. Your best bet is to decide which size fits your needs, and then compare the EnergyGuide label on each so you can purchase the most energy efficient make and model.
- A manual defrost refrigerator uses half the energy of an automatic defrost model but must be defrosted regularly to stay energy efficient.
- Refrigerators with anti-sweat heaters consume 5 percent to 10 percent more energy. Look for models with an "energy saver" switch that lets you turn down—or off—the heating coils (which prevent condensation).

Technology Requirements

The improvement in the energy efficiency over the past three decades is due to the:

- addition of vacuum insulation panels around the freezer section to reduce heat transfer;
- addition of polyurethane foam to the doors to double insulation thickness;
- replacement of AC motors with more efficient DC motors;
- replacement of automatic defrost control with an adaptive defrost that operates only when needed.

Refrigerators and Environmental Protection

Here are some things you can control to minimize the environmental impact of your refrigerator.

- Keep your refrigerator or freezer at the following temperatures: 37–40°F for the fresh food compartment of the refrigerator, 0–5°F for the freezer section. Use a thermometer to check inside temperatures.
- Regularly defrost manual-defrost refrigerators and freezers; don't allow frost to build up more than 1/4 inch.
- Make sure your refrigerator and freezer door seals are airtight. Check the seal on door gaskets periodically by closing the door on a dollar bill. If it pulls out easily, you may need a new gasket.
- Keep the doors closed as much as possible and make sure they are closed tightly.
- To ensure proper cooling of its contents, don't crowd food items. Too many dishes obstruct air circulation.
- Cover liquids and wrap foods stored in the refrigerator. Uncovered foods release moisture and make the compressor work harder.
- Replace paper wrappings on food items with aluminum foil or plastic wrap. Paper is an insulator.
- Consider turning off the butter conditioner since it is a little heater inside your refrigerator.
- Experiment with the "energy saver" switch in your refrigerator—it allows you to adjust the heating coil under the "skin" of the refrigerator (the purpose of the heating coils is to prevent condensation on your refrigerator).
- Placement of the refrigerator is very important. Direct sunlight and close contact with hot appliances will make the compressor work harder. More importantly, heat from the compressor and condensing coil must be able to escape freely, or it will cause the same problem. Don't suffocate the refrigerator by enclosing it tightly in cabinets or against the wall. The proper breathing space will vary depending on the location of the coils and compressor on each model—something important to know before the cabinets are redesigned.
- Regularly brush off or vacuum the refrigerator coils on the back or bottom of the unit.
- Because most refrigerators reject heat from the bottom and/or back, they need adequate clearance to allow sufficient airflow. While no specific studies have been done to calculate the optimum clearance space, one general rule-of-thumb is to double the space recommended by manufacturers for refrigerator installation. Another rule-of-thumb is to allow 2 inches of air flow around the refrigerator.
- Don't keep that old, inefficient fridge running day and night in the garage for those few occasions when you need extra refreshments. A 15-year-old refrigerator could cost $100 to $150 per year.

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5.5: Clothes Washers

Clothes washers and dryers account for 10 percent of the residential energy consumption, with most of the energy consumed for hot water used for washing.

- An estimated 85% to 90% of the energy is used for heating the water.
- Relatively 10% to 15% of the energy is used by the clothes washer itself to operate the motor and controls.

A typical household does nearly 400 loads of laundry a year, and each load in a conventional washer uses 40 gallons of water. Therefore, any reduction in energy consumption for clothes washing application would involve reduction in hot water use.

Types of Clothes Washers

The basic principle for cleaning clothes has remained unchanged—wet the garment, agitate it to loosen the dirt from the cloth fibers and then use more water to rinse the dirt off. What has changed over the millennia is the method of **agitation**. Pounding garments with stones was common for several thousand years and along the way someone also figured out that using heated water got out a lot more dirt.

Clothes washers come in two types: Horizontal axis (h-axis) or front loading and Vertical axis (v-axis) or top loading (shown in Figure 5.5.1).

Figure 5.5.1. Horizontal axis (front loading), as shown on the left, and vertical axis (top loading), as shown on the right

Most clothes washers produced for the U.S. consumer are **vertical axis (v-axis)** washers with a central agitator. While there are variations, most v-axis washers suspend the clothes in a tub of water for washing and rinsing.

As an alternative, the **horizontal axis (h-axis)** washer tumbles the wash load repeatedly through a small pool of water at the bottom of the tub to produce the needed agitation. This tends to reduce the need for both hot and cold water.

The h-axis washer, popular in Europe, has a very limited market share in the United States at present. Yet, estimates have shown that a large quantity of energy and water could be saved through the replacement of conventional v-axis washers with the h-axis design.

H-Axis Washer

H-axis or tumble-action machines repeatedly lift and drop clothes, instead of moving clothes around a central axis. H-axis washers also use sensor technology to closely control the incoming water temperature. To reduce water consumption, they spray clothes with repeated high-pressure rinses to remove soap residues rather than soaking them in a full tub of rinse water.

The following video explains how an H-axis washing machine works.

YouTube Video

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In a study conducted by Oak Ridge national Laboratory (ORNL) in 1998 for U.S. Department of Energy, it was found that, on

average, the h-axis washer used 62.2 percent of the water used by the v-axis washer, and this yielded total water savings of 37.8 percent. Moreover, the average h-axis washer consumed 42.4 percent of the energy used by a typical v-axis washer in the study, resulting in energy savings of 57.6 percent.

Features of the h-axis washer include:

- **Auto temperature**. The machine will mix hot and cold water to a preset "warm" and "cold" so that the water is warm enough for the detergent to dissolve and optimally perform. During the winter in many parts of the country, cold tap water can be too cold to wash your clothes well.
- **Water level settings.** Some of the very high-end machines sense the amount of clothing and automatically adjust the water level, but all except the most basic machines offer at least four settings.
- **Capacity.** If you have a large household or athletes who produce an astounding amount of laundry each week, a larger capacity machine is a must. The front loaders generally hold more because they don't have the agitator. A definite minus for the front loaders, however, is the actual loading because you have to bend over to put in the clothes. To minimize this fact, the machines and their matching dryers are often displayed in stores on a raised platform.

Energy Efficiency and Water Usage

Stricter new federal standards for clothes washers took effect in two stages. The first stage was in force as of January 2004. Then in 2007, the second stage further strengthened the standard. Three factors are used in determining the federal standards:

- **Energy Factor** is a metric that was previously used to compare relative efficiencies of clothes washers. The higher the Energy Factor is, the more efficient the clothes washer is. For clothes washers, Energy Factor is calculated using the formula

$$Energy\,Factor = 392 * \frac{Volume\,(ft^3)}{Annual\,Energy\,Use\,(KWh)} \tag{5.5.1}$$

- **Water Factor** is the number of gallons per cycle per cubic foot that the clothes washer uses. The lower the water factor, the more efficient the washer is. So, if a clothes washer uses 30 gallons per cycle and has a tub volume of 3.0 cubic feet, then the water factor is 10.0. Note: the energy factor for washers does not indicate the real energy efficiency because of the tub size and other factors. Therefore, the Energy Factor is modified to include the tub size and drying characteristics.
- **Modified Energy Factor (MEF)** is a new equation that replaced Energy Factor as a way to compare the relative efficiency of different units' clothes washers. MEF takes into account the amount of dryer energy used to remove the remaining moisture content in washed items and is calculated using

$$MEF = \frac{ft^3}{\frac{kWh}{Cycle}} \tag{5.5.2}$$

Additional Information

For more information about MEF circulation, please see the August 27, 1997 Federal Register entry regarding 10 CFR Part 430.

Clothes Washers and Environmental Protection

Here are some things you can control to minimize the environmental impact of your clothes washer.

- Wash full loads—Clothes washers are most efficient when operated with full loads.
- Wash clothes in cold water – It will conserve energy and is also recommended for colored and many delicate fabrics.

In addition:

- Consider Front loaders – Since they use less water, they use less energy. The most efficient front loaders use less than half the amount of water used in the average top loaders.
- Purchase washing machines with the Energy Star designation – They are 50 percent more energy efficient than the current

minimal allowable standard.

Many new energy-efficient, water-conserving clothes washers have been introduced over the past few years. These resource-efficient washers are available in a variety of sizes and configurations offering consumers a wide range of front-loading and top-loading styles in many different price ranges.

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5.6: Clothes Dryers

A clothes dryer dries wet clothes in a rotating drum through which hot air is circulated.

- The hot air removes the residual moisture from the clothes.
- The humid air from the dryer is vented out of the house.
- The drum is rotated with the help of a motor at relatively slow speeds to create a tumbling effect.

Clothes dryers can be of two types: electric and gas.

- In an electric dryer, electrical energy is used for both the motor to rotate the drum and heating the air.
- In a gas dryer, the motor requires electrical energy but the air is heated by natural gas.

Energy Efficiency of Dryers

Dryers work by heating and aerating clothes. The efficiency of clothes dryer is measured by a term called the **Energy Factor**. It is similar to the miles per gallon for a car, but in this case the measure is pounds of clothing per kilowatt-hour of electricity.

The minimum Energy Factor rating for a standard capacity electric dryer is 3.01. For gas dryers the minimum energy factor is 2.67. The rating for gas dryers is provided in kilowatt-hours though the primary source of fuel is natural gas.

Unlike most other types of appliances, energy consumption does not vary significantly among comparable models of clothes dryers. Clothes dryers are NOT required to display EnergyGuide labels.

Here are some things you can do to minimize the environmental impact of your clothes dryer.

- Locate your dryer in a heated space. Putting it in a cold or damp basement will make the dryer work harder and less efficiently.
- Make sure your dryer is vented properly. If you vent the exhaust outside, use the straightest and shortest metal duct available. Flexible vinyl duct isn't recommended because it restricts the airflow, can be crushed, and may not withstand high temperatures from the dryer.
- Check the outside dryer exhaust vent periodically. If it doesn't close tightly, replace it with one that does in order to keep the outside air from leaking in. This will reduce heating and cooling bills.
- Clean the lint filter in the dryer after every load in order to improve air circulation and reduce risk of fire. Regularly clean the lint from vent hoods.
- Dry only full loads, as small loads are less economical; but do not overload the dryer.
- When drying, separate your clothes and dry similar types of clothes together. Lightweight synthetics, for example, dry much more quickly than bath towels and natural fiber clothes.
- Dry two or more loads in a row, taking advantage of the dryer's retained heat.
- Use the cool-down cycle (permanent press cycle) to allow the clothes to finish drying with the residual heat in the dryer.
- In good weather, hang clothes dry outside. This is the ultimate energy saver for clothes drying.

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5.7: Dishwashers

A dishwasher typically uses the equivalent of 700–850 kWh of electricity annually, or nearly as much energy as a clothes dryer or freezer. About 80 percent of this energy is used, not to run the machine, but to heat the water for washing the dishes.

- Older dishwashers use about 8–14 gallons of water for a complete wash cycle.
- Newer dishwashers, built in the past 10 years, have been using 7–10 gallons per cycle.

The dishwasher is the only device at home that requires a water heater temperature that is about 140°F. The units built recently have supplemental heaters in the dishwashers to bump up the temperature so that the main water heater temperature can be set at 120°F or less. Remember that each 10°F reduction in water heater temperature lowers the water heater energy cost by 3 percent to 5 percent.

How a Dishwasher Works

A dishwasher is essentially an insulated water tight box. The dirty dishes are systematically arranged in the dishwasher. As shown in Figure 5.7.1, hot water is sprayed on to the dishes as jets. Repeated jets of water emanating from a spray arm clean the dishes. Some models have two spray arms: one at the bottom of the dish washer (lower spray arm) and one at the top (upper spray arm). The dirty water passes through a filter and re-circulates until the dishes are finished. Fresh water is then spayed during the rinse cycle to remove the soapy water. Then the dishes are dried with either electric heat or simply with air.

Figure 5.7.1. The inside of a dishwasher

The following video illustrates how a dishwasher works.

YouTube Video

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View this YouTube Video online

Features of a Dishwasher

Dishwashers can be built-in or portable. Built-ins are mounted under a kitchen countertop usually next to a sink. Portables are on wheels with finished tops and sides. Most models can be converted into under-counter mounting. However, because of the additional connection hardware and finished sides, portables usually cost more than similar built-in models.

Some of the additional features that are offered are:

- **Interior layout**—configuration of sliding racks, baskets, and trays. Does the washing arm reduce the amount of loadable space?
- **Water heating**—Most homes have water heaters set to 110 degrees. However, to clean well, a dishwasher should use water at 140 degrees. Many budget units now offer a water heating feature.
- **Number of cycles**—light cycles, normal, heavy or pans, and rinse and hold to remove food if dishes will sit in the washer a while before the wash cycle is run.
- **Water-saving cycles**—If you live in an area where fresh water is scarce, you'll want to consider this feature.
- **Sound insulation**—The sound level will vary from one model to another. Consider how important a quiet wash cycle is before you purchase.

- **Build in food disposers**—will grind up food similar to in-sink units, allowing the user to spend less time cleaning dishes before they go into the dishwasher.
- **Controls**—Entry-level machines feature knob and dial controls. On mid- to upper-end models, you will find push-button switches hidden behind smooth, one-piece, plastic console covers. Some of the highest priced dishwashers feature electronic touchpad controls with lighted displays for an uncluttered, high-tech look. And the highest-end European models now integrate controls on the top of the door so they can't be seen when the machine is closed.
  - Countdown timer — lets you know how much time is left in a cycle.
  - Clean light — signals that cycle is complete and dishes are clean.
  - Soil sensors — take the guesswork out of cycle selection. Sensors optically analyze dirtiness of water and adjust water level and wash length accordingly.
  - Delay-start — timer that allows starting dishwasher automatically; lets you take advantage of late-night off-peak power rates or run the dishwasher after everyone has taken a shower.
- **Color and Appearance**—Does the dishwasher fit in your kitchen? Do you like its appearance?
- **Delay Start Timer**—Allows the user to load the washer and have it start a few hours later.

Energy Efficiency and Test Criteria

Energy Factor (EF) is the dishwasher energy performance metric and is calculated using

$$EF\,(kWh) = \frac{1}{M + W} \tag{5.7.1}$$

Equation 5.7.1 may vary based on dishwasher features such as water-heating boosters or truncated cycles. The greater the EF, the more efficient the dishwasher is.

The EF is the energy performance metric of both the federal standard and the ENERGY STAR qualified dishwasher program. The federal EnergyGuide label on dishwashers shows the annual energy consumption and cost. These figures use the energy factor, average cycles per year, and the average cost of energy to make the energy and cost estimates. The EF may not appear on the EnergyGuide label.

Test Criteria for ENERGY STAR Qualified Dishwashers

Dishwasher manufacturers must self-test their equipment according to the new Department of Energy (DOE) test procedure defined in 10 CFR 430, Subpart B, Appendix C. This DOE test procedure was announced on August 29, 2003, and all models had to be tested using the new procedure by February 25, 2004.

This test procedure establishes a separate test for soil-sensing machines. Included in the final rule was a decision to add standby energy consumption to the annual energy and cost calculation, but not to the energy factor calculation. Also, the average cycles per year has been lowered from **264 cycles** per year to **215 cycles** per year. Energy Star dishwashers are at least 25 percent more energy efficient than minimum federal government standards.

Table 5.7.1 lists the standard and the ENERGY STAR approved dishwasher energy factors.

Table 5.7.1. Energy standards for dishwashers

Product Type	Federal Standard EF	ENERGY STAR EF
Standard (>8 place settings + 6 serving pieces)	>0.46	>0.58
Compact (<8 place settings + 6 serving pieces)	>0.62	N/A

The current ENERGY STAR criteria for dishwashers became effective January 1, 2001. This criteria of at least 25 percent above the federal standard and applies only to models manufactured after January 1, 2001. The previous ENERGY STAR criterion was 13 percent above the federal standard.

Dishwashers and Environmental Protection

Buying the correct size appliance for your needs is critical to saving money, energy, and water. In dishwashers, there are compact and standard-capacity units. Compact models use less energy and water per load, but you may actually consume more energy operating them more frequently. The following tips help you to save even more:

- Avoid rinsing dishes before you load them in the dishwasher or, if you must rinse, use cold water.
- Run your dishwasher with a full load. Most of the energy used by a dishwasher goes to heat water. Since you can't decrease the amount of water used per cycle, fill your dishwasher to get the most from the energy used to run it.
- Avoid using the heat-dry, rinse-hold, and pre-rinse features. Instead use your dishwasher's air-dry option. If your dishwasher does not have an air-dry option, prop the door open after the final rinse to dry the dishes.

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6: LIGHTING

6.1: How Lighting is Measured
6.2: How Much Lighting is Needed
6.3: Types of Lighting
6.4: Life Cycle Cost Analysis
6.5: Efficacy of Light Bulbs
6.6: Improved Lighting Controls
6.7: Comparison of Different Bulbs

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6.1: How Lighting is Measured

When most people buy a light bulb, they look for watts (W). Recall that a watt is a unit of power, (i.e., the rate at which energy is consumed from the electricity supplier). It does not say anything about the light.

The most common measure of light output (or luminous flux) is the lumen. All lamps are rated in lumens, as shown in the figure below, and every bulb has 3 parameters listed on the package, as shown in Figure 6.1.1:

- Lamp lumen output or light output
- Power consumption in watts
- Life of the bulb in hours

Figure 6.1.1. Parameters listed on light bulbs

Watch the video below to find out more about lumens.

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Footcandles

A **footcandle (fc)** is the standard unit of measure for illumination on a surface. It is a lumen of light distributed over a 1-square-foot (0.09-square-meter) area, as depicted in Figure 6.1.2.

Figure 6.1.2. Footcandle

The average footcandle level on a square surface is equal to the amount of lumens striking the surface, divided by the area of the surface.

$$FC = \frac{Lumens\ of\ Light}{Area(ft^2)} \tag{6.1.1}$$

Example 1

A 40 watt bulb produces about 505 lumens and has a life of about 1,000 hours. When this bulb is used to light a room of 10 x 10 feet, these 505 lumens are distributed over 100 square feet of floor area. What is the illumination?

Image of a 40 W bulb (505 lumnens) sitting in a 10ft by 10 ft room.

Answer available at the end of this section.

Additional Information

A useful conversion is

$$1\,fc = \frac{lumen}{ft^2} = 1\,Lux\,(metric)$$

The following video shows how a light meter is used to measure lumens per ft^2.

YouTube Video

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Answers

Example 1

$$Illumination = \frac{505\,lumens}{100\,ft^2} = 5.05\,lumens/ft^2 = 5.05\,fc$$

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6.2: How Much Lighting is Needed

How much light is needed in a room depends on the task(s) being performed (contrast, requirements, space, size, etc.). There are three different types of task-oriented lighting: Ambient, Task, and Accent. The light requirement also depends on the ages of the occupants and the importance of speed and accuracy of the task.

- **Ambient lighting** is general purpose lighting—an example is the lighting used in hallways for safety and security. An illumination of 30–50 fc is generally the maximum that one needs for this purpose.
- **Task lighting** is lighting that is designed for specific tasks. Reading and writing are the most light-intensive tasks and require about 50 fc at home. Tasks like cooking, sewing, or repairing a wrist watch require more -- about 200–300 fc. However, the area with this level of illumination will be small. Increasing the light everywhere is not required and is a waste of energy.
- **Accent lighting** is the lighting that is provided to highlight certain objects or areas, for example, the use of flood lights to highlight a painting or a statue. Accent lighting also illuminates walls so they blend more closely with naturally bright areas like ceilings and windows. Accent lighting can be high intensity or subtle.

The video below explains more about the three types of lighting.

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Color Rendering Index

Lamps are assigned a color temperature (according to the Kelvin temperature scale) based on their "coolness" or "warmness." The human eye perceives colors as cool if they are at the blue-green end of the color spectrum, and warm if they are at the red end of the spectrum.

The video below shows examples of the light sources that temperatures represent.

YouTube Video

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The ability to see colors properly is another aspect of lighting quality. Objects' colors appear to be different under different types of light. The color rendering index (CRI) scale is used to compare the effect of a light source on the color appearance of its surroundings. A scale of 0 to 100 defines the CRI. A higher CRI means better color rendering, or less color shift.

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6.3: Types of Lighting

There are four basic types of lighting:

- Incandescent
- Fluorescent
- High-intensity discharge
- Low-pressure sodium

Incandescent Bulbs

Thomas Alva Edison invented the incandescent light bulb with reasonable life. Lewis Latimer has perfected it with the use of carbon filament.

The incandescent bulb consists of a sealed glass bulb with a filament inside. When electricity is passed through the filament, the filament gets hot. Depending on the temperature of the filament, radiation is emitted from the filament.

The filament's temperature is very high, generally over 2,000° C, or 3,600° F. In a "standard" 60-, 75-, or 100-Watt bulb, the filament temperature is roughly 2,550° C, or roughly 4,600° F. At high temperatures like this, the thermal radiation from the filament includes a significant amount of visible light.

This principle of obtaining light from heat is called ‘incandescence.” At this high temperature of 2,000° C, about 5 percent of the electrical energy converts into visible light and the rest of it is emitted as heat or infrared radiation.

The following video shows how an incandescent light bulb works.

YouTube Video

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Let’s now look at several different types of incandescent bulbs.

Standard Incandescent Bulbs

Standard incandescent bulbs are most common and yet are the most inefficient. Larger wattage bulbs have a higher efficacy (more lumens per Watt) than smaller wattage bulbs.

Tungsten Halogen Bulbs

Tungsten halogen is an incandescent lamp with gases from the halogen family sealed inside the bulb and an inner coating that reflects heat back to the filament, as shown in Figure 6.3.1. It has similar light output to a regular incandescent bulb, but with less power. Halogens in the gas filling reduce the material losses of the filament caused by evaporation and increase the performance of the lamp.

Figure 6.3.1. A tungsten halogen lamp

Tubular Tungsten-Halogen Bulbs

Tubular tungsten-halogen bulbs are commonly used in “torchiere” floor lamps, as shown in Figure 6.3.2, which reflect light off of the ceiling, providing more diffused and suitable general lighting.

Although these provide better energy efficiency than the standard A-type bulb, these lamps consume significant amounts of energy (typically drawing 300 to 600 W) and become very hot (a 300-W tubular tungsten-halogen bulb reaches a temperature of about 2600° C compared to about 600° C for a compact fluorescent bulb). Because Tungsten-halogen lamps operate at very high temperatures (high enough to literally fry eggs), they should not be used in fixtures that have paper- or cellulose-lined sockets.

Figure 6.3.2. Tubular tungsten halogen lamp

Halogen Bulb

A halogen bulb is often 10 to 20 percent more efficient than an ordinary incandescent bulb of similar voltage, wattage, and life expectancy. Halogen bulbs may also have two to three times as long a lifetime as ordinary bulbs. How much the lifetime and efficiency are improved depends largely on whether a premium fill gas (usually krypton, sometimes xenon) or argon is used. Figure 6.3.3 shows a picture taken with an Infrared camera comparing the heat produced by a halogen and a compact fluorescent light bulb. The red and white color zones are extremely hot and the blue zones are cooler.

Figure 6.3.3. A comparison of heat generated by a halogen and CFL light bulbs

Reflector Lamps

Reflector Lamps - Light waves from a bulb spread in all directions. The light that goes toward the back is not useful when the light is most needed in the front. Reflector lamps (Type R) are designed to spread light over specific areas.

Reflector lamps have silver coating on the sides, like any mirror, and therefore all the light waves passing through the sides or the back are reflected to the front. Therefore, they are called reflector lamps and are also called floodlighting, spotlighting, and down lighting bulbs.

The videos below show the difference between a regular and reflective lamp light bulb.

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Parabolic Aluminized Reflector (PAR) Lamps

Parabolic aluminized reflector (PAR) lamps (shown in Figure 6.3.4) are also available with halogen technology to operate at 120 volts. A standard 150-W incandescent spotlight can be replaced with a lower wattage halogen lamp, reducing electricity consumption by up to 40 percent.

Figure 6.3.4. A reflector lamp (type R) light bulb

Fluorescent Bulbs

The fluorescent lamp is a major advancement and a commercial success in small-scale lighting since the original tungsten incandescent bulb. These bulbs are highly efficient compared to incandescent bulbs. Fluorescence is the phenomenon in which absorption of light of a given wavelength by a fluorescent molecule is followed by the emission of light at longer wavelengths. The following video provides more information on fluorescent bulbs.

YouTube Video

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A fluorescent bulb consists of a glass tube with a phosphorus coating, a small amount of inert gas (usually argon or krypton), mercury, and a set of electrodes. Contact points on the outside of the tube carry electricity into the bulb.

The video below shows a step-by-step depiction of how fluorescent lamps provide light.

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Fluorescent lamps are about 2 to 4 times as efficient as incandescent lamps at producing light at the wavelengths that are useful to humans. Thus, they run cooler for the same effective light output. The bulbs themselves also last a lot longer—10,000 to 20,000 hours versus 1,000 hours for a typical incandescent.

Fluorescent lights need ballasts (devices that control the electricity used by the unit) for starting and for circuit protection. Ballasts require energy, and for some type of ballasts, efficiency is only achieved if the fluorescent lamp is left on for long periods of time without frequent on-off cycles.

Figure 6.3.5. shows a picture of a full-size fluorescent lamp fixture. The energy savings for existing fluorescent lighting can be increased by:

- re-lamping (e.g., replacing an existing lamp with one of a lower wattage);
- replacing ballasts;
- replacing fixtures with more efficient models.

Figure 6.3.5. Full-size fluorescent lamp fixture

Full-size fluorescent lamps are available in several shapes, including straight, U-shaped, and circular configurations. Lamp diameters range from 1" to 2.5". The most common lamp type is the four-foot (F40), 1.5" diameter (also called T12) straight fluorescent lamp. More efficient fluorescent lamps are now available in smaller diameters, including the 1.25 " (also called T10) and 1" (also called T8).

Fluorescent lamps are available in color temperatures ranging from warm (2700 K) "incandescent-like" colors to very cool (6500 K) "daylight" colors.

Cool white (4100 K) is the most common fluorescent lamp color. **Neutral white** (3500 K) is becoming popular for office and retail use.

Compact Fluorescent Lamps

Compact fluorescent lamps (CFLs) are miniaturized fluorescent lamps that usually have premium phosphors which often come packaged with integral or modular ballast, as shown in Figure 6.3.6.

Figure 6.3.6. Types of compact fluorescent bulbs on the market

CFLs come in a variety of sizes and shapes, as shown in Figure 6.3.7, including (a) twin-tube integral, (b and c) triple-tube integral, (d) integral model with casing that reduces glare, (e) modular circline and ballast, and (f) modular quad-tube and ballast. CFLs can be installed in regular incandescent fixtures, and they consume less than one-third as much electricity as incandescent lamps.

CFLs have the following characteristics. They:

- Typically have a standard screw base that can be installed into nearly any table lamp or lighting fixture that accepts an incandescent lamp.
- Come in a variety of sizes and shapes and are being used as energy saving alternatives to incandescent lamps.
- Have a much longer life—6,000 to 20,000 hours (10 to 20 times longer), compared to 750 to 1000 hours for a standard incandescent.
- Can replace incandescent bulbs that are roughly 3 to 4 times their wattage, but can cost up to 10 times more than comparable incandescent bulbs.
- Are one of the best energy-efficiency investments available. Although they cost more, they are very economical in the long run.

Figure 6.3.7. CFLs

High-Intensity Discharge

High-intensity discharge (HID) lamps are similar to fluorescents in that an arc is generated between two electrodes. The arc in an HID source is shorter, yet it generates much more light, heat, and pressure within the arc tube.

Below are HID sources, listed in increasing order of efficacy (lumens per watt):

- mercury vapor
- metal halide
- high-pressure sodium
- low-pressure sodium

Like fluorescent lights, HID also requires ballasts, and they take a few seconds to produce light when first turned on because the ballast needs time to establish the electric arc.

Additional Information

Originally developed for outdoor and industrial applications, HID lamps are now used in office, retail, and other indoor applications. Their color rendering characteristics have been improved, and lower wattages have recently become available (as low as 18 watts).

Table 6.3.1 analyzes the details of HID lamps.

Table 6.3.1. Advantages and disadvantages of HID lamps

Advantages	Disadvantages
• Relatively long life (5,000 to 24,000+ hrs) • Relatively high lumen output per watt • Relatively small in physical size	• Require time to warm up. It varies from lamp to lamp, but the average warm-up time is two to six minutes. • Have a "restrike" time, meaning a momentary interruption of current or a voltage drop too low to maintain the arc will extinguish the lamp.

Additional Information

When HID lamps reach "restrike" time, the gasses inside the lamp are too hot to ionize, and time is needed for the gasses to cool and pressure to drop before the arc will restrike. This process of restriking takes between 5 and 15 minutes, depending on which HID source is being used. Therefore, good applications of HID lamps are areas where lamps are not switched on and off intermittently.

Types of HID Lamps

Mercury Vapor Lamps

Mercury vapor lamps, shown in Figure 6.3.8, are widely used to light both indoor and outdoor areas such as gymnasiums, factories, department stores, banks, highways, parks, and sports fields.

Mercury vapor lamps consist of an inner arc discharge tube constructed of quartz surrounded by an outer hard borosilicate glass envelope. Shortwave UV, a result of the decay of mercury atom electrons from an excited to a stable state, is readily transmitted through the inner quartz tube but is virtually blocked by the outer glass envelope during normal operation.

Figure 6.3.8. Mercury vapor lamp

Metal Halide Lamps

Metal Halide lamps are similar to mercury vapor lamps but use metal halide additives inside the arc tube along with the mercury and argon. These additives enable the lamp to produce more visible light per watt with improved color rendition.

Wattages range from 32 to 2,000, offering a wide range of indoor and outdoor applications. The efficacy of metal halide lamps ranges from 50 to 115 lumens per watt, typically about double that of mercury vapor.

Because of the good color rendition and high lumen output, these lamps are good for sports arenas and stadiums. Indoor uses include large auditoriums and convention halls. These lamps are sometimes used for general outdoor lighting, such as parking facilities, but a high-pressure sodium system is typically a better choice.

Table 6.3.2 analyzes metal halide lamps.

Table 6.3.2. Advantages and disadvantages of metal halide lamps

Advantages	Disadvantages
• High efficiency • Good color rendering • Wide range of wattages	• The rated life of metal halide lamps is shorter than other HID sources; lower-wattage lamps last less than 7,500 hours while high-wattage lamps last an average of 15,000 to 20,000 hours. • The color may vary from lamp to lamp and may shift over the life of the lamp and during dimming.

High-Pressure Sodium (HPS) Lamps

The high-pressure sodium (HPS) lamp is widely used for outdoor and industrial applications. Its higher efficacy makes it a better choice than metal halide for these applications, especially when good color rendering is not a priority.

HPS lamps differ from mercury and metal-halide lamps in that they do not contain starting electrodes; the ballast circuit includes a high-voltage electronic starter. The arc tube is made of a ceramic material which can withstand temperatures up to 2,372°F. It is filled with xenon to help start the arc, as well as a sodium-mercury gas mixture.

The efficacy of the HPS lamp is very high (as much as 140 lumens per watt.) For example, a 400-watt high pressure sodium lamp produces 50,000 initial lumens. The same wattage metal halide lamp produces 40,000 initial lumens, and the 400-watt mercury vapor lamp produces only 21,000 initially.

Sodium, the major element used, produces the "golden" color that is characteristic of HPS lamps. Although HPS lamps are not generally recommended for applications where color rendering is critical, HPS color rendering properties are being improved. Some HPS lamps are now available in "deluxe" and "white" colors that provide higher color temperature and improved color rendition. The efficacy of low-wattage "white" HPS lamps is lower than that of metal halide lamps (lumens per watt of low-wattage metal halide is 75-85, while white HPS is 50-60 LPW).

Low-Pressure Sodium Lamps

Low-pressure sodium lamps—producing up to 180 lumens per watt—have the highest efficacy of all commercially available lighting sources. A low-pressure sodium lamp is shown in Figure 6.3.9.

Even though they emit a yellow light, a low-pressure sodium lamp should NOT be confused with a standard high-pressure sodium lamp, which is a high-intensity discharge lamp.

Figure 6.3.9. Low-pressure sodium lamp

Low-pressure sodium lamps operate much like fluorescent lamps and require ballast. The lamps are also physically large—about 4-feet long for the 180-watt size—so light distribution from fixtures is less controllable. There is a brief warm-up period for the lamp to reach full brightness.

With a CRI of 0, low-pressure sodium lamps are used where color rendition is not important but energy efficiency is. They're commonly used for outdoor, roadway, parking lot, and pathway lighting. Low-pressure sodium lamps are preferred around astronomical observatories because the yellow light can be filtered out of the random light surrounding the telescope.

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6.4: Life Cycle Cost Analysis

Performing a life-cycle cost analysis (LCC) gives the total cost of a lighting system—including all expenses incurred over the life of the system. This analysis can be applied not only to lighting but for most of the appliances, automobiles, heating systems, and so on, when two systems are compared to determine the most cost effective options.

There are two reasons to do an LCC analysis:

1. To compare different systems, or bulbs in this case.
2. To determine the most cost-effective system or a bulb.

For some lighting systems, one of two situations may exist:

1. The initial cost may be high but the energy costs will be low over its lifetime.
2. The initial cost to buy a bulb or a system and the energy or the maintenance costs may be low, but the useful life of such a bulb or system may be short. (In this case, we may have to replace the appliance several times to get the same useful life as the other option.)

Therefore, a life-cycle cost (LCC) analysis can be helpful for comparing the total costs incurred over the lifetime of a lighting system. It is, in essence, calculating all the costs incurred to buy, maintain, and run the system over its lifetime.

$$Life\,Cycle\,Costs = (Cost\,to\,buy) + (Cost\,to\,maintain\,it\,(if\,any) + (Cost\,of\,energy\,to\,run\,it) + (Replacement\,costs) - (Any\,salv$$

In equation 6.4.1,

- **Cost to buy** is the purchase price of the bulb or the system.
- **Cost to maintain** is the cost incurred to maintain it in good operating condition. (For example in the case of a car, an engine oil change every 3,000 miles is part of maintenance costs.)
- **Cost of energy** is the energy or the fuel it takes to run the appliance or bulb for its lifetime.
- **Replacement cost** is the cost to replace the bulb. If bulb A has a life of 1000 hrs and bulb B has a life of 10,000 hours, then Bulb A needs to be replaced 10 times to get the same useful life period as that of bulb B. Therefore, 10 A bulbs need to be purchased for each B Bulb.

Table 6.4.1 shows a life cycle cost analysis in comparing an incandescent bulb and a compact fluorescent light (CFL).

Table 6.4.1. Life cycle cost analysis: incandescent vs. CFL bulb

	Incandescent	CFL
Rating	60 Watts	15 Watts
Lumen output	865 Lumens	900 Lumens
Cost of one bulb	$0.60	$5.00
Lifetime of one bulb	1,000 hr	10,000 hr
Bulbs needed for a lifetime of 10,000 hr	10 bulbs	1 bulb
Cost of bulbs needed for 10,000 hr	$6.00	$5.00
Energy consumption for 10,000 hr	600 kWh	150,000 kWh
Price of electricity	$0.085	$0.085
Cost of electricity for 10,000 hr	$51.00	$12.75
Total life cycle costs to own and operate bulbs for 10,000 hr	$(51.00 + 6.00) = **$57.00**	$(12.75 + 5.00) = **$17.75**

Additional Information

This analysis shows clearly that each incandescent bulb replaced with a CFL that would fit into a regular incandescent bulb fixture would save about $39.25 over 10,000 hours of operation. Imagine the number of bulbs that you have at home: living room, kitchen, bath rooms, bed rooms, table lights, floor lamps, ceiling lights, closets, garage, basement, and so on. There are energy saving options all over the home.

Although they save energy, there are some disadvantages with CFLs:

- They are often physically larger than the incandescent bulbs they replace and simply may not fit the lamp.
- The light is generally cooler—less yellow—than incandescent light bulbs. This may result in less than pleasing contrast with ordinary lamps and ceiling fixtures. Newer models have been addressing this issue.
- Some types (usually iron ballasts) may produce an annoying flicker.
- Ordinary dimmers cannot be used with compact fluorescents.
- Like other fluorescents, operation at cold temperatures (under around 50–60 degrees F) may result in reduced light output.
- There may be an audible buzz from the ballast.

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6.5: Efficacy of Light Bulbs

Efficacy is the ratio of light output from a lamp to the electric power it consumes and is measured in lumens per watt (LPW). Figure 6.5.1 shows the efficacy of numerous types of light bulbs.

Figure 6.5.1. Efficacy of light bulbs

LED lighting - A typical signalized four-way intersection may have three lanes per approach (two through lanes and a left turn lane), plus pedestrian crossings.

Conventional incandescent lamps in a single four-way traffic light, shown in Figure 6.5.2, consume roughly 85 kWh of electricity per day and cost about $1,600 per year to operate. LED lights use just 10 percent of the electricity that incandescent lamps use, so the opportunity for savings is enormous.

Figure 6.5.2. Traffic light

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6.6: Improved Lighting Controls

Lighting controls give you the flexibility to design a space for multiple use and easy access. They should be a part of the lighting plan for every room. Both manual and automatic controls can cut energy costs by making it easier to use lights only when and where they are needed.

Controls used with high-wattage incandescent bulbs are especially effective for saving energy, but they should be considered for use with any lights that might be left on when no one is using them.

Always choose controls that are compatible with the bulb and ballast. Try to obtain the best quality so the controls will perform well over time.

Types of Lighting Controls

Switches

The simple on-off switch, whether mounted on a wall or on the light fixture, should always be obvious and convenient.

- On fixtures with pull-cord switches, attach an object at the end that is easy to see and grasp.
- Install multiple wall switches in areas that have more than one entrance, such as hallways, staircases, and large rooms.
- Ensure that these switches should be easy to find as well by adding devices such as oversized toggles or switch plates that glow in the dark.
- A small indicator light near a switch can signal when lights that are out of sight—in the basement or outdoors, for example—have been left on.
- If a main switch in a room controls several lights, each fixture should have its own switch so individual lights can be turned off if they are not needed.
- In rooms such as kitchens, where lights are used for different purposes, overhead ambient lights, counter, or island lights should be on separate switches.
- A three-level switch in lamps is a simple way to use one fixture for several lighting needs. When the higher levels are not necessary, switch it to the lowest level to save energy.

Photocells

A photosensor measures the light level in an area and turns on an electric light when that level drops below a set minimum. They are most effective with lights that stay on all night long, such as some outdoor fixtures or night lights. If a light does not need to remain on throughout the night, use a timer or motion detector.

Timers

Timers are an inexpensive way to control the amount of time a light stays on inside the home or outdoors. They can be located at a light switch, at a plug, or in a socket. Some models are turned on manually and set to turn off after a designated number of minutes or hours. Others can be programmed to turn on and off at specified times. Both mechanical and solid-state timers are available, and some offer the option of a manual override. Some screw-base compact fluorescent bulbs cannot be used with timers, so check the manufacturer's recommendations.

Be careful not to set timers so a light might turn off in an area when someone could be left in the dark. Or, install a glow-in-the-dark switch plate or a very low-wattage night-light with a photosensor near the switch so it is easy to find.

Motion or Occupancy Sensors

Motion detectors, or occupancy sensors, have proven to be an excellent way to save energy, especially in bathrooms and bedrooms where lights are frequently left on. They are also popular outdoors for walkways, driveways, and as security lights.

Sensors can operate automatically to turn lights on when movement is detected, then off after a specified period of no motion, or they can have manual on or off switches. Some models feature dimmers that reduce light to a preset level rather than turn completely off when there is no movement; others come with photo sensors that turn lights on only when the light level is below a preset point and motion is detected.

Follow manufacturer's instructions for installing sensors to ensure the proper coverage area. Also, be sure the lights are compatible with the sensors. Some compact fluorescents should not be used with motion detectors, nor should high intensity discharge lights because of their inability to relight quickly.

Dimmers

Dimming fluorescent lamps is not all that easy to do. If you reduce power to the lamp, the filaments will not be as hot, and will not be able to thermionically emit electrons as easily. If the filaments get too cool by dimming the lamp greatly, usually the lamp will just go out. If you force current to continue flowing while the electrodes are at an improper temperature, then severe rapid degradation of the thermionic material on the filaments is likely. To effectively, reliably, and safely dim fluorescent lamps below around half brightness or so, you need special equipment that may only work properly with a specific lamp. Such equipment typically gives some power to the filaments to keep them at a workable temperature, while the current flowing through the bulb is greatly reduced.

Manual dimming controls allow occupants of a space to adjust the light output or illumination. This can result in energy savings through reductions in input power, as well as reductions in peak power demand, and enhanced lighting flexibility.

Fluorescent lighting fixtures require special dimming ballasts and compatible control devices. Some dimming systems for high-intensity discharge lamps also require special dimming ballasts.

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6.7: Comparison of Different Bulbs

Incandescent Bulbs

- Do not require a ballast
- Have a warm color appearance with a low color temperature and excellent color rendering (CRI 100)
- Are a compact light source
- Require simple maintenance due to screw-in Edison base
- Are a less efficacious light source
- Have a shorter service life than other light sources in most cases
- Have a filament that is sensitive to vibrations and jarring
- Can get very hot during operation
- Must be properly shielded because incandescent lamps can produce direct glare as a point source
- Require proper line voltage, as line voltage variations can severely affect light output and service life

Figure 6.7.1 shows an incandescent bulb.

Figure 6.7.1. Incandescent bulb

Fluorescent Bulbs

- Require a ballast
- Have a range of color temperatures and color rendering capabilities
- Have low surface brightness compared to point sources
- Have a cooler operation
- Are more efficacious compared to incandescent
- Ambient temperatures and convection currents can affect light output and life
- All fixtures installed indoors must use a Class P ballast that disconnects the ballast in the event it begins to overheat; high ballast operating temperatures can shorten ballast life
- Have options for starting methods and lamp current loadings
- Require compatibility with ballast
- Low temperatures can affect starting unless a "cold weather" ballast is specified

Figure 6.7.2 shows a fluorescent bulb.

Figure 6.7.2. Fluorescent bulb

High-Intensity Discharge (HID) Bulbs

- Require a ballast
- Ambient temperature does not affect light output, although low ambient temperatures can affect starting, requiring a special ballast
- Are a compact light source
- Are high lumen packages
- Are a point light source
- Have a range of color temperatures and color rendering abilities depending on the lamp type
- Have a long service life
- Are highly efficacious in many cases
- Have line voltage variations, possible line voltage drops, and circuits sized for high starting current requirements which must be considered

Figure 6.7.3 shows a HID bulb.

Figure 6.7.3. HID bulb

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7: HOME HEATING BASICS

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7.1: Residental Heat Loss (I)

Houses are heated to keep the temperature inside at about 65°F when the outside temperature is lower. A house requires heat continuously because of the heat loss. Heat can escape from a house through various places; some are well known and some are not noticeable. Heat can escape from the roof, walls, doors, windows, basement walls, chimney, vents, and even the floor, as shown in Figure 7.1.1.

Figure 7.1.1. Heat loss examples in a house

As shown in Figure 7.1.2, the more heat the house leaks, the more the furnace has to put out to make up for the loss. For the furnace to generate more heat to compensate the heat loss, more fuel needs to be put into the furnace, hence higher fuel or heating costs.

Figure 7.1.2. Heat loss flowchart

As you will recall from Chapter 3, not all energy conversion devices are efficient. Thus, it is important to note that furnaces are not 100 percent efficient. When a furnace's efficiency is lower, the fuel consumption for the same amount of heat output will be even *higher*.

Mechanisms of Heat Loss/Transfer

As shown in Figure 7.1.3, heat escapes (or transfers) from inside to outside (high temperature to low temperature) by three mechanisms (either individually or in combination) from a home:

- Conduction
- Convection
- Radiation

Figure 7.1.3. Heat transfer by conduction, convection, and radiation

Conduction

Conduction is a process by which heat is transferred from the hot area of a solid object to the cool area of a solid object by the collisions of particles.

In other words, in solids the atoms or molecules do not have the freedom to move, as liquids or gases do, so the energy is stored in the vibration of atoms. An atom or molecule with more energy transfers energy to an adjacent atom or molecule by physical contact or collision.

In the image below, heat (energy) is conducted from the end of the rod in the candle flame further down to the cooler end of the rod as the vibrations of one molecule are passed to the next; however, there is no movement of energetic atoms or molecules.

The following video illustrates conduction.

YouTube Video

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With regard to residential heating, the heat is transferred by conduction through solids like walls, floors, and the roof, as shown in the video below.

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Convection

Convection is a process by which heat is transferred from one part of a fluid (liquid or gas) to another by the bulk movement of the fluid itself. Hot regions of a fluid or gas are less dense than cooler regions, so they tend to rise. As the warmer fluids rise, they are replaced by cooler fluid or gases from above.

In the video below, heat (energy) coming from candle flame rises and is replaced by the cool air surrounding it.

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In residential heating, convection is the mechanism by which heat is lost by warm air leaking to the outside when the doors are opened, or cold air leaking into the house through the cracks or openings in walls, windows, or doors. When cold air comes in contact with the heater in a room, it absorbs the heat and rises. Cold air, being heavy, sinks to the floor and gets heated, and thus slowly heats the whole room air. This is depicted in the video below.

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Radiation

Radiation is transfer of heat through electromagnetic waves through space. Unlike convection or conduction, where energy from gases, liquids, and solids is transferred by the molecules with or without their physical movement, radiation does not need any medium (molecules or atoms). Energy can be transferred by radiation even in a vacuum.

In the video below, sunlight travels to the earth through space, where there are no gases, solids, or liquids.

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Reducing Energy Consumption

There are two ways in which we can reduce energy consumption.

1. The most cost-effective way is to improve the home's "envelope"—the walls, windows, doors, roof, and floors that enclose the home—by improving the insulation (conduction losses) and sealing the air leaks with caulking (convection losses).
2. The second way to reduce the energy consumption is by improving the efficiency of the furnace that provides the heat.

Conduction Heat Loss

Most heat is lost through a house's walls through conduction. As you learned from the activity on the previous screen, the amount of heat loss depends on three factors:

- **Size of the house (area through which the heat can escape)**
- **Local weather or climatic conditions:**
  - The inside temperature is often constant at a comfortable temperature of 65°F.
  - As the outside temperature falls lower than 65°F, the heat is lost to the outside.
  - The higher the temperature difference, the higher the heat loss to outside.
  - By calculating the **Heating Degree Days (HDD)**, we can determine how many degrees the mean temperature fell below 65°F for the day.
- **Wall's capacity to resist heat loss.**
  - Insulation is rated in terms of thermal resistance, called **R-value**, which indicates the resistance to heat flow.
  - The higher the R-value, the greater is the insulating effectiveness.

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7.2: Residential Heat Loss (II)

Heating Degree Days

Local weather or climatic conditions are one of three factors that affects the amount of heat loss through conduction. When examining weather conditions, we look at both the inside and outside temperature of a home.

As shown in Figure 7.2.1, the inside temperature is usually taken as a standard comfort temperature of 65°F. The outside temperature varies by the hour. Knowing this information can help us to understand two concepts:

- **Average outside temperature** = Average of the maximum and minimum temperature during the day
- **Heating Degree Day (HDD)** = The temperature difference through which air has to be treated, or how many degrees the mean temperature fell below 65°F for the day. It is also an index of fuel consumption.

Figure 7.2.1 Temperatures inside and outside a house

Determining HDD

The formula for determining the HDD is

$$HDD = T_{base} - T_a \tag{7.2.1}$$

where T_a is the average outside temperature given by

$$T_a = \frac{T_{max} + T_{min}}{2} \tag{7.2.2}$$

To calculate HDD:

1. Determine the **base temperature** (i.e., inside temperature), which is usually about 65°F.
2. Find the day's **average outside temperature** using equation 7.2.2.
3. Use equation 7.2.1 to find the HDD.

Note

If the T_a is equal to or above 65 °F, there are no heating degree days for that 24-hour period, or HDD = 0.

Example Problem

Example 1

Calculate the HDD for one day when the average outside temperature is:

(a) 13°F

(b) 2°C

Answer available at the end of this section.

Answers

Example 1

Part (a)

Using equation 7.2.1,

$$HDD = 65 - 13 = 52°F$$

Part (b)

Convert the temperature to Fahrenheit to get 2°C = 35.6°F.

Then, using equation 7.2.1,

$$HDD = 65 - 35.6 = 29.4°F$$

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7.3: Residential Heat Loss (III)

Seasonal Heating Degree Days

In the previous section, we are assuming that the outside temperature remains the same for all 150 heating days in a season. This is not realistic, but it explains the method to calculate the HDD. In a more realistic example we need to find the temperature difference for each day and add all the temperature differences.

We will now look at Seasonal Heating Degree Days (HDD), which is the sum of temperature differences of ALL days - rather than just 1 day or 1 week - during which heating is required.

Table 7.3.1 provides Seasonal HDDs for selected places in the U.S. The higher HDD indicates a higher heat loss and therefore, higher fuel requirements.

HDDs are used to estimate the amount of energy required for residential space heating during a cool season, and the data are published in local newspapers or on the National Weather Service website.

Table 7.3.1. Annual degree days for selected places

Place	Degree Days
Birmingham, AL	2,823
Anchorage, AK	10,470
Barrow, AK	19,893
Tucson, AZ	1,578
Miami, FL	155
Pittsburgh, PA	5,829
State College, PA	6,345

Source: NOAA

Calculating Seasonal HDD

To calculate seasonal HDDs, use the equation

$$Seasonal\ HDD = ((T_b - T_a) * (\#\ days\ in\ month\ 1)) + ((T_b - T_a) * (\#\ days\ in\ month\ 2)) + ((T_b - T_a) * (\#\ days\ in\ month\ 3)) \quad (7$$

Remember, in months where the average temperature is equal to or greater than 65, there will be no heating degree days, so the value for the month will be 0.

Example Problems

Example 1

Given the following set of average temperatures, by month, for State College, PA, calculate the HDD for the heating season.

Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.	Sep.	Oct.	Nov.	Dec.
25°F	28°F	37°F	48°F	59°F	67°F	71°F	70°F	62°F	51°F	41°F	31°F

Answer available at the end of this section.

Example 2

If Ms. S. Belle moves from Birmingham, AL (HDD = 2,800) to State College, PA (HDD = 6,000) how much can she expect her heating bill to increase?

Answer available at the end of this section.

Answers

Example 1

The following video goes over the solution.

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Example 2

The following video goes over the solution.

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7.4: Residental Heat Loss (IV)

Calculating Hourly Heat Loss

As we have learned, most heat is lost through a house's walls through conduction. One of the three factors that affect heat loss is a wall's capacity to resist heat loss.

We will now look at how to calculate the rate of heat loss of the walls of a house, using the formula

$$Hourly\,Heat\,Loss = \frac{Area * (Temperature\,Difference)}{R - value} \tag{7.4.1}$$

where the area has units of ft^2, temperature difference has units of °F, and R-value has units of ft^2 °F h/BTUs to obtain a heat loss with units of BTUs/h.

From the above equation it can be seen that once the house is built, these two variables will NOT change:

- The area of the walls
- The R-value of the walls

The only variable that will change is the temperature difference between inside and outside.

Example Problem

The following video provides an example problem with the solution.

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Calculating Daily Heat Loss

To calculate daily heat loss, you would simply multiply the hourly heat loss, determined in equation 7.4.1, by 24 hours, i.e.,

$$Daily\,Heat\,Loss = \frac{Area * (Temperature\,Difference)}{R - value} * 24\,h/day \tag{7.4.2}$$

where daily heat loss would have units of BTUs/day.

Example Problem

Example 1

What is the hourly and daily heat loss of a 15-ft by 15-ft room with an 8-ft ceiling, with all surfaces insulated to R13, with inside temperature 65°F and outside temperature 25°F?

Answer available at the end of this section.

Calculating Annual Heat Loss

In the previous calculations, we determined hourly and daily heat loss. How do we calculate annual or seasonal heat loss?

Since the temperature outside the house may not remain the same day after day, the heat loss will vary by the day. Thus, to obtain the heat loss for a whole year, we do the following:

- Calculate heat loss for each day.
- Add the heat loss for all days in a year that needed heating.
- Leave the The R-value of the wall and the area of the wall the same – they will not change.
- Determine the difference between inside and outside temperature, since it will change for each day.

Theoretically, we would need to perform calculations using equation 7.4.2 for every day of the 365-day calendar year.

For example, if the average outside temperature were to be 35°F, 32°F, 28°F, and so on for each day, the heat loss for the whole year or the season can be calculated as shown in Figure 7.4.1.

Figure 7.4.1. Calculations of annual heat loss

Since the area (480 ft^2), R-value (13 ft2 °F Btu/h), and 24 hr/day are common for ALL heating days, we can bring those out and rewrite the equation in Figure 7.1.5 as

$$Heat\ Loss = \frac{480}{13} * 24\frac{h}{day} * ((65-35)°F + (65-32)°F + (65-28)°F + ...\forall\ heating\ days) \tag{7.4.3}$$

where $\forall$ symbolizes "for all" and $((65-35)\ °F + (65-32)\ °F + (65-28)\ °F + ...\forall\ heating\ days$ is the sum of all HDDs.

Equation 7.4.3 can be further simplified to general terms as

$$Heat\ Loss\ in\ a\ Season = \frac{Area}{R-value} * 24 * HDD \tag{7.4.4}$$

Example Problems

Example 1

For the 150-day heating season in Roanoke, VA, the average temperature was 47°F. How much heat is lost through a 176 ft^2 wall (R = 16) during the entire season?

Answer available at the end of this section.

Example 2

In Fargo, ND, the heating season lasts about 220 days and the average outside temperature is around 27°F. How much heat is lost through an 8 ft by 6 ft window (R=1) during the heating season?

Answer available at the end of this section.

Answers

Example 1

Determine the surface area by first computing the area of one wall, i.e.,

$$Area\,of\,one\,wall = 8 * 15 = 120\,ft^2$$

Then multiply this area by 4 to obtain the total area of the room, i.e.,

$$Area\,of\,room = 4 * 120 = 480\,ft^2$$

To obtain the hourly heat loss, use equation 7.4.1, i.e.,

$$Hourly\,Heat\,Loss = \frac{480 * (65 - 25)}{13} = 1.477\frac{BTUs}{h}$$

Once we know the heat loss rate per hour, we can determine the heat loss per day by using equation 7.4.2, i.e.,

$$Daily\,Heat\,Loss = 1.477\frac{BTUs}{h} * 24\frac{h}{day} = 35,448\frac{BTUs}{day}$$

Example 1

The following video covers the solution.

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Example 2

The following video covers the solution.

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7.5: Insulation and Home Heating Fuels (I)

R-Value

As you may recall from the first part of this lesson, R-value is a wall's capacity to resist heat loss or its thermal resistance. Insulation materials are rated in terms of their R-value, with a higher R-value indicating better insulating effectiveness.

The R-value of thermal insulation depends on the type of material, its thickness, and its density. Generally, walls are not made up of just one material or one layer.

R-values for most commonly used building materials are given in the table below. From looking at Table 7.5.1, we can see that natural materials like stone and bricks are not good insulation materials, but most of the synthetic insulation products such as polystyrene or polyurethane are very effective insulation materials.

Table 7.5.1. Building materials and their R-values

Material	R-Value (ft^2 ° Fh / BTU)
Plain glass (1/8 inch)	0.03
Stone (1 inch)	0.08
Common brick (1 inch)	0.20
Asphalt roof shingles	0.44
Gypsum board, drywall or plasterboard (1/2 inch)	0.45
Wood siding (1/2 inch)	0.81
Plywood (3/4 inch)	0.94
Insulating sheathing (3/4 inch)	2.06
Fiberglass, battens (1 inch)	3.50
Polystyrene (1 inch)	5.00
Polyurethane board	6.25

If insulation materials have a low R-value per inch, then they will need to be thicker than those materials with a higher R-value per inch to achieve the same degree of effectiveness in resisting heat loss.

Figure 7.5.1 compares the thickness required of various insulation materials to achieve the same R-Value of 22.

Figure 7.5.1. Thicknesses to attain R-value of 22

Types of Insulation

Refer to Table 7.5.2 to learn about various types of insulation.

Table 7.5.2. Types of insulation

Insulation	What is it made of?	What does it look like?	Additional Information
Fiberglass	Molten glass spun into microfibers	Pink or yellow in the form of batts or rolled blankets	
Rock wool	Rock	Gray or brown fibers in batts or blankets, or shredded loose fill	Manufactured in a similar way as fiberglass, but with molten rock instead of glass
Cellulose	Recycled paper - newspaper or cardboard shredded into small bits of fiber	Blown in as loose fill	Treated with fire- and insect-resistant chemicals
Rigid foam	Different types, but some are made from post-consumer recycled content from fast food containers and cups	Rigid sheets that are applied directly to framing	Best where space is limited, but a high R-value is needed. Can be installed on the interior of a wall, but if installed inside, must be covered by fire-resistant material like woodboard. One drawback to foam is that it deteriorates unless it is protected from prolonged exposure to sunlight and water. It is also more expensive than other insulation.
Synthetic insulation	Usually polystyrene or polyurethane foam	Polystyrene: rigid boards Polyurethane: rigid boards or sprayed in space systems	Polystyrene is used for insulating basements, cathedral ceilings, or sidewalls. Polyurethane foams are high-performance insulating materials.

Composite Wall R-Values

Generally, walls are made up of several layers of different materials. The R-value of a composite wall is calculated by adding the effective R-values of each of the layers of the wall.

For example, Figure 7.5.2 shows a wall made up of four layers — ½ inch drywall inside for aesthetic purposes, real insulation in between the studs, ¾ inch plywood sheathing outside, and wood siding as the final exterior finish. Together, the layers of the wall are preventing heat loss.

Figure 7.5.2. Diagram of a wall

We can calculate this wall's composite R-value by adding the R-values of each layer.

Plasterboard (1/2 inch)
+ Fiberglass (3.5 inches @ 3.70 per inch)
+ Plywood (3/4 inches)
+ Wood Siding (1/2 inch)

Total R-Value of Composite Wall

We can find the R-values for the walls by using Table 7.2.1 from the R-values section.

Thus,

Plasterboard (1/2 inch) = 0.4524
+ Fiberglass (3.5 inches @ 3.70 per inch) = 12.95
+ Plywood (3/4 inches) = 0.94

+ Wood Siding (1/2 inch) = 0.81

Total R-Value of Composite Wall = 15.15 $\frac{ft^2°Fh}{Btu}$

Example Problems

Example 1

A ceiling is insulated with 0.75" plywood, 2" of polystyrene board, and a 3" layer of fiberglass. What is the R-value for the ceiling?

Answer available at the end of this section.

Example 2

A wall consists of 0.5” wood siding (R = 0.81), 0.75” plywood (R = 0.94), 3.5” of fiberglass (R = 13.0), and 0.5” plasterboard (R = 0.45). What is the composite R-value of the wall?

Answer available at the end of this section.

Example 3

What is the R-value of a wall that is made up of wood siding (R = 0.81), 5” of fiberglass (R = 3.70 per inch), and a layer of 0.5” drywall (R = 0.45)?

Answer available at the end of this section.

Example 4

A wall is made up of 8” of stone, 3” of polyurethane board, and 0.75” of plywood. Calculate the composite R-value for the wall.

Answer available at the end of this section.

Answers

Example 1

The ceiling consists of three layers, and all three layers together prevent the heat loss. So, we need to add the R-values of all three layers
3/4" in plywood has an R-value of 0.94
2" of polystyrene at 5.0 per inch will have an R-value of 10.00
3" of fiberglass at 3.7 per inch will have an R-value of 11.10

So the R-value of the ceiling is $\frac{ft^2°Fh}{Btu}$.

Example 2

The following video provides the solution.

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Example 3

The following video covers the solution.

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Example 4

The following video covers the solution.

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7.6: Insulation and Home Heating Fuels (II)

Calculating Wall Heat Loss

Heat loss from the surface of a wall can be calculated by using equations 7.6.1, 7.6.2, and/or 7.6.3.

Equations

Hourly Heat Loss

$$Hourly\,Heat\,Loss\,(\frac{BTUs}{h}) = \frac{Area\,(ft^2) * Temperature\,Difference\,(°F)}{R-Value\,(\frac{ft^2\,°Fh}{BTUs})} \tag{7.6.1}$$

Daily Heat Loss

$$Daily\,Heat\,Loss\,(\frac{BTUs}{day}) = \frac{Area\,(ft^2) * Temperature\,Difference\,(°F)}{R-Value\,(\frac{ft^2\,°Fh}{BTUs})} * 24\,\frac{h}{day} \tag{7.6.2}$$

Full Heating Season Heat Loss

$$Seasonal\,Heat\,Loss = \frac{Area\,(ft^2)}{R-Value\,(\frac{ft^2\,°Fh}{BTUs})} * 24\,\frac{h}{day} * HDD \tag{7.6.3}$$

The heat loss from walls, windows, roof, and flooring should be calculated separately, because of different R-Values for each of these surfaces. If the R-value of walls and the roof is the same, the sum of the areas of the walls and the roof can be used with a single R-value.

Example Problems

Example 1

A house in Denver, CO has 580 ft^2 of windows (R = 1), 1920 ft^2 of walls and 2750 ft^2 of roof (R = 22). The walls are made up of wood siding (R = 0.81), 0.75” plywood, 3.5” of fiberglass insulation, 1.0” of polyurethane board, and 0.5” gypsum board. Calculate the heating requirement for the house for the heating season, given that the HDD for Denver is 6,100.

Answer available at the end of this section.

Example 2

A single-story house in Anchorage, AK (HDD = 11,000) is 50 ft by 70 ft with an 8 ft high ceiling. There are six windows (R = 1) of identical size, 4 ft wide by 6 ft high. The roof is insulated to R-30. The walls consist of a layer of wood siding (R = 0.81), 2” of polyurethane board (R = 6.25 per inch), 4” of fiberglass (R = 3.70 per inch), and a layer of drywall (R = 0.45). Calculate the heat loss through the house (not counting the floor) for the season.

Hint: A good estimate for the area of the roof is 1.1 times the area of the walls, before you subtract out the area for the windows.

Answer available at the end of this section.

Answers

Example 1

The heating requirement for the house is equal to the heat loss from the house in the whole year.

To calculate the heat loss from the whole house, we need to calculate the heat loss from the walls, windows, and roof separately, and add all the heat losses.

Heat loss from the walls:

Area of the walls = 1,920 ft^2, HDD = 6,100, and the composite R-value of the wall needs to be calculated.

Materials and their R-values

Material	Total R-value
Wood siding	0.81
3/4 inch plywood	0.94
3.5 inches of fiberglass (R-value = 3.7 per inch)	12.95
1 inch of polyurethane	5.25
1/2 inch of Gypsum board	0.45
Total R-value of the walls	**20.40**

$$Heat\ Loss\ from\ Walls = \frac{1920 ft^2 * 6100°F}{20.40\ \frac{ft^2°Fh}{BTUs}} * 24\ \frac{h}{day} * 1\ day = 13.78\ MMBTUs$$

$$Heat\ Loss\ from\ Windows = \frac{580 ft^2 * 6100°F}{1\ \frac{ft^2°Fh}{BTUs}} * 24\ \frac{h}{day} * 1\ day = 84.91\ MMBTUs$$

$$Heat\ Loss\ from\ Roof = \frac{2750 ft^2 * 6100°F}{22\ \frac{ft^2°Fh}{BTUs}} * 24\ \frac{h}{day} * 1\ day = 18.30\ MMBTUs$$

Total heat loss from the house = 13.78 + 84.91 + 18.30 =116.99 MMBTUs in a year

Therefore, the heating requirement is **116.99 MMBTUs per year**.

The following video also provides an explanation for the problem.

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Example 2

The following video provides the solution.

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7.7: Insulation and Home Heating Fuels (III)

Fuel Choices

Various fuels such as natural gas, electricity, fuel oil, and so on, are used to heat a house. Table 7.7.1 shows the percentages of households that use each type of heating fuel.

Table 7.7.1. Choice of fuels by percent of households

Fuel type	Percentage used
Natural gas	49%
Electricity	34%
Fuel oil / LPG	11%
Other	6%

Source: Department of Energy

As you see, more than 50 percent (56% to be exact) of the households in the United States use natural gas as their main heating fuel, and about 26 percent of the households use electricity to heat their homes. Another 11% use fuel oil, and the last 10% use something other than natural gas, electricity and fuel oil.

Capacity and Consumption

Capacity

The amount of heat a furnace can deliver is called its capacity. Heating units are manufactured and sold by their capacity. The heating capacities of Natural Gas, Propane and Fuel Oil are measured according to BTU/h, and the capacity of Electricity is measured in kilowatts.

Consumption

The amount of energy a furnace actually uses is called consumption. In other words, we pay monthly bills for the consumption of a particular heating fuel. Heating Fuels are sold to consumers in different units of measure. For example, Natural gas is sold by cubic feet (ft^3).

The video below explains the difference between capacity and consumption in a gas-heated home.

YouTube Video

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Fuel Comparison

Table 7.7.2 compares details about different types of fuel.

Table 7.7.2. Capacity, consumption, and other information about various types of fuel

Fuel	Capacity	Consumption	Additional Information
Natural gas	Measured in BTU/hr. Most heating appliances for home use have heating capacities of 40,000 to 150,000 BTU/hr. In the past, gas furnaces were often rated only on heat input. Today, the heat output is given.	Measured in cubic feet (ft^3). This is the amount that the gas meter registers and the amount that the gas utility records when a reading is taken. One ft^3 of natural gas contains about 1,000 BTU of energy.	Utility companies often bill customers for CCF (100 ft^3) or therms (1 therm = 100,000 BTU) of gas used. Some companies also use a unit of MCF, where 1 MCF = 1,000,000 BTUs.
Propane or liquefied petroleum gas (LPG)	Measured in BTU/hr	Usually measured in gallons. Propane has an energy content of about 91,300 BTUs per gallon.	Can be used in many of the same types of equipment as natural gas. Stored as a liquid in a tank in the house, so it can be used anywhere, even in areas where natural gas hookups are not available.
Fuel oil	The heating (bonnet) capacity of oil heating appliances is the steady-state heat output of the furnace, measured in BTU/hr. Typical oil-fired central heating appliances sold for home use today have heating capacities of 56,000 to 150,000 BTUs.	Usually billed by gallons. One gallon of #2 fuel oil contains about 140,000 BTUs of potential heat energy.	Several grades of fuel oil are produced by the petroleum industry, but only #2 fuel oil is commonly used for home heating.
Electricity	Usually expressed in kW. A kWh is the amount of electrical energy supplied by 1 kW of power over 1 hour. Electric systems come in a wide range of capacities, usually from 10 kW to 50 kW.	Sold in kWh	The watt (W) is the basic unit of measurement of electric power.

Heating Values of Various Fuels

Each unit of fuel when burned gives different amounts of energy. The energy that is released when a unit amount of fuel is burned is called the heating value. The heating value of a fuel is determined under a standard set of conditions. A comparison of approximate heating values of various fuels is shown in Table 7.7.3.

Table 7.7.3. Heating values of commonly used heating fuels

Fuel	Unit	Heating value (BTUs)
Natural gas	CCF (100 ft^3) or therm	100,000
Natural gas	MCF (1,000 ft^3)	1,000,000
Fuel oil	Gallon	140,000
Electricity	kWh	3,412
Propane	Gallon	91,300

Fuel	Unit	Heating value (BTUs)
Bituminous coal	Ton	23,000,000
Anthracite coal	Ton	26,000,000
Hardwood	Cord	24,000,000

From Table 7.7.3, it should be noted that if a gallon of fuel oil is burned, one would get 140,000 BTUs. Similarly, a CCF of natural gas would fetch 100,000 BTUs.

Heating Efficiency

An assumption is made here that all the energy from the fuel is released, and all the heat is available to heat the place. However, generally, when a fuel is burned in a furnace, not all the energy (heat) is available for the final end user.

The energy efficiency of a furnace is not 100 percent. Not all the energy from the fuel is released, and not all the heat is available to heat the place. For example, if a furnace's efficiency is, say, 50 percent, then twice as much fuel would be needed to heat a home.

Looking again at Table 7.7.3, we saw that the heating value of fuel oil is given as 140,000 BTUs. However, if the furnace's efficiency is 50 percent, then the actual heating value of fuel oil is 140,000 BTUs x 0.5 (efficiency) = 70,000 BTUs. In other words, when a gallon of oil is burned, 70,000 BTUs of heat is actually available to the user. This is shown in Table 7.7.4.

Table 7.7.4. Heating values of commonly used heating fuels with 50% efficiency

Fuel	Unit	Heating value (BTUs), 100% efficiency	Heating value (BTUs), 50% efficiency
Natural gas	CCF (100 ft^3) or therm	100,000	50,000
Natural gas	MCF (1,000 ft^3)	1,000,000	500,000
Fuel oil	Gallon	140,000	70,000
Electricity	kWh	3,412	1706
Propane	Gallon	91,300	45,650
Bituminous coal	Ton	23,000,000	11,500,000
Anthracite coal	Ton	26,000,000	13,000,000
Hardwood	Cord	24,000,000	12,000,000

Table 7.7.5 shows efficiencies of a furnace.

Table 7.7.5. Efficiencies of a furnace

Efficiency	Heating value of fuel oil (BTUs)
50%	70,000
55%	77,000
60%	84,000
65%	90,000
70%	100,000
75%	105,000
80%	111,000
85%	122,000

Efficiency	Heating value of fuel oil (BTUs)
90%	125,000
95%	131,000
100%	140,000

It can be clearly seen that as the efficiency of the furnace increases, the amount of heat available increases proportionally.

The higher the efficiency, the less oil needs to be put into the furnace to get the same amount of heat output.

Most of the heating furnaces burn fuel and release hot combustion gases. The hot combustion gases heat the incoming cold air and go out through the chimney. In older furnaces, all the heat in the fuel is not released or not transferred to the cold air (or water, in the case of heat registers and water heaters), and therefore is lost through the chimney. The air or water that is heated distributes the heat throughout the house. Newer models of furnaces have gotten better at getting more of the heat into the cold air and, therefore, into your house.

The video below shows how a wood burning furnace operates at 75% efficiency.

YouTube Video

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Furnaces usually are not as efficient when they are first firing up as they are running at steady-state. It is sort of like a car getting better mileage in steady highway driving than in stop-and-go city traffic.

What matters over the course of the year is the total useful heat the furnace delivers to your house versus the heat value of the fuel it consumes. This is kind of like measuring the gas mileage your car gets by asking how many miles you drove this year and dividing it by how many gallons of gas you bought.

For furnaces, they call this measure the **AFUE (Annual Fuel Utilization Efficiency)**. The federal minimum-efficiency standards for furnaces and boilers took effect in 1992, requiring that new furnace units have an AFUE of at least 78 percent and new boiler units have an AFUE of at least 80 percent. In comparison, many old furnaces and boilers have AFUE ratings of only 55 to 65 percent.

To find out how efficient your furnace is, look for an energy guide label like in Figure 7.2.3.

Figure 7.7.1. EnergyGuide label for furnace efficiency

Table 7.7.6 lists the efficiencies of most efficient furnaces that were available in 2002–2003.

Table 7.7.6. Efficiency range of furnaces in 2002-2003

Fuel	Furnace type	Efficiencies (%)
Natural gas	Hot air	93.0 to 96.6
Natural gas	Hot water	83.0 to 95.0
Natural gas	Steam	81.0 to 82.7
Fuel oil	Furnace	83.8 to 86.3

Fuel	Furnace type	Efficiencies (%)
Fuel oil	Hot water	86.0 to 87.6
Fuel oil	Steam	82.5 to 86.0

When buying a new furnace, make sure its heating capacity (output) is appropriate for your home. If the insulation and/or windows in your home have been upgraded since the old heating equipment was installed, you can probably use a much less powerful furnace or boiler. Oversized furnaces operate less efficiently because they cycle on and off more frequently; in addition, larger furnaces are more expensive to buy.

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7.8: Insulation and Home Heating Fuels (IV)

Energy Cost

It is clear now that when a unit of fuel is burned not all of it is available to the end user, and that as the furnace efficiency increases, higher amounts of heat will be available. An important question that needs to be addressed is how much it costs to buy the energy or heat to heat a place.

Fuel is usually sold in gallons or CCF or kWh. Comparing the actual cost of energy to produce a certain amount of heat for the end user would be easy if the comparison is made on an energy basis rather than on a unit basis. That is, $/BTUs rather than $/gal or CCF or kWh.

To calculate the actual energy cost, use the formula

$$Actual\ Energy\ Cost = \frac{Fuel\ Cost(\frac{\$}{Unit\ of\ Fuel})}{Heating\ Value\ (\frac{MMBTUs}{Unit\ of\ Fuel}) \times Efficiency} \tag{7.8.1}$$

Example Problems

Example 1

Let's say we need one million BTUs to keep a place warm at a certain temperature. What would it cost to get those million BTUs from oil or gas or electricity? Let's assume that:

Cost, efficiency, and heating value of different materials

Material	Cost per unit	Efficiency	Heating value
Natural gas	$6.60 per MCF	0.90	1,000,000 BTUs (1 MMBTU) per MCF
Oil	$1.25 per gallon	0.85	140,000 BTUs (0.14 MMBTUs) per gallon
Electricity	$0.082 per kWh	0.97	3,412 BTUs (0.003412 MMBTUs) per kWh

Answer available at the end of this section.

Example 2

Your old oil furnace runs at about 68% efficiency. If you buy your oil for $1.02/gal, calculate your actual cost on an MMBTU basis.

Answer available at the end of this section.

Example 3

Natural gas costs $9.74/MCF. Heating oil costs 0.99 cents/gal. The natural gas furnace runs at 90% efficiency and the oil furnace runs at 80% efficiency. Which fuel is cheaper?

Answer available at the end of this section.

Annual Heating Costs

Example Problems

Example 1

A house in International Falls, MN (HDD = 10,500) consists of 1248 ft^2 of walls with an R-value of 13 and 1150 ft^2 of roof with an R value of 29. The home is heated with natural gas. The AFUE is 0.90 and the price of natural gas is $0.88/CCF. What is the annual heating cost?

Answer available at the end of this section.

Example 2

A house in Bismark, ND (HDD = 9,000) has 860 ft^2 of windows (R = 1), 2,920 ft^2 of walls (R = 19), and 3,850 ft^2 of roof (R = 22). Calculate how much heating oil is required to heat this house for the heating season. The furnace efficiency is 80%.

Answer available at the end of this section.

Answers

Example 1

Use equation 7.9.1 to calculate the actual energy costs for each material.

For natural gas,

$$Gas\,Cost = \frac{\frac{\$6.60}{MCF}}{\frac{1\,MMBTU}{MCF} * 0.90} = \$7.33\,per\,MMBTU$$

For oil in a central heating system,

$$Oil\,Cost = \frac{\frac{\$1.25}{gallon}}{\frac{0.14\,MMBTUs}{gallon} * 0.85} = \$10.50\,per\,MMBTU$$

For electricity,

$$Electrical\,Resistance\,Cost = \frac{\frac{\$0.082}{kWh}}{\frac{0.003412 MMBTUs}{kWh} * 0.97} = \$24.77\,per\,MMBTU$$

Example 2

The following video goes over the solution.

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Example 3

The following video goes over the solution.

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Example 1

Using equation 7.9.1,

$$Actual\,Energy\,Cost = \frac{\frac{\$0.88}{CCF}}{\frac{0.1\,MMBTUs}{CCF} * 0.90} = \$9.80/MMBTU$$

Heat required can be calculated from the heat loss. Heat loss from the house is from two sources: walls and the roof. Heat loss from each of these sources for a year (season) can be calculated by using the following equations.

$$Heat\,Loss\,from\,Walls = \frac{1248\,ft^2 * 10500°F}{\frac{13 ft^2 °Fh}{BTUs}} * 24\frac{h}{day} * 1\,day = 24.19\,MMBTUs$$

$$Heat\,Loss\,from\,Roof = \frac{1150\,ft^2 * 10500°F}{\frac{29 ft^2 °Fh}{BTUs}} * 24\frac{h}{day} * 1\,day = 9.99\,MMBTUs$$

Thus, the annual heat cost can be determined using the following equations.

$$Total\,Heat\,Loss = 24.19 + 9.99 = 34.18 MMBTUs$$

\[Annual \, Heat \, Cost = 34.18 MMBTUs * \dfrac{$9.80}{MMBTU} = **$334.96** \nonumber\]

Example 2

The following video covers the solution.

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7.9: Insulation and Home Heating Fuels (V)

Payback Period

Earlier sections illustrated that adding more insulation and improving the R-value of a wall would help in cutting heat loss. Less heat loss reduces the amount of fuel that needs to be burned, thereby reducing the heating costs and protecting the environment. However, adding insulation often involves additional investment.

The money invested into insulation can be recovered or paid back using the money saved because of the reduction of fuel usage. The time it takes to recover the additional cost through savings is called the **payback period**. A simple pay back is the initial investment divided by annual savings after taxes.

A simple calculation illustrates this term. If the R-value of the wall used in an earlier example is improved to R-23 by adding additional insulation, which costs $254, the heat loss can be reduced. The new heat loss after improvement can be calculated using the equation below.

$$New\,Heat\,Loss\,from\,Walls = \frac{1,248 ft^2 * 10,500°F days * \frac{24h}{day}}{23 \frac{ft^2 °F h}{BTU}} = 13.7\,\frac{MMBTU}{Year}$$

Heat loss from the roof remains the same and is equal to 9.99 MM BTUs (from section 7.9, example 2). Therefore, new annual total heat loss is only 13.7 + 9.99 =23.69 MM BTUs. The annual cost of heating after this improvement would be

$$Annual\,Cost\,of\,Heating = 23.69 MMBTUs * \frac{\$9.80}{MMBTUs} = \$232.16$$

The savings is $334.96 - $232.16 = $102.80 every year. Remember that to get this savings, an investment of $254 was made. So if this investment was paid off by the savings, it would take

$$Time = \frac{\$254}{\$102.80/year} = 2.47\,years$$

The payback period is 2.47 years. Shorter pay-back periods indicate that the additional investment can be paid off quickly and the homeowner can start saving money after that.

The formula below will help you to estimate the cost effectiveness of adding insulation in terms of the "years to payback" for savings in heating costs.

$$Years\,to\,Payback = \frac{C_i * R_1 * R_2 * E}{C_e * (R_2 - R_1) * HDD * 24} \tag{7.9.1}$$

where

- C_i is the cost of insulation in $/ft^2
  - Collect insulation cost information, and include labor, equipment, and vapor barrier if needed
- C_e is the cost of energy in $/BTUs
  - To calculate this, divide the actual price you pay per gallon of oil, kWh of electricity, gallon of propane, or therm (100 CCF) of natural gas by the BTU content per unit of fuel
- E = efficiency of the heating system
  - For gas, propane, and fuel oil systems, this is the annual fuel utilization efficiency (AFUE)
- R_1 = initial R-value of section
- R_2 = final R-value of section
- $R_2 - R_1$ = R-value of additional insulation being considered
- HDD = heating degree days per year
  - This information can be obtained from your local weather station, utility, or oil dealer
- 24 = multipler to convert HDD to heating hours

Equation 7.9.1 works only for uniform sections of the home. For example, you can estimate years to pay back for a wall or several walls that have the same R-values, if you add the same amount of insulation everywhere. Ceilings, walls, or sections of walls with different R-values must be figured separately.

Example 1

Mr. Energy Conscious (who lives in East Lansing, MI with an HDD of 7,164) wants to know how many years it will take to recover the cost of installing additional insulation in his attic. He renovated his attic and increased the level of insulation from R-19 to R-30 by adding additional insulation. He has a gas furnace with an AFUE of 0.88 and pays $0.95/CCF for natural gas. The attic insulation costs $340 to cover 1,100 ft^2. What is his years to payback?

Answer available at the end of this section.

Example 2

For a house in Hackensack, NJ (HDD = 4,600), the installed cost to upgrade from R-13 to R-22 is $0.60/$ft^2$. The AFUE for the oil furnace is 0.78 and heating oil costs $1.13/gal. How long will it take to recover the initial investment?

Answer available at the end of this section.

Example 3

Lt. Dave Rajakovich has 1200 ft^2 of roof in his home in Pittsburgh, PA (HDD = 6,000). He is considering upgrading the insulation from R-16 to R-22. The estimate from the contractor was $775. His home is heated with natural gas. Last year, the average price he paid for natural gas was $9.86/MCF. Assuming an AFUE of 86%, how long will it take Dave to recover his investment?

Answer available at the end of this section.

Answers

Example 1

Let R_1 = 19 and R_2 = 30.

The most important part of this problem is to determine the cost of insulation per one sq. ft (C_i) and cost of energy per one BTU (C_e).

$$C_i = \frac{\$340}{1100 ft^2} = \$0.31/ft^2$$

$$C_e = \frac{\$0.95}{1\,CCF * \frac{100000\ BTUs}{CCF}} = \$0.0000095/BTU$$

Substituting the values into equation 7.9.1,

$$Years\ to\ Payback = \frac{0.31 * 19 * 30 * 0.88}{0.0000095 * 11 * 7164 * 24} = 8.65\ years$$

After **8.65 years**, Mr. Energy Conscious can start saving money for himself for the rest of the period that he lives in that home. During the entire period, the energy that he is not using can help the environment.

Example 2

The following video covers the solution.

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Example 3

The following video covers the solution.

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8: HOME HEATING SYSTEMS

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8.1: Comparison of Home Heating Systems (I)

Central Heating Systems

Home heating systems are classified based on the fuel and/or the method by which the heat is transferred and distributed into the house:

- Furnaces, boilers, or electric resistance heat powered by conventional fuels supply most of the heating in homes and commercial buildings today.
- Heat pumps are used to a lesser (but increasing) extent to provide space heating.

Most newer homes are heated using central heating systems. Those without central heating systems utilize electric baseboard heaters or, in some cases, in-the-wall or in-floor gas heaters or radiant heat.

Central Ducted Air Systems

Ducted air systems are the most common type of central heating and cooling used. If a home has a central air conditioner, heat pump, or furnace, it is a ducted air system. There are two main types: **forced-air heating systems** and **gravity heating systems**.

Forced Air Heating Systems

Almost 35 million homes in America are heated by natural gas-fired, forced-air heating systems- by far the most popular form of central heating.

With a forced-air system, a furnace warms air, an air conditioner cools air, or a heat pump either warms or cools air, then a blower forces the air through the system. Therefore, the same duct system can be used for both heating and cooling.

Additional Information

Households using forced air have been sending 30 percent or more of their energy dollars up the furnace flue, contributing to an additional 50 tons of carbon dioxide every year per household. Most conventional forced-air furnaces operate at very low efficiencies of about 50 percent. This is like utilizing only 50 percent of the energy that we buy and feed into the furnace

In a forced-air heating system, room air (cooler) is drawn by a fan or a blower through return air registers and ductwork, and passes through a filter (to remove any dust particles) into a furnace, where the air is heated. The warmed air is then blown back to rooms through a system of supply ducts and registers.

The video below shows how a forced-air heating system works.

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Gravity Heating System

With a gravity furnace, convection currents (caused by the natural tendency of heated air to rise) carry heated air through the system from a furnace that is located on or below the main floor level. Gravity systems, somewhat older, do not have blowers, and tend to have very large air ducts; they can only deliver warmed air.

The video below how a gravity heating system works.

YouTube Video

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Important Point

In gravity heating systems, the ducts are larger than forced-air heating systems, and only warm air travels through them.

Conventional Furnaces

Most furnaces are gas-fired, but other fuels include oil, coal, wood, and electricity.

With a conventional furnace, natural gas is piped to a burner located inside a combustion chamber. There, the gas is mixed with air, then ignited by a pilot light, a spark, or a similar device controlled by a thermostat. The flame heats up a metal box—the heat exchanger—where room air is heated as it flows through. Exhaust gases given off by burners vent outside through a flue that goes up through the roof or, with newer high-efficiency models, out through a wall.

The video below shows how a gas furnace works.

YouTube Video

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An **electric furnace** uses heating elements rather than burners to heat in the heat exchanger.

The video below explains how an electric furnace works.

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8.2: Comparison of Home Heating Systems (II)

Heat Distribution

The main components of a forced-air heating system include the furnace, main duct, branches, and registers.

In a hot-air system, warm air is distributed via a **main duct** and a series of **branches** that lead to individual rooms or zones. Where the branches meet the main duct, heat is controlled by **dampers** (act as valves for air flow), which open or close to release or block heat from entry. These dampers, usually motorized, are run by thermostatic controls at each zone. Individual **registers** may also be closed to block heat, but this is a less efficient use of the energy and heat produced than when there are thermostatic or automatic controls.

An **upward-flow furnace** draws cold air in through the bottom and sends heated air out the top. Upward-flow furnaces are often used in houses that have basements or that deliver heat through overhead ductwork.

A **downward-flow or counter-flow furnace** draws cool return air through the top and delivers heated air out the bottom. This type is favored where there is no basement, or where air ducts are located in the floor.

A forced-air heating system can be combined with air conditioning (for cooling), a humidifier (for maintaining proper moisture balance), and an air filter (for purifying the air). Ductwork is generally metal, wrapped with insulation to help keep heat in. In some cases, flexible insulation-style ductwork is preferred. This system has several advantages and disadvantages as described below.

Advantages

- Air ducts and registers distribute heat from a central furnace, providing rapid heat delivery.
- The system can also be used to filter and humidify the household air, to provide central air conditioning.
- The system circulates air for ventilation.

Disadvantages

- Air coming from the heating registers sometimes feels cool (especially with certain heat pumps), even when it is warmer than the room temperature.
- There can also be short bursts of very hot air, especially with oversized units.
- Ductwork may transmit furnace noise, and can circulate dust and odors throughout the house.
- Ducts are also notoriously leaky, typically raising a home's heating costs by 20% to 30%.

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8.3: Comparison of Home Heating Systems (III)

Radiant Heating Systems: Baseboards

Baseboard Radiators

In the baseboard hydronic heating systems (shown in the video below), water is heated in a gas-fired or oil-fired furnace located in the basement. The heated water is distributed through pipes into baseboards in various rooms. The heat is then delivered through radiation and convection. Although these are called radiant heating systems, most of the heat delivered is by convection. Heat delivery into rooms or zones can be controlled by flaps or louvers.

YouTube Video

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A picture of a baseboard heater is shown in Figure 8.1.1. Closely spaced metallic sheets called “fins” increase the surface area for efficient heat transfer into the room.

Baseboard Heater

Figure 8.1.1. Baseboard heater

Table 8.1.1 analyzes the aspects of radiant baseboard heating.

Table 8.1.1 analyzes the aspects of radiant baseboard heating.

Table 8.1.1. Advantages and disadvantages of radiant baseboard heating

Advantages	Disadvantages
In general, operates quietly	Cannot be used for heating
Delivers constant heat and doesn't stir up allergens or dust	High installation costs
Feels warm even if a door is opened or a room is somewhat drafty or slightly cooler than normal, since it warms people and objects rather than just air	Interferes with furniture placement
Less heat loss compared to a forced air system because there is no leakage	Air entrapment can reduce efficiency

Radiant Heating Systems: Floors

Types of Radiant Floor Heat

There are three types of radiant floor heat:

- Radiant air floors (air is the heat-carrying medium)

- Electric radiant floors
- Hot water (hydronic) radiant floors.

Compare conventional baseboard heating to radiant floor heat by watching the videos below.

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Types of Installation

All three types of radiant floor heat (air, electric, hot water) can be further subdivided by the type of installation:

- Those that make use of the large thermal mass of a concrete slab floor or lightweight concrete over a wooden subfloor (these are called “wet installations”), as shown in Figure 8.1.2

Image of a concrete slab above the radiant water tubing.

Figure 8.1.2. Concrete radiant

- Those in which the installer “sandwiches” the radiant floor tubing between two layers of plywood or attaches the tubing under the finished floor or subfloor (“dry installations”), as shown in Figure 8.1.3

Image of a plywood slab above the radiant water tubing.

Figure 8.1.3. Wood radiant

Cost Effectiveness

Radiant Air Floors

Because air cannot hold large amounts of heat, **radiant air floors** are not cost-effective in residential applications and are seldom installed.

Electric radiant floors

Electric radiant floors are usually only cost-effective if your electric utility company offers time-of-use rates. Time-of-use rates allow you to “charge” the concrete floor with heat during off-peak hours (approximately 9 p.m. to 6 a.m.). If the floor's thermal mass is large enough, the heat stored in it will keep the house comfortable for eight to ten hours without any further electrical

input. This practice saves a considerable number of energy dollars compared to heating at peak electric rates during the day.

The video below explains how a concrete floor is charged during time-of-use rates.

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Hydronic systems

Hydronic (liquid) systems, popular and cost-effective systems for heating-dominated climates, have been in extensive use in Europe for decades.

Hydronic radiant floor systems pump heated water from a boiler through tubing laid in a pattern underneath the floor. The temperature in each room is controlled by regulating the flow of hot water through each tubing loop via a system of zoning valves or pumps and thermostats.

The video below shows how a hydronic radiant floor system works.

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Installation

Wet installations are the oldest form of modern radiant floor systems. As shown in Figure 8.1.4, in a wet installation, the tubing is embedded in the concrete foundation slab, or in a lightweight concrete slab on top of a subfloor, or over a previously poured slab.

Diagrams of wet installations on top of both a concrete foundation and a subfloor.

Figure 8.1.4. Wet installations: slab on grade and thin slab over frame floor

A new generation of in-floor hydronic heating that employs corrosion-proof, hot-water tubing has enjoyed widespread popularity in recent years. With this type of system, heat is evenly distributed and floors are warm under foot. A variety of heating equipment may heat water: natural gas or propane water heater or boiler, electric boiler, wood boiler, heat pump, solar collector, or even geothermal energy.

Tubing for a hydronic system may be installed in a conventional concrete slab or in a lightweight, gypsum-cement slab. It can also be stapled to the undersides of subflooring as shown in Figure 8.1.5.

Diagrams show "staple up" tubing in which tubes are suspended underneath the flooring and "sandwich over frame floor" tubing in which tubes are placed between flooring and subflooring.

Figure 8.1.5. Staple up and sandwich over frame floor installations

Figure 8.1.6 depicts corrosion-proof, hot-water tubing stapled to the underside of subflooring.

Corrosion-proof, hot-water tubing stapled to the underside of subflooring

Figure 8.1.6. Corrosion-free hot water tubing

Radiant Floor Coverings

Although ceramic tile is the most common floor covering for radiant floor heating, almost any floor covering can be used. However, some perform better than others. Common floor coverings like vinyl and linoleum sheet goods, carpeting, wood, or bare concrete are often specified.

- **Carpeting**
  It is wise to always remember that anything that can insulate the floor also reduces or slows the heat entering the space from the floor system, which in turn increases fuel consumption. If carpeting is required, a thin carpet with dense padding is preferred. If some rooms, but not all, will have a floor covering, then those rooms should have a separate tubing loop to make the system heat these spaces more efficiently, because the water flowing under the covered floor will need to be hotter to compensate for the floor covering.
- **Wood Flooring**
  Most radiant floor references also recommend using laminated wood flooring instead of solid wood, thus reducing the possibility of the wood shrinking and cracking from the drying effects of the heat. While solid wood flooring can be used, the installer is strongly advised to be very familiar with radiant floor systems before attempting to install natural wood flooring over a radiant floor system. Most manufacturers and manuals relating to radiant floors offer guidelines to help you resolve these issues.

Radiant Floor Tubing

There are various types of tubing used in Radiant floor heating systems.

- **Copper or Steel Tubing** - Older radiant floor systems used either copper or steel tubing embedded in the concrete floors. Unless the builder coated the tubing with a protective compound, a chemical reaction between the metal and the concrete often led to corrosion of the tubing, and to eventual leaks.
- **PEX or Rubber Tubing** - Major manufacturers of hydronic radiant floor systems now use cross-linked polyethylene (PEX) or rubber tubing with an oxygen diffusion barrier. These materials have proven themselves to be more reliable than the older choices in tubing. Fluid additives also help protect the system from corrosion.
- **Defective Tubing** - There have been recent reports of problems with rubber tubing produced by one chemical manufacturer. Leaks develop at the metal connections or fittings, and, in some cases, the tubing becomes rigid and brittle. It is still not clear what causes this problem, but, theoretically, excessively high water temperatures may be to blame. Tightening the connections and clamps only temporarily fixes the leaks. Remember, this problem only concerns a specific brand of rubber tubing; it does not have anything to do with the PEX tubing, which has performed very reliably for many decades. Since the price of copper tubing is considerably lower now than several years ago, it is again gaining some popularity because of its superior heat transfer abilities over plastic-based tubing.

Table 8.1.2 analyzes the details of radiant floor heating systems.

Table 8.1.2. Advantages and disadvantages of radiant floor heating systems

Advantages	Disadvantages
Allow even heating throughout the whole floor, not just in localized spots as with wood stoves, hot air systems, and other types of radiators	Does not respond quickly to temperature settings
The room heats from the bottom up, warming the heat and body first	Relatively expensive to install but can save money in the long run
Eliminates the draft, dust, and allergen problems asociated with forced-air heating systems	Requires professional installers

Advantages	Disadvantages
Able to set the thermostat several degrees lower, relative to other types of heating systems	
No heat registers or radiators to obstruct furniture arrangements and interior design plans	

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8.4: Comparison of Home Heating Systems (IV)

Direct or In-Situ Heating Systems

Instead of generating heated air or water at a central location and then distributing it throughout the home, some systems generate heat where it is needed locally. The most common method is electric baseboard heat. Other ways include kerosene heat; wood-burning stoves; and fireplaces burning wood, coal, or natural gas. These systems can heat the whole house, part of the house, or a single room.

Electric Resistance Heat

Electric resistance heating converts nearly 100 percent of the energy in the electricity to heat. However, most electricity is produced from oil, gas, or coal generators that convert only about 30 percent of the fuel's energy into electricity. Because of electricity's generation and transmission losses, electric heat is often more expensive than heat produced in the home with combustion appliances such as natural gas, propane, and oil furnaces.

Electric resistance heat can be supplied by centralized forced-air furnaces or by zonal heaters in each room, both of which can be composed of a variety of heater types.

- Zonal heaters distribute electric resistance heat more efficiently than electric furnaces because you set room temperatures according to occupancy.
- Zonal heaters have no ducts (unlike electric furnaces) that can lose heat before it reaches the room.
- Electric furnaces can accommodate central cooling more easily than zonal electric heating because the air conditioner can share the furnace's ducts.
- Electric resistance heat can be provided by electric baseboard heaters, electric wall heaters, electric radiant heat, electric space heaters, electric furnaces, or electric thermal storage systems.

Table 8.1.3 provides more details on electric direct heating systems.

Table 8.1.3. Electric direct heating systems

Type of heater	Description	Method of heating	Installation	Advantages	Disadvantages
Baseboard heaters	Zonal heaters controlled by thermostats located in each room. Contain electric heating elements encased in metal pipes, which are surrounded by aluminum fins to aid heat transfer and run the length of the baseboard heater's housing (cabinet).	Convection and radiation. As air within the heater is warmed, it rises into the room, and cooler air is drawn to the bottom of the heater. Some heat is also radiated from the pipe, fins, and housing.	Usually installed underneath windows, where the heater's rising warm air counteracts falling cool air from the cold window glass. Seldom located on interior walls because the standard heating practice is to supply heat at the home's perimeter where the greatest heat loss occurs. Should sit at least 3/4 inch (1.9 centimeters) above the floor or carpet, to allow the cooler air on the floor to flow under and through the radiator fins so it can be heated. Should also fit tightly to the wall to prevent the warm air from convecting behind it and streaking the wall with dust particles.		The quality of baseboard heaters varies considerably. Cheaper models can be noisy and often give poor temperature control. Look for labels from Underwriter's Laboratories (UL) and the National Electrical Manufacturer's Association (NEMA). Compare warranties of the different models you are considering.
Wall heaters	Consist of an electric element with a reflector behind it to reflect heat into the room, and usually a fan to move air through the heater.	Convection and radiation.	Usually installed on interior walls because installing them in an exterior wall makes that wall difficult to insulate.		

Type of heater	Description	Method of heating	Installation	Advantages	Disadvantages
Radiant heaters	Several types, including electrical heating cables (most common), gypsum ceiling panels and metal radiant panels (provide radiant heat faster than other types because they contain less material to warm up.	Radiation. Radiates heat to the room's objects, including its people. For example, you can feel a ceiling-mounted radiant heating panel warming your head and shoulders if you stand underneath it.	Electric heating cables are imbedded in floors or ceilings; gypsum ceiling panels are already equipped with factory-imbedded heating cables; and metal radiant panels are ceiling-mounted.	Offers draft-free heating that is easily zoned. It occupies no interior space, allowing you complete freedom to place furniture without worrying about impeding air flow from registers or baseboard heaters. Manufacturers claim that radiant heat can provide comfort similar to other systems at lower indoor air temperatures, saving around 5 percent of space heating costs.	Critics say that it can be difficult to control air temperature with a thermostat. The large heat-storage capacity of the concrete or plaster surrounding the heating cables may result in greater-than-normal fluctuations in the room air temperature, since it takes quite a while to heat up the storage mass. Also, some occupants complain about their heads being too warm in rooms that utilize ceiling radiant heat. Supplying heat at the ceiling or floor, which are locations that typically border the outdoors or unheated spaces, can result in greater heat losses. For example, if there are any flaws in a heated concrete slab or gaps in the ceiling insulation above heating elements, a large percent of the electric heat may escape to the outdoors without ever heating the home.
Space heaters	Come in a wide variety of models, either built-in or portable. Portable space heaters, as well as many built-in space heaters for small rooms, have built-in thermostats. Larger rooms heated with built-in electric space heaters should have low-voltage thermostats installed in an area that maintains the room's average temperature.	May have fans to circulate heated air, and may also be designed to transfer some of their heat by radiation.	All of these heaters must be given adequate clearance to allow air to circulate safely.		

Fireplaces

Fireplaces are very commonly used in family rooms and other living areas to give a warm and cozy feeling. These fireplaces can be wood or natural-gas fired.

Generally, fireplaces transfer the heat by radiation, and hot combustion gases (carrying a lot of thermal energy) go out through the stack. Hot gases are lighter and rise up the chimney; a natural suction created by this flow draws the heated warm air from the room.

Most of the time, the warm air heated in the room by the main heating fuel is also drawn into the fireplace and goes up the chimney, resulting in a net loss of energy. It is estimated that about 75 percent of the heated air is lost through the chimney. However, many people still use fireplaces inefficiently.

The video below shows how fireplaces work.

YouTube Video

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Advantages and Disadvantages of Direct Heating Systems

Table 8.1.4 analyzes the details of direct heating systems.

Table 8.1.4. Advantages and disadvantages of direct heating systems

Advantages	Disadvantages
Generates heat at the point of use (no transmission losses)	Heats only certain parts of the home
Inexpensive to purchase and install	Cannot be used for cooling
Easy local control in each room	Takes up space in rooms
In well-insulated homes, may be cheaper than other systems	Generally less efficient than other central heating systems

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8.5: Cooling and Heating (I)

Heat Movers

So far, we have discussed systems in which a fuel is burned and heat is produced and delivered into the home. In these systems, we buy all the energy, and (depending on the system) we reject or lose some heat to the surroundings, reducing the efficiency.

One of the ways in which we can improve the heating efficiency is to make use of the heat that is available outside, even on a cold winter day. On a cold winter day with outside temperature at 30°F, the air still has more energy compared to air at 10 °F or 5°F. Air at any temperature above absolute zero (0°K or -273 °C) will have energy.

The higher the temperature of air, the higher its energy content. This energy can be transferred to the interior.

A device that moves the heat from a low temperature environment to a high temperature environment is called a **heat mover**.

Under natural circumstances, heat only flows from high temperatures to low temperatures. In order to move heat from a low temperature environment to a high temperature environment, work needs to be done (or rather energy needs to be spent), as shown in Figure 8.2.1.

Heat mover diagram showing how low heat moves to high heat.

Figure 8.2.1. Heat mover

Heat Pumps

An example of a heat mover is a heat pump. A heat pump is a heating/cooling system and also a forced-air system. Cooled (and sometimes humidified or electronically cleaned) air is usually delivered through the same ductwork and registers used by heated air.

A heat pump uses air-conditioning principles to extract heat from one place and deliver it to another, and vice versa. In addition to expelling heat from indoors, the system can be reversed to heat the home in the winter. Thus a heat pump is a device that moves heat from a low-temperature to a high-temperature environment with the help of work that is put in.

Heat pumps are classified based on the low-temperature heat source:

1. ***Air-source heat pump* or *Air-to-air heat pump***. Heat is transferred from the low-temperature air outside to the high-temperature interior.
2. ***Ground-source heat pump* or *Ground-to-air heat pump***. The earth is used as a heat sink in the summer and a heat source in the winter; the pump relies on the relative warmth of the earth for its heating and cooling production.
3. ***Water-source heat pump* or *Water-to-air heat pump*.** Heat is transferred from low-temperature water outside (from a pond or a lake) to a high-temperature interior.

Additional Information

An air conditioner is a cooling system and also a forced-air system. It runs on electricity and removes heat from the air with basic refrigeration principles.

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8.6: Cooling and Heating (II)

Air-Source Heat Pump or Air-to-Air Heat Pump

An air-source or air-to-air heat pump can provide both heating and cooling.

- In the winter, a heat pump extracts heat from outside air and delivers it indoors.
- On hot summer days, it works in reverse, extracting heat from room air and pumping it outdoors to cool the house.

Nearly all air-source and air-to-air heat pumps are powered by electricity. They have an outdoor compressor/ condenser unit that is connected with refrigerant-filled tubing to an indoor air handler. As the refrigerant moves through the tubing of the system, it completes a basic refrigeration cycle, warming or cooling the coils inside the air handler. The blower pulls in room air, circulates it across the coils, and pushes the air through ductwork back into rooms.

When extra heat is needed on particularly cold days, supplemental electric-resistance elements kick on inside the air handler to add warmth to the air that is passing through.

In the winter, a heat pump extracts heat from outside air and delivers it indoors. In the summer, the heat pump extracts heat from room air and pumps it outdoors to cool the house.

The videos below explains the heating and cooling cycles of a heat pump.

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YouTube Video

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The Balance Point

As we have learned, air-source and air-to-air heat pumps work by extracting heat from the outside air. These heat pumps require a backup system to supplement their heating ability when the outdoor temperature gets below a certain temperature.

As the outdoor temperature drops, the heating requirement of the house increases and the output of the heat pump decreases. At some point, the temperature of the home's heating requirement and the heat pump output match. This temperature is called the **balance point** and usually falls between 30-45 degrees Fahrenheit. For any temperatures below the balance point, supplemental heat will be required.

To locate the balance point, the heating requirement (BTUs/h) of the house and the heat pump output (BTUs/h) are plotted against

the changes in outside temperature. The place where the home heating requirement and heat pump output lines cross is the balance point.

Figure 8.6.2 shows a graph of the balance point.

Graph of the Balance Point. Described in text above.

Figure 8.6.2. Balance point

Efficiency of a Heat Pump

Efficiency of a heat pump is measured using a term **coefficient of performance** (**COP**), and it is the ratio of the useful heat that is pumped to a higher temperature, to a unit amount of work that is put in. We will look at COP in terms of air-source heat pumps.

A general expression for the efficiency of a heat engine can be written as

$$COP = \frac{(Heat\ Energy)_{hot}}{Work} \tag{8.6.1}$$

Using the same logic that was used for heat engines, equation 8.6.1 becomes

$$COP = \frac{Q_{hot}}{Q_{hot} - Q_{cold}} \tag{8.6.2}$$

where Q_{hot} is the heat input at high temperature and Q_{cold} is the heat rejected at low temperature. Thus, equation 8.6.2 can be rewritten as

$$COP = \frac{T_{hot}}{T_{hot} - T_{cold}} \tag{8.6.3}$$

Note

T_{hot} and T_{cold} must be expressed in units of Kelvin.

Example Problems

Example 1

Calculate the ideal COP for an air-to-air heat pump used to maintain the temperature of a house at 70°F when the outside temperature is 30°F.

Answer available at the end of this section.

Example 1 shows that for every watt of power we use (and pay for) to drive this ideal heat pump, 13.3 W is delivered to the interior of the house and 12.3 from the outside (we don't pay for this). This seems to be a deal that one cannot refuse. However, the theoretical maximum is never achieved in the real world. In practice, a COP in the range of 2 to 6 is typical. Even with this range, it is an excellent choice, because for every watt of power that we use, we transfer 1 to 5 additional watts from outside.

Example 2

Compare the ideal coefficients of performance of the same heat pump installed in State College, PA and Ann Arbor, MI when the inside temperature of a house is maintained at 70°F at both locations and the outside temperatures on a given day were 40°F and 15°F at State College and Ann Arbor, respectively.

Answer available at the end of this section.

Note

During a heating season, the heat pump's efficiency increases on mild days and decreases on cold days.

Answers

Example 1

Add texts here. Do not delete this text first.

First, convert the Fahrenheit temperatures to Celsius temperatures using

$$T_{hot} = (70 - 32) * \frac{5}{9} = 21°C$$

$$T_{cold} = (30 - 32) * \frac{5}{9} = -1°C$$

Next, convert the Celsius temperatures to Kelvin temperatures by adding 273:

$$T_{hot} = 21°C + 273 = 294K$$

$$T_{cold} = -1°C + 273 = 272K$$

Finally, use equation 8.6.3 to solve for the COP:

$$COP = \frac{T_{hot}}{T_{hot} - T_{cold}}$$

$$COP = \frac{294\,K}{294\,K - 272\,K} = 13.3$$

Example 2

Add texts here. Do not delete this text first.

State College, PA
T_{hot} = 70°F = 294 K
T_{cold} = 40°F = 277 K
$$COP = \frac{294\,K}{294\,K - 272\,K} = 17.3$$

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8.7: Cooling and Heating (III)

Ground Source (Geothermal) Heat Pumps

Ground-source or geothermal heat pumps (GHPs) are similar to the air-source heat pumps, except that the source of heat is the ground instead of outdoor air.

The following video explains where does the heat in the ground come from.

YouTube Video

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As you observed in the video, the earth absorbs and stores energy from the sun as heat, resulting in underground temperatures that range between 40 to 80°F, depending on the location. These temperatures, which are located below the frost line (which is generally 4–5 feet in Pennsylvania), remain constant throughout the year.

The geothermal heat pumps (GHPs) use the earth as a heat sink in the summer and as a heat source in the winter, and therefore rely on the relative warmth of the earth for their heating and cooling production.

Through a system of underground pipes, they transfer heat from the warmer earth to the building in the winter, and take the heat from the building in the summer and discharge it into the cooler ground. Therefore, GHPs do not *create* heat; they *move* it from one area to another.

Operating Principle

The GHP system operates much like an air-source or air-to-air heat pump, except that:

- The outside tubing is buried to extract or discharge the heat in the ground;
- The compressor/condenser unit is inside rather than outside the house.

The GHP system also has additional valves to allow heat-exchange fluid (refrigerant) to follow two different paths: one for heating and one for cooling. The GHP takes heat from a warm area and exchanges the heat to a cooler area, and vice versa.

The following video shows how a geothermal heat pump operates.

YouTube Video

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Classifications of GHPs

Closed-Looped Systems

Horizontal

The horizontal type of installation is generally most cost-effective for residential installations, particularly for new construction where sufficient land is available. It requires trenches at least four feet deep.

Horizontal systems come in two types of layouts, the two pipes method and the slinky method.

Two Pipes

The most common horizontal layouts include:

Two Pipes Layout (Option 1) - One pipe buried at six feet, and another pipe buried at four feet, as shown in Figure 8.7.1.

Diagram of a horizontal closed-loop system - two pipe layout. Described in the text above.

Figure 8.7.1. Horizontal closed-loop system: option 1

Two Pipes Layout (Option 2) - Both pipes placed side-by-side at five feet in the ground in a two-foot wide trench, as shown in Figure 8.7.2.

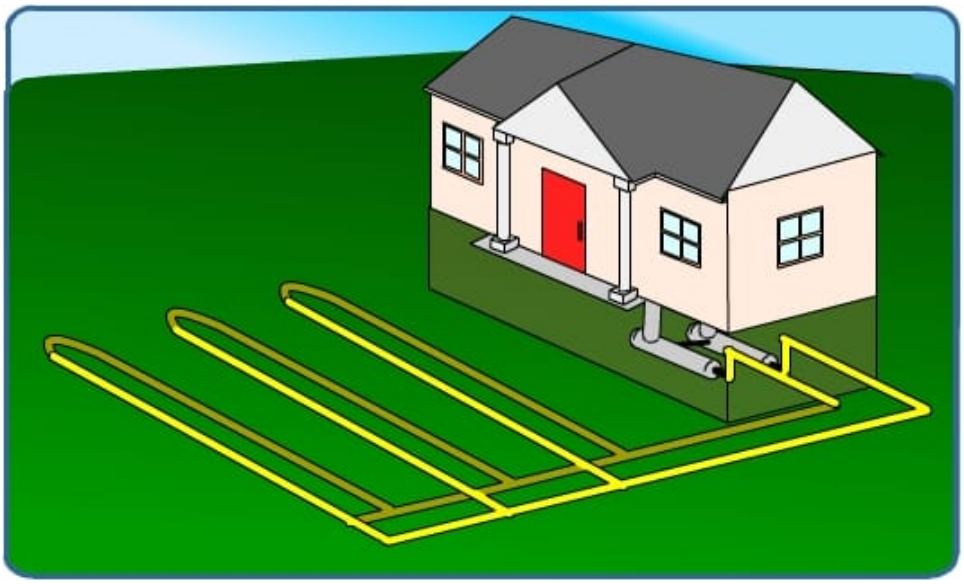


Figure 8.7.2. Horizontal closed-loop system: option 2

The Slinky™ Method

As shown in Figure 8.7.3, the pipe is looped to allow more pipes in a shorter trench, which cuts down on installation costs and makes horizontal installation possible in areas not possible with conventional horizontal applications. Large commercial buildings and schools often use vertical systems because the land area required for horizontal loops would be prohibitive.

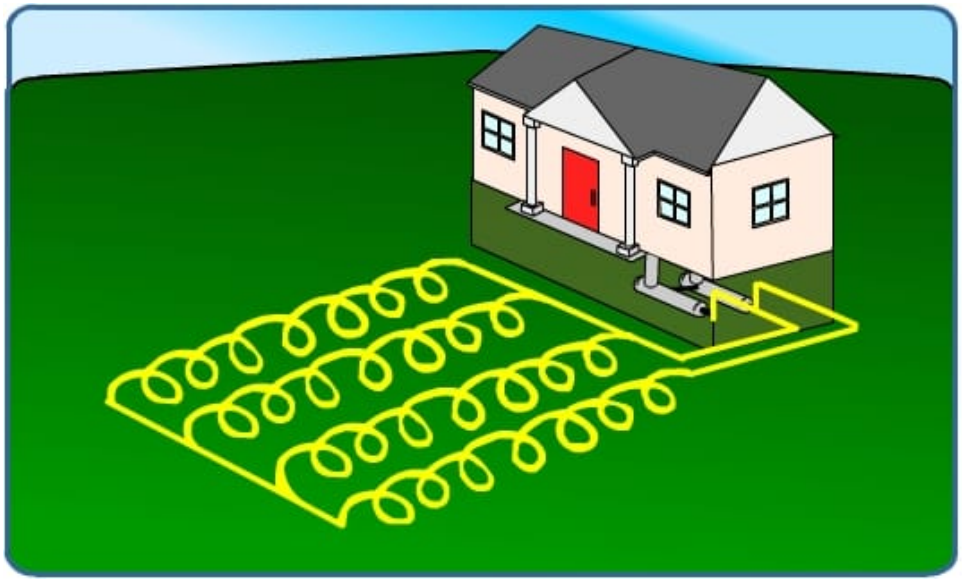


Figure 8.7.3. Horizontal closed-loop system: Slinky™ Method

Vertical

This type of system may be used when the soil is too shallow for trenching or when one does not want to disturb the existing landscaping.

For a vertical system, holes (approximately four inches in diameter) are drilled about 20 feet apart and 100 to 400 feet deep. Into these holes go two pipes that are connected at the bottom with a U-bend to form a loop. The vertical loops are connected with horizontal pipe (i.e., manifold), placed in trenches, and connected to the heat pump in the building. This is illustrated in Figure 8.7.4.

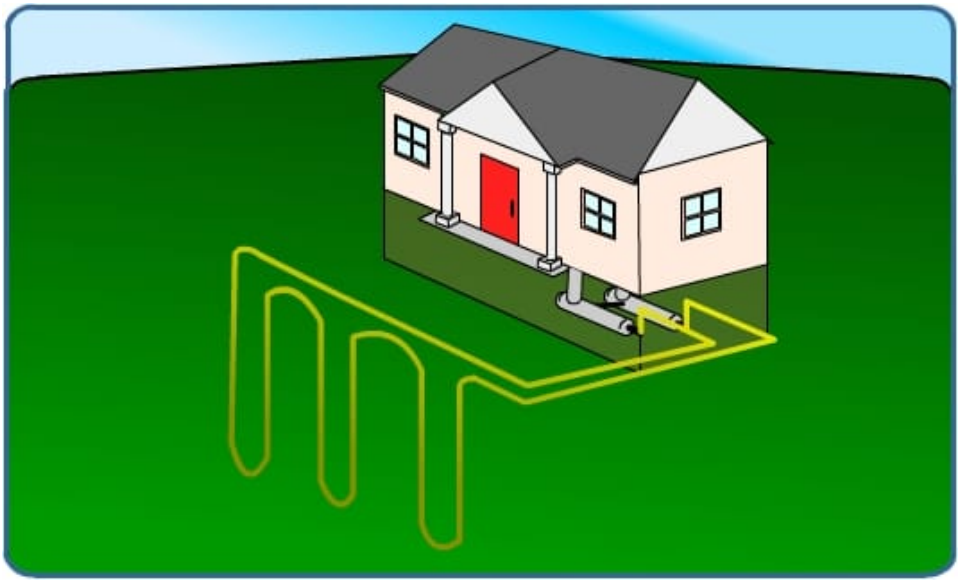


Figure 8.7.4. Vertical closed-loop system

Pond

If a home has source surface water, such as a pond or lake, this type of loop design may be the most economical, since there

is no need to dig a trench or a well for the pipes in the ground. In this type of system, the fluid circulates through polyethylene piping in a body of water, just as it does in the ground loops. The pipe may be coiled in a slinky shape to fit more of it into a given amount of space. This loop is recommended only if the water level never drops below six to eight feet at its lowest level, to assure sufficient heat-transfer capability. Pond loops used in a closed system result in no adverse impacts on the aquatic system. This is illustrated in Figure 8.7.5.

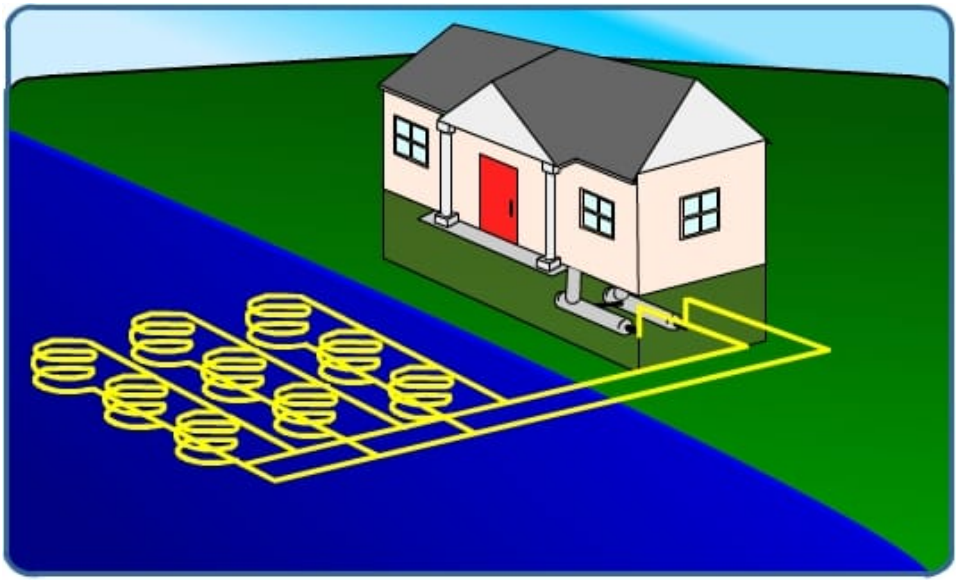


Figure 8.7.5. Closed-loop system: pond

Open-Loop Systems

This type of system uses well(s) or surface body water as the heat exchange fluid that circulates directly through the GHP system, as shown in Figure 8.7.6. Once it has circulated through the system, the water returns to the ground through the well, a recharge well, or a surface discharge. This option is obviously practical only where there is an adequate supply of relatively clean water, and all local codes and regulations regarding groundwater discharge are met.

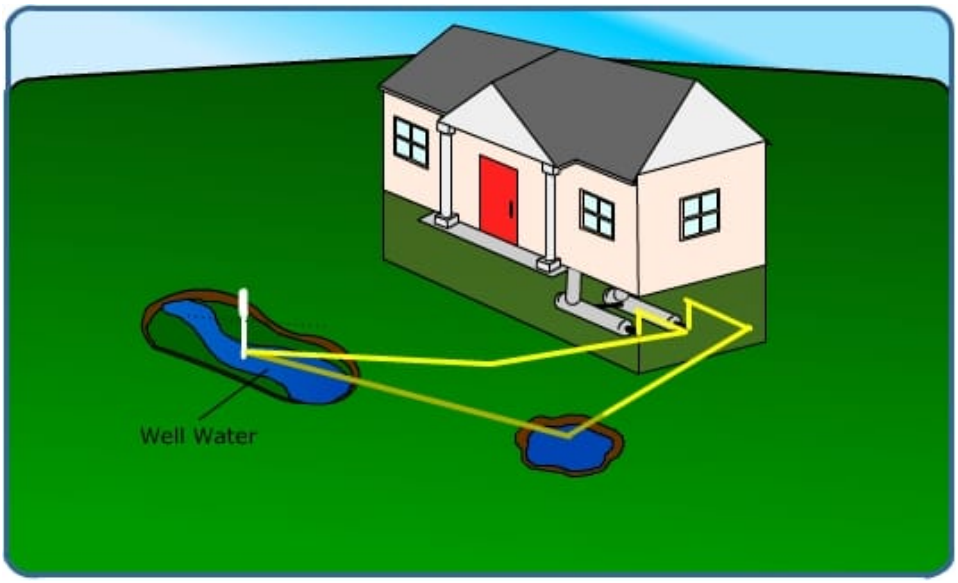


Figure 8.7.6. Open-loop system

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8.8: Cooling and Heating (IV)

Factors Affecting the Type of GHP Loop

Geothermal heat pumps (GHPs) can be used effectively almost anywhere in the country. However, the specific geological, hydrological, and spatial characteristics of a site determine the best type of ground loop for a specific location.

Benefits of a GHP System

Low energy use

- The biggest benefit of GHP's is that they use 20 to 50 percent less electricity than conventional heating or cooling systems. This translates into a GHP using one unit of electricity to move three units of heat from the earth.
- According to a report by Oak Ridge National Laboratory, statistically valid findings show that the 4,003-unit GHP retrofit project at Fort Polk, LA, will save 25.8 million kilowatt-hours (kWh) in a typical year, or 32.5 percent of pre-retrofit whole-community electrical consumption. This translates to an average annual savings of 6,445 kWh per housing unit. In addition, 100 percent of the whole-community natural gas previously used for space conditioning and water heating (260,000 therms) will be saved.
- In housing units that were all-electric in the pre-retrofit period, the GHP's were found to save about 42 percent of the pre-retrofit electrical consumption for heating, cooling, and water heating.

Free or reduced-cost hot water

- Unlike any other heating and cooling system, a geothermal heat pump can provide free hot water. A device called a super heater transfers excess heat from the heat pump's compressor to the hot water tank. In the summer, hot water is provided free; in the winter, water heating costs are cut roughly in half.

Year-round comfort

- While producing lower heating bills, geothermal heat pumps are quieter than conventional systems, and improve humidity control. These features help explain why customer surveys regularly show high levels of user satisfaction, usually well over 90 percent.

Design features

- Geothermal heat pump systems allow for design flexibility, and can be installed in both new and retrofit situations. Because the hardware requires less space than that needed by conventional HVAC systems, the equipment rooms can be greatly scaled down in size, freeing space for productive use. Also, geothermal heat pump systems usually use the existing ductwork in the building and provide simultaneous heating and cooling without the need for a four-pipe system.

Improved aesthetics

- Architects and building owners like the design flexibility offered by GHP's. Historic buildings like the Oklahoma State Capital and some Williamsburg, Virginia, structures use GHPs because they are easy to use in retrofit situations and easy to conceal, as they don't require cooling towers.
- GHP systems eliminate conventional rooftop equipment, allowing for more aesthetically pleasing architectural designs and roof lines. The lack of rooftop penetrations also means less potential for leaks and ongoing maintenance, and better roof warranties. In addition, the aboveground components of a GHP system are inside the building, sheltering the equipment both from weather-related damage and from potential vandalism.

Low environmental impact

- Because a GHP system is so efficient, it uses a lot less energy to maintain comfortable indoor temperatures. This means that less energy is often created from burning fossil fuels than is needed to operate a GHP. According to the EPA, geothermal heat pumps can reduce energy consumption and corresponding emissions up to 44% compared to air-source heat pumps, and up to 72% compared to electric resistance heating with standard air conditioning equipment.

Low maintenance

- According to a study completed for the Geothermal Heat Pump Consortium (GHPC), buildings with GHP systems had average total maintenance costs ranging from 6 to 11 cents per square foot, or about one third that of conventional systems. Because the workhorse part of the system, the piping, is underground or underwater, there is little maintenance required. Occasional cleaning of the heat exchanger coils and regularly changing the air filters are about all the work necessary to keep the system in good running order.

Zone heating and cooling

- These systems provide excellent zone space conditioning - different areas of the building heated or cooled to different temperatures simultaneously. For example, GHP systems can easily move heat from computer rooms (which need constant cooling) to the perimeter walls for winter heating in commercial buildings. School officials like the flexibility of heating or cooling just auditoriums or gymnasiums for special events rather than the entire school.

Durability

- Because GHP systems have relatively few moving parts, and because those parts are sheltered inside a building, they are durable and highly reliable. The underground piping often carries warranties of 25 to 50 years, and the GHP's often last 20 years or more.

Reduced vandalism

- GHPs usually have no outdoor compressors or cooling towers, so the potential for vandalism is eliminated.

Typically when heating systems or appliances are compared, all the costs that are incurred—purchase, installation, operation, and maintenance costs—can be combined into a life-cycle cost, the cost of ownership over a period of years. Table 8.8.1 compares the various types of central heating systems.

Table 8.8.1. Comparison of life cycle costs for heat pumps

Compare	Safety	Installation Cost	Operating Cost	Maintenance Cost	Life-Cycle Cost
Combustion-based	A concern	Moderate	Moderate	High	Moderate
Heat pump	Excellent	Moderate	Moderate	Moderate	Moderate
Geothermal heat pump	Excellent	High	Low	Low	Low

Installation and Operating Costs of GHP Systems

On average, a geothermal heat pump (GHP) system costs about $2,500 to $3,500 per ton of capacity, or roughly $7,500 to 10,000 for a 3-ton unit (typical residential size). In comparison, other systems would cost about $4,000 with air conditioning.

When included in the mortgage, the homeowner has a positive cash flow from the beginning. For example, say that the extra $3,500 will add $30 per month to each mortgage payment. A 3,000 square-foot house in Oklahoma City, shown in Figure 8.8.1, has a verified average electric bill of $60 per month, using a geothermal heat pump. This represents significant savings.

A photo of a house using GHP in Oklahoma City

Figure 8.8.1. A 3,000 square-foot house using GHP in Oklahoma City

Credit: Office of Energy Efficiency & Renewable Energy

A system using horizontal ground loops will generally cost less than a system with vertical loops.

Geothermal heat pump installations in both new and existing homes can reduce energy consumption 25 to 75 percent compared to older or conventional replacement systems. Annual operating costs were also lowest with geothermal heat pumps. Add in the benefits of the desuperheater for hot water savings, and it's easy to see how a GHP system is the most efficient available.

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8.9: Cooling and Heating (V)

Solar Energy for Home Heating

Energy that is received on the roof of a house is more than enough to supply the heating needs of the home. The energy reaching the earth from the sun ranges from 600 to 2000 BTUs per square foot per day (averaged over a year). It is a function of the latitude of the place. The amount of solar radiation reaching the earth is called the **insolation**. This is a short from for **in**cident **sol**ar radia**tion** per day.

The earth revolves around the sun with its axis tilted toward the plane of rotation, as shown in Figure 8.9.1.

- In June, the North Pole is tilted toward the sun and the solar rays are incident perpendicularly. Therefore, the sun appears to be at a higher angle.
- In December, the North Pole is tilted away from the sun and therefore days are shorter and the solar rays are incident more obliquely, with lower energy flux (winter).

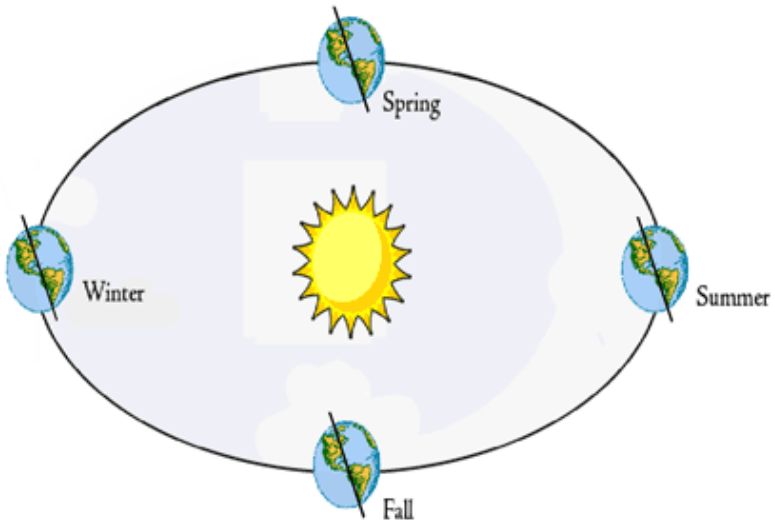


Figure 8.9.1. Illustration of seasons for northern hemisphere

The sun also changes in position and angle from the earth during various times of the year.

The following video shows the movement of the sun as a function of the seasons.

YouTube Video

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Active Solar Heating Systems

Solar heating systems are classified as “active” or “passive” solar heating systems, or a combination of both. We will first look at active systems.

Active solar heating systems are comprised of collectors, a distribution system, and a storage device.

Active solar heating systems operate as follows:

- Flat plate collectors are usually placed on the roof or ground in the sunlight. The top or sunny side has a glass or plastic cover to let the solar energy in. The inside space is a black (absorbing) material to maximize the absorption of the solar energy.
- Cold water is drawn from the storage tank by pump #1 and is pumped through the flat plate collector mounted on the roof of the house.
- The water absorbs the solar energy and is returned back to the tank.
- Warm water from the tank is pumped by pump #2 though the heating coil.
- The fan blows air (from the room) over the heated coil, and the heated air then passes into the room and heats the room.
- Cold air sinks to the bottom and is re-circulated over the heating coil.

Note: The standby electric coil is automatically turned on and provides the heat when the water temperature to the heating coil drops because of consecutive cloudy days.

The following video shows the operation of an active solar heating system.

YouTube Video

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Collector’s efficiency is the ratio of **solar radiation** that is captured and transferred to the collector or heat transfer fluid.

The efficiency of a collector, depicted in Figure 8.9.2, can be expressed as

$$Collector's\ Efficiency = \frac{Useful\ energy\ delivered}{Isolation\ on\ collector} \times 100 \tag{8.9.1}$$

Typical collector efficiencies range from 50–70%.

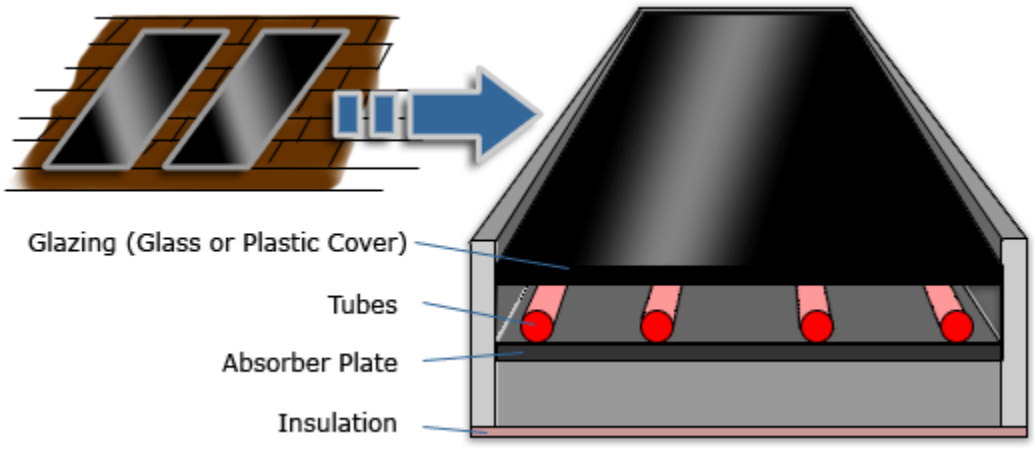


Figure 8.9.2. Solar plate collector

Passive Solar Heating System

Passive systems do not use mechanical devices such as fans, blowers, or pumps to distribute solar heat from a collector. Instead, they take advantage of natural heat flow to distribute warmth. An example of a passive system for space heating is a sunspace or solar greenhouse.

Passive systems also make use of materials with large heat capacities (stone, water, or concrete) to store and deliver heat. These are called thermal masses.

Passive systems can be categorized into three types:

- **Direct Gain** - Allows the solar energy to come in through the south-facing window panes.
- **Indirect Gain** - Allows the solar radiation to heat a wall and then the energy is slowly delivered into the interior of the house. Openings in the wall (called a Trombe Wall), as shown in the figure below, promote convective currents:
  - Cold room air enters the space between the glass panel and the wall through the bottom opening.
  - As this cold air gets heated, it rises to the top and comes in through the top opening.
- **Greenhouse Addition -** An attached sunspace and/or solar greenhouse heated by the solar energy - where some of the energy is used to grow the plants and some of it is used to heat the interior of the house.

These systems are shown in Figure 8.9.3.

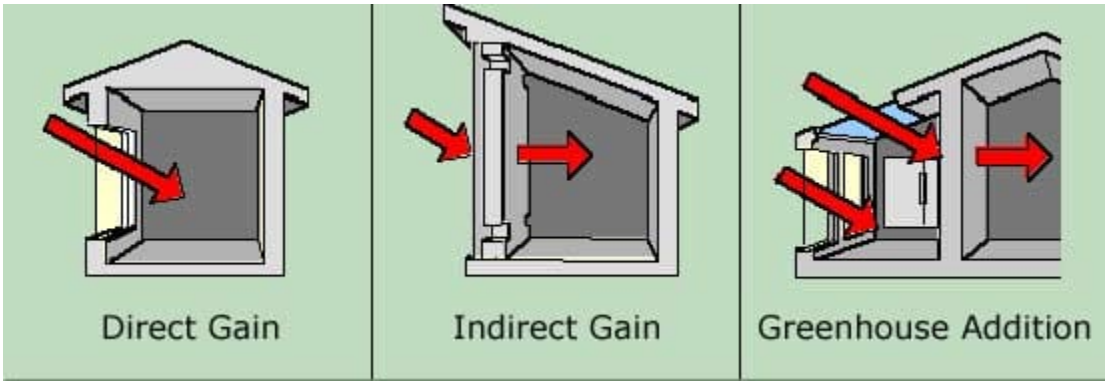


Figure 8.9.3. Illustration of the 3 types of passive systems

Costs and Benefits

It is usually most economical to design an active system to provide 40 to 80 percent of the home's heating needs. Systems providing less than 40 percent of the heat needed for a home are rarely cost-effective except when using solar air heater collectors that heat one or two rooms and require no heat storage.

A well-designed and insulated home that incorporates passive solar heating techniques will require a smaller and less costly heating system of any type, and may need very little supplemental heat other than solar.

The cost of an active solar heating system will vary. A simple window air heater collector can be made for a few hundred dollars. Commercial systems range from $30 to $80 per square foot of collector area, installed. Usually, the larger the system, the less it costs per unit of collector area. Commercially available collectors come with warranties of 10 years or more, and should easily last decades longer.

Additional information

Heating your home with an active solar energy system can significantly reduce your fuel bills in the winter. A solar heating system will also reduce the amount of air pollution and greenhouse gases.

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9: HOME COOLING

9.1: Humidity

9.2: Air Conditioning

9.3: How Air Conditioners Work

9.4: Air Conditioner Efficiency

9.5: Air Conditioner Sizing

9.6: Natural Cooling

9.7: Saving Energy

9.8: Environmental Protection

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9.1: Humidity

Air is a mixture of several gases, including nitrogen, oxygen, and water vapor.

- The total **air pressure** exerted by a volume of air in a given container on that container is the sum of the individual (partial) pressures of these gases.
- The **vapor pressure** is the individual or partial pressure of the water vapor.

The warmer the air is, the more moisture it can hold. So its moisture holding capacity changes with temperature.

A Psychometric chart, shown in Figure 9.1.1, represents the moisture content of air at various temperatures. This chart shows that as the air temperature increases, the amount of moisture that can be held in dry air also increases.

- **Dry bulb temperature:** Temperature with no moisture in the air; known as “absolute air".
- **Dew point Temperature:** Complete saturation – the maximum amount of water vapor that air can hold. Note that water vapor can carry more heat than air.

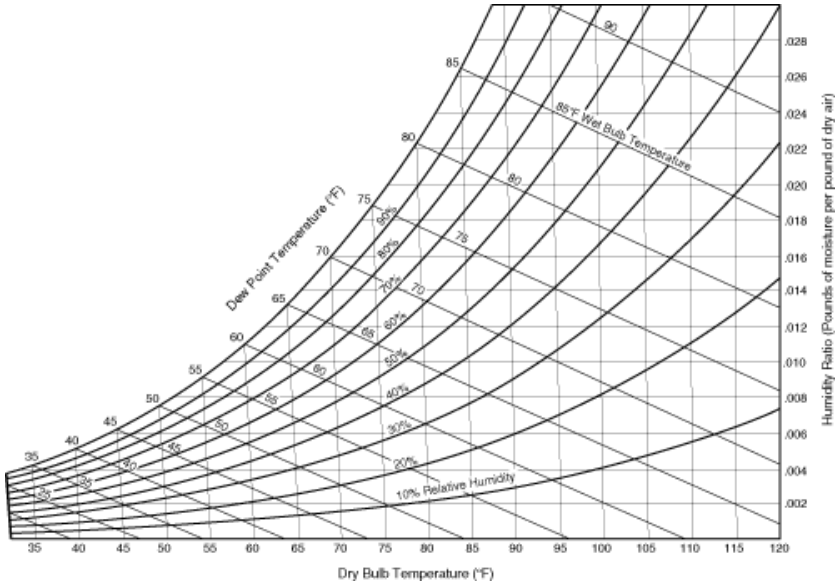


Figure 9.1.1. Psychometric chart

Credit: http://hem.dis.anl.gov/eehem/95/951108.html

As we know, varying amounts of moisture (in the gaseous or vapor form) exist in the air. **Absolute Humidity** is the actual amount of moisture that is contained in air. It is represented in the formula

$$Absolute\ Humidity = \frac{Amount\ of\ Water\ Vapor\ (lb)}{Amount\ of\ Dry\ Air\ (lb)} \tag{9.1.1}$$

Relative humidity, in contrast, is the ratio of the amount of moisture in the air to the maximum amount of moisture the air can hold at a given temperature. It is represented in the formula

$$Relative\ Humidity\ (at\ given\ temp) = \frac{Amount\ of\ Water\ Vapor\ (lb)}{Max\ Amount\ of\ Water\ Vapor\ Air\ can\ Hold} * 100 \tag{9.1.2}$$

Example 1

Calculate the relative humidity of air when the air contains 0.002 lb of moisture per pound of dry air while the maximum moisture air can hold at that temperature is 0.005 lb per lb of dry air.

Answer available at the end of this section.

Air is said to be **saturated** when the amount of water vapor in the air is the maximum possible at an existing temperature and pressure.

- Air is said to be saturated at 100% *relative* humidity when it contains the maximum amount of moisture possible at that specific temperature.
- Air holding half the maximum amount of moisture at a given temperature has a *relative* humidity of 50 percent.

When relative humidity reaches 100% or is saturated, moisture will **condense**, meaning the water vapor changes to liquid vapor.

Thus, the saturation level of air is related to the air's temperature. As air temperature increases (or becomes warmer), more water remains in a gas phase. As temperature decreases (or becomes colder), the water molecules slow down and it is more likely that they will condense onto nearby surfaces.

Dew Point is the temperature at which air reaches 100 percent relative humidity. If the air is cooled below dew point, moisture in the air condenses.

Moisture will condense on a surface whose temperature is below the dew point temperature of the air next to it. For air at a given absolute humidity, the colder the surface, the higher the relative humidity next to that surface. So the coldest surface in a room is the place where condensation will probably occur first (called the first condensing surface).

Important Point

Saturation is the maximum amount of water vapor in the air at an existing temperature and pressure. Air is said to be saturated at 100 percent relative humidity when it contains the maximum amount of moisture possible at that specific temperature.

Dew point is the temperature when air reaches 100% relative humidity.

The following video further explains humidity and condensation.

YouTube Video

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Answers

Example 1

$$Relative\ Humidity = \frac{\frac{0.002\,lb}{lb\,dry\,air}}{\frac{0.005\,lb}{lb\,of\,dry\,air}} * 100 = 40\% \tag{9.1.3}$$

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9.2: Air Conditioning

Now we will look at how air conditioning systems work. With air conditioning, the adjustment of humidity is important because we always try to cool warm air inside the room.

When the temperature of the air decreases, the maximum amount of water the air can hold also decreases. So the relative humidity always increases. This is more conspicuous when the room air is humid or already saturated. When the saturated air is cooled in an air conditioner, it precipitates or condenses. Water can be seen dripping outside from an AC.

Humidity is generally maintained at about 50 percent. Too low or high humidity is very uncomfortable.

Air conditioning (A/C) involves cooling/heating and cleaning of air, plus controlling its moisture level or humidity to provide maximum indoor comfort.

- An air conditioner transfers **heat energy** from the inside of a room, or multiple rooms in a building, to the outside.
- The air conditioner does NOT transfer **air** from the inside of a room, or multiple rooms in a building, to the outside.

More specifically, refrigerant in the system absorbs the excess heat from the inside and is pumped through a closed system of piping to an outside coil. A fan blows outside air over the hot coil, transferring heat from the refrigerant to the outdoor air. Because the heat is removed from the indoor air, the indoor area is cooled.

An example of a refrigerant system is shown in Figure 9.2.1.

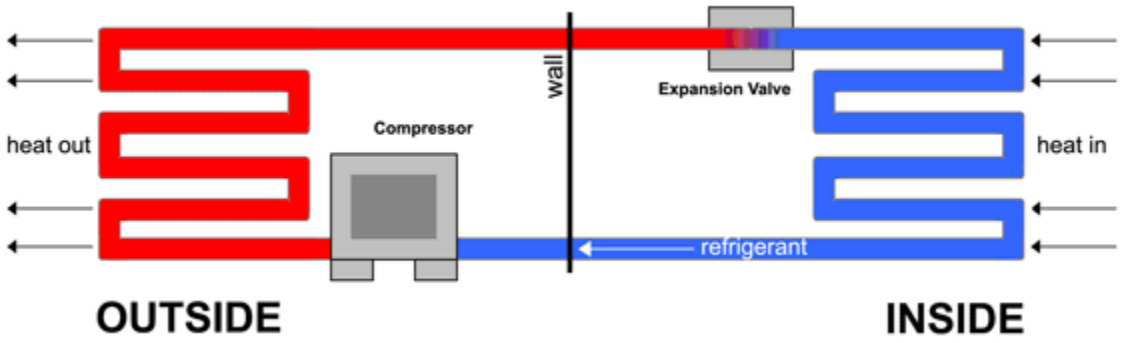


Figure 9.2.1. Refrigerant system

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9.3: How Air Conditioners Work

Contrary to what is generally assumed, outside air is not cooled inside the air conditioner and then supplied inside. Only heat energy is moved or pumped by the air conditioner from a low temperature environment (inside the building) to a high temperature environment (outside the building).

The following video shows an animation of how an air conditioner works.

YouTube Video

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9.4: Air Conditioner Efficiency

Air conditioners are rated by the number of British Thermal Units (BTU) of heat they can remove per hour. Another common rating term for air conditioning size is the "ton," which is 12,000 BTU per hour.

Each air conditioner has an energy-efficiency rating that lists how many BTUs per hour are removed or “pulled out” for each watt of power it draws.

- The efficiency rating for room conditioners is the **Energy Efficiency Ratio** (EER).
- The efficiency rating for central air conditioners, is the **Seasonal Energy Efficiency Ratio** (SEER).

These ratings are posted on an Energy Guide Label, which must be conspicuously attached to all new air conditioners. Energy Star-labeled appliances mean that they have high EER and SEER ratings.

Energy Guide Label, lists type of appliance, model #, capacity, cost of operation, etc.

Figure 9.4.1. EnergyGuide label, which lists the type of appliance, model number, capacity, cost of operation, etc.

Room Air Conditioners — EER

The Energy Efficient Ratio (EER) measures how efficiently a room air conditioner will operate at a specific outdoor temperature. The higher the EER, the more efficient the system.

The EER can be calculated using the equation

$$EER = \frac{\frac{BTUs}{hr}\, pulled\, out}{Watt} \tag{9.4.1}$$

Remember that the EER energy-efficiency rating lists how many BTUs per hour are removed or “pulled out” for each watt of power it draws. Room air conditioners generally range from 5,500 BTU per hour to 14,000 BTU per hour.

National appliance standards require room air conditioners built after January 1, 1990, to have an EER of 8.0 or greater. A room air conditioner with an EER of at least 9.0 is recommended for milder climates, whereas in hotter climates an EER over 10 is preferred.

The Association of Home Appliance Manufacturers reports that the average EER of room air conditioners rose 47 percent from 1972 to 1991. If a 1970s-vintage room air conditioner with an EER of 5 is replaced with a new one with an EER of 10, air conditioning energy costs will be cut by 50 percent.

Central Air Conditioners—SEER

Seasonal Energy Efficiency Ratio (SEER) measures how efficiently a central air conditioner will operate at a specific outdoor temperature. The higher the SEER, the more efficient the system.

The SEER can be calculated using this equation:

$$SEER = \frac{\frac{BTUs}{hr}\, pulled\, out}{Watt} \tag{9.4.2}$$

Again, the SEER energy-efficiency rating lists how many BTUs per hour are removed or “pulled out” for each watt of power it draws.

National minimum standards for central air conditioners require a SEER of 9.7 and 10.0, for single-package and split-systems, respectively. But you do not need to settle for the minimum standard—there is a wide selection of units with SEERs reaching nearly 17.

Before 1979, the SEERs of central air conditioners ranged from 4.5 to 8.0. Replacing a 1970s-era central air conditioner with a SEER of 6 with a new unit having a SEER of 12 will cut your air conditioning costs in half. Today's best air conditioners use 30% to 50% less energy to produce the same amount of cooling as air conditioners made in the mid 1970s. Even if your air conditioner is only 10 years old, you may save 20 to 40 percent of your cooling energy costs by replacing it with a newer, more efficient model.

In general, new air conditioners with higher EERs or SEERs have higher price tags. However, the higher initial cost of an energy-efficient model will be recovered several times during its lifespan. Some utility companies encourage the purchase of a more efficient air conditioner by offering incentives. Buy the most efficient air conditioner you can afford, especially if you use (or think you will use) an air conditioner frequently and/or if your electricity rates are high.

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9.5: Air Conditioner Sizing

An air conditioner's efficiency, performance, durability, and initial cost depends on matching its size to the following factors:

- How large is your home and how many windows does it have?
- How much shade is on your home's windows, walls, and roof?
- How much insulation is in your home's ceiling and walls?
- How much air leaks into your home from the outside?
- How much heat do the occupants and appliances in your home generate?

A system that is too large will cool the room or home quickly but will not provide the comfort that is needed, because the cool air reaches the thermostat quickly and the thermostat sends a signal to shut the system before the relative humidity is reduced to a comfortable level. As the cold air is distributed in the room, the thermostat realizes that the temperature is not at the set point and then turns on the air conditioner. This quick cycling of the unit (start and stop) reduces the lifespan of the equipment and increases the energy consumption. A larger air conditioner also consumes more energy.

A system that is small will have to work all the time and is not energy efficient. So the right size is very important for energy efficiency.

To determine the size air conditioner needed, follow three steps:

Step 1: Determine the square footage of the area to be cooled, by multiplying a rectangular or square room's length by its width.

Step 2: Determine the correct cooling capacity - measured in British thermal units (BTUs) per hour - using the square footage and Table 9.5.1.

Table 9.5.1. Capacity needed to cool an area based on size

Area to be cooled (ft^2)	Capacity needed (BTU/hr)
100 to 150	5,000
150 to 250	6,000
250 to 300	7,000
300 to 350	8,000
350 to 400	9,000
400 to 450	10,000
450 to 550	12,000
550 to 700	14,000
700 to 1,000	18,000
1,000 to 1,200	21,000
1,200 to 1,400	23,000
1,400 to 1,500	24,000
1,500 to 2,000	30,000
2,000 to 2,500	34,000

Step 3: Make any adjustments for the following circumstances:

- If the room is heavily shaded, reduce capacity by 10 percent.
- If the room is very sunny, increase capacity by 10 percent.

- If more than two people regularly occupy the room, add 600 BTUs for each additional person.
- If the unit is used in a kitchen, increase capacity by 4,000 BTUs.
- Consider where you install the unit. If you are mounting an air conditioner near the corner of a room, look for a unit that can send the airflow in the right direction.

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9.6: Natural Cooling

Energy Savings by Naturally Cooling Your Home

Keeping cool indoors when it is hot outdoors is a problem. The sun beating down on the homes causes indoor temperatures to rise to uncomfortable levels. Air conditioning provides some relief. But the initial costs of installing an air conditioner and the electricity costs to run it can be high. In addition, conventional air conditioners use refrigerants made of chlorine compounds, suspected contributors to the depletion of the ozone layer and global warming. But there are alternatives to air conditioning.

An alternative way to maintain a cool house or reduce air-conditioning use is natural (or passive) cooling. Passive cooling uses non-mechanical methods to maintain a comfortable indoor temperature.

Specific methods to prevent heat gain include:

- reflecting heat (i.e., sunlight) away from your house;
- blocking the heat;
- removing built-up heat
- reducing or eliminating heat-generating sources in your home.

Reflecting Heat Away

Dull, dark-colored home exteriors absorb 70 to 90 percent of the radiant energy from the sun that strikes the home's surfaces. Some of this absorbed energy is then transferred into a home by way of conduction, resulting in heat gain. In contrast, light-colored surfaces effectively reflect most of the heat away from a home.

Blocking the Heat

Two excellent methods to block heat are insulation and shading.

Insulation helps keep your home comfortable and saves money on mechanical cooling systems such as air conditioners and electric fans.

- Shading devices block the sun's rays, absorb or reflect the solar heat, and reduce indoor temperatures by as much as 20° F. Shading can be provided by trees and other vegetation or exterior or interior shades.
- Exterior shades are generally more effective than interior shades at controlling heat gain because they block sunlight before it enters windows. Exterior shading devices include awnings, louvers, shutters, rolling shutters and shades, and solar screens.
- When deciding which devices to use and where to use them, consider whether you are willing to open and close them daily or just put them up for the hottest season. You also want to know how they will affect ventilation.

Removing Built-Up Heat

Nothing feels better on a hot day than a cool breeze. Encouraging cool air to enter your house forces warm air out, keeping your house comfortably cool. However, this strategy only works when the inside temperature is higher than the outside temperature.

Natural ventilation maintains indoor temperatures close to outdoor temperatures and helps remove heat from your home. But only ventilate during the coolest parts of the day or night, and seal off your house from the hot sun and air during the hottest parts of the day.

The climate you live in determines the best ventilation strategy, some of which are listed in Table 9.6.1.

Table 9.6.1. Cooling strategies for various climates

Climate	Strategy
Cool nights, very hot days	Let night air cool the house. A well-insulated house will gain only 1° F (0.6° C) per hour if the outside temperature is 85° to 90° F (29° to 32° C). By the time the interior heats up, the outside air should be cooler and can be allowed indoors.
Daytime breezes	Open windows on the side from where the breeze is coming and on the opposite side of the house. Keep interior doors open to encourage whole-house ventilation. If your location lacks consistent breezes, create them by opening windows at the lowest and highest points in your house. This natural "thermosiphoning," or "chimney," effect can be taken a step further by adding a clerestory or a vented skylight.
Hot and humid, temperature doesn't change much between day and night	Ventilate when humidity is not excessive. Ventilating your attic greatly reduces the amount of accumulated heat, which eventually works its way into the main part of your house. Ventilated attics are about 30° F (16° C) cooler than unventilated attics. Properly sized and placed louvers and roof vents help prevent moisture buildup and overheating in your attic.

Reducing Heat-Generating Sources

Often-overlooked sources of interior heat gain are lights and household appliances, such as ovens, dishwashers, and dryers. Table 9.6.2 lists more examples.

Table 9.6.2. Reducing heat-generating sources

Heat generating light or appliance	Reducing heat
Incandescent lamps	Use only when necessary and take advantage of daylight to illuminate house. Also consider switching to fluorescent lamps, which use 75% less energy than incandescent lamps and emit 90% less heat for the same amount of light.
Kitchen appliances	Use in the morning or late evening when extra heat can be tolerated. Consider cooking on an outside grill or using the microwave oven, which does not generate as much heat and uses less energy than a gas or electric range.
Laundry appliances	Seal off laundry room and water heater from rest of room. Purchase new energy-efficient appliances that generate less heat and use less energy. Look for the Energy Guide label indicating the annual estimated cost for operating the appliance or a standardized efficiency ratio, and use this information to select the most efficient model for your needs.

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9.7: Saving Energy

Using any or all of the strategies just discussed will help keep you cool. Even if you use air conditioning, many of these strategies, particularly reflecting heat and shading, will help reduce the energy costs of running an air conditioner.

However, adopting all of these strategies may not be enough. Sometimes you need to supplement natural cooling with mechanical devices. Fans and evaporative coolers can supplement your cooling strategies and cost less to install and run than air conditioners.

Ceiling fans make you feel cooler. Their effect is equivalent to lowering the air temperature by about 4°F (2°C). Evaporative coolers use about one-fourth the energy of conventional air conditioners but are effective only in dry climates.

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9.8: Environmental Protection

If your home has Central Air Conditioning:

- **Set your thermostat at 78°F or higher**. Each degree setting below 78°F will increase your energy consumption by approximately 8 percent.
- **Use bath and kitchen fans sparingly when the air conditioner is operating.**
- **Inspect and clean both the indoor and outdoor coils.** The indoor coil in your air conditioner acts as a magnet for dust because it is constantly wetted during the cooling season. Dirt build-up on the indoor coil is the single most common cause of poor efficiency. The outdoor coil must also be checked periodically for dirt build-up, and cleaned if necessary.
- **Check the refrigerant charge**. The circulating fluid in your air conditioner is a special refrigerant gas that is put in when the system is installed. If the system is overcharged or undercharged with refrigerant, it will not work properly. You may need a service contractor to check the fluid and adjust it appropriately.
- **Reduce the cooling load by using cost-effective conservation measures**. For example, effectively shade east and west windows. When possible, delay heat-generating activities, such as dishwashing, until the evening on hot days.
- **Keep the house closed** tight during the day over most of the cooling season. Don't let in unwanted heat and humidity. If practical, ventilate at night either naturally or with fans.
- **Don’t use a dehumidifier**: Try not to use a dehumidifier at the same time your air conditioner is operating. The dehumidifier will increase the cooling load and force the air conditioner to work harder.

If your home has Room Air Conditioning:

- **Keep the unit leveled when installing, so that the inside drainage system and other mechanisms operate efficiently.** If possible, install the unit in a shaded spot on your home's north or east side. Direct sunshine on the unit's outdoor heat exchanger decreases efficiency by as much as 10%. You can plant trees and shrubs to shade the air conditioner, but do not block the airflow.
- **Don't place lamps or televisions near your air-conditioner's thermostat.** The thermostat senses heat from these appliances, which can cause the air conditioner to run longer than necessary.
- **Set your air conditioner's thermostat as high as is comfortably possible in the summer.** The less difference between the indoor and outdoor temperatures, the lower your overall cooling bill will be. And don't set your thermostat at a colder setting than normal when you turn on your air conditioner. It will not cool your home any faster and could result in excessive cooling and, therefore, unnecessary expense.
- **Set the fan speed on high, except on very humid days.** When humidity is high, set the fan speed on low for more comfort. The low speed on humid days will cool your home better and will remove more moisture from the air because of slower air movement through the cooling equipment. Consider using an interior fan in conjunction with your window air conditioner to spread the cooled air more effectively through your home without greatly increasing electricity use.
- **Ensure proper maintenance of your air conditioner to save energy**. Be sure to do the following:
  - At the start of each cooling season, inspect the seal between the air conditioner and the window frame to ensure it makes contact with the unit's metal case. Moisture can damage this seal, allowing cool air to escape from your house.
  - Check your unit's air filter once a month, and clean or replace filters as necessary. Keeping the filter clean can lower your air conditioner's energy consumption by 5% to 15%.
  - Occasionally check the unit's drain channels. Clogged drain channels prevent a unit from reducing humidity, and the resulting excess moisture may discolor walls or carpet.

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10: WINDOWS

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10.1: Windows and Heat Loss

Windows typically occupy about 15 to 20% of the surface area of the walls. Windows not only add aesthetic looks and often a very important aspect of a home, but also a very significant component of home heating and cooling costs. Windows lose more heat per square foot of area in winter and gain more heat in summer than any other surface in the home.

We already discussed in Chapter 5 that simple glass (1/8 inch) has a very low R-value (0.03). So even if the walls are well insulated to an R-value of about 13 to 19 and the windows have poor R-value, most of the heat escapes through the windows and the purpose of having a well insulated wall is lost.

It is estimated that in 1990 alone, the energy used to offset unwanted heat losses and gains through windows in residential and commercial buildings cost the United States $20 billion (one-fourth of all the energy used for space heating and cooling). However, when properly selected and installed, windows can help minimize a home's heating, cooling, and lighting costs.

Heat Loss through Windows

The following video shows how heat loss occurs through a window.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

Although energy is spent heating the air in the room, windows can make the temperatures uncomfortable. However, by making the windows efficient, a significant amount of the energy and money can be saved.

Figure 10.1.1 compares heating costs for different types of windows. The numbers are based on a typical home in Boston, MA, a relatively heating intensive place.

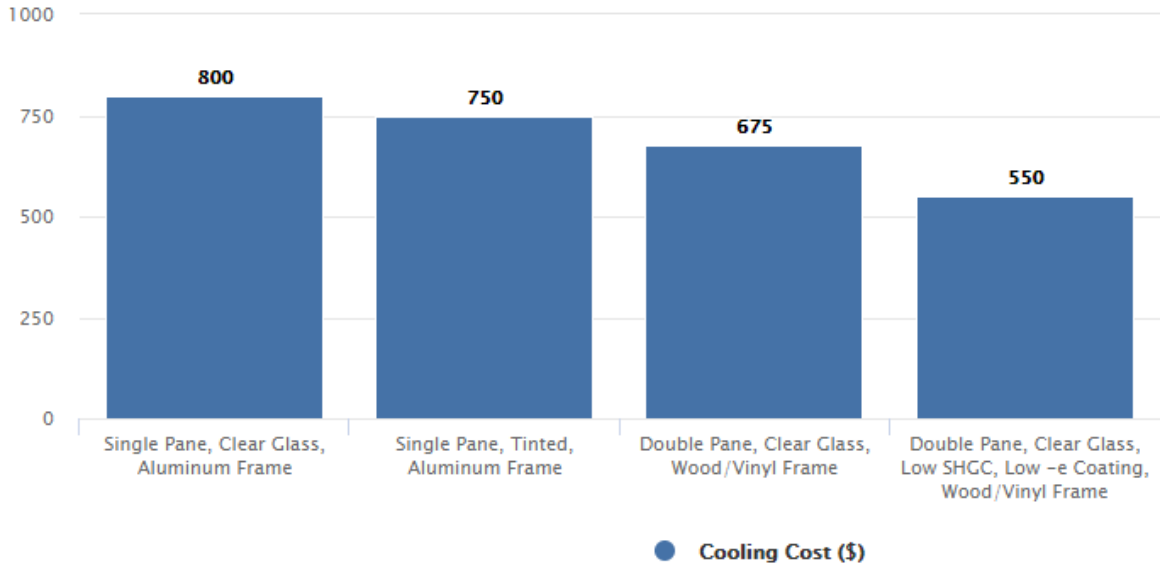


Figure 10.1.1. Heating costs for different window types

Similarly, poor windows allow the solar energy to penetrate through the windows and heat the space. The incoming solar radiation consists of infrared (IR), ultraviolet (UV), and visible waves.

The IR radiation, which is also called heat radiation, heats the space excessively and adds to the air conditioning in the summer time. Therefore, energy efficient windows are critical in summer time or even in places where the cooling requirement is high.

The following video explains the effects of solar energy on windows.

YouTube Video

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Figure 10.1.2 compares cooling costs for different types of windows. The numbers are based on a typical home in Phoenix, AZ.

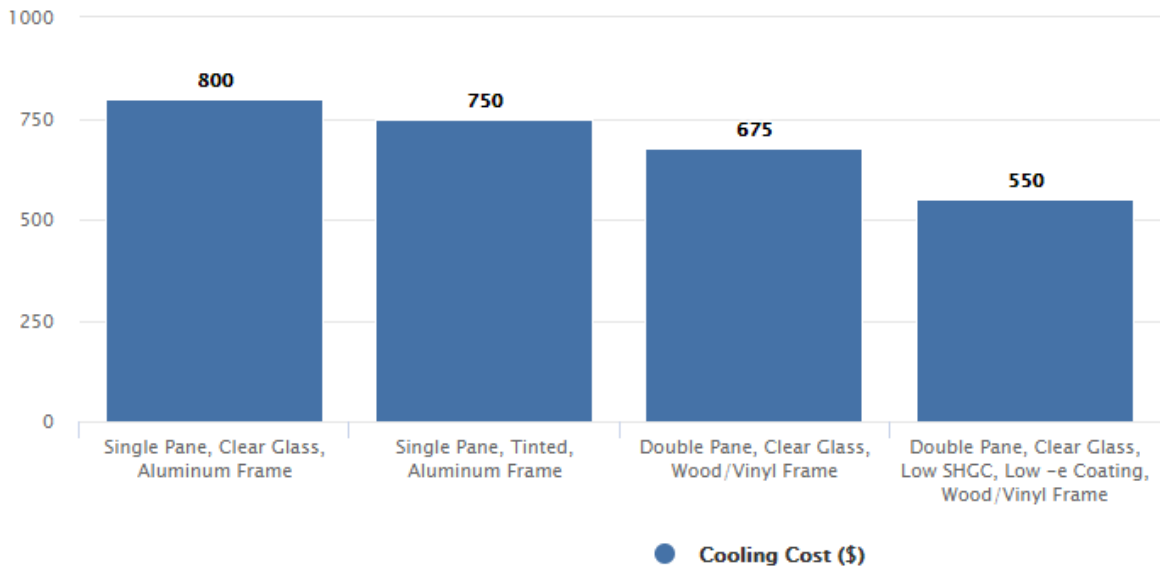


Figure 10.1.2. Cooling costs for different window types

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10.2: Factors in Window Selection (I)

The National Fenestration Rating Council (NFRC) developed an energy performance label, shown in Figure 10.2.1, that helps to determine how well a window performs the functions of helping to cool a building in the summer, warm a building in the winter, keep out wind, and resist condensation.

Figure 10.2.1. NFRC's window label

By using the information contained on the label, builders and consumers can reliably compare one product with another, and make informed decisions about the windows, doors, and skylights they buy. NFRC adopted a new energy performance label in 1998. It lists the manufacturer, describes the product, provides a source for additional information, and includes ratings for one or more energy performance characteristics.

NFRC rates all products in two standard sizes so that consumers and others can be sure they are comparing products of the same size. There are three factors that will be listed on the label with some additional information. These factors are U factor, Visible Transmittance (VT) and Solar Heat Gain Coefficient (SHGC).

U-Factor or Value

U-factor measures how well a product prevents heat from escaping. The rate of heat loss is indicated in terms of the U-factor (U-value) of a window assembly.

- U-Factor ratings generally fall between 0.20 and 1.20.
- The ratings are based on an outdoor temperature of 0°F (-18°C) and an indoor temperature of 70°F (21°C)
- Most window manufacturers label their windows with a U-value (conductance of heat, Btu/h °F ft 2).

U-values are the reciprocals of R-values (h °F ft 2/Btu).

- The lower the U-value, the less heat is lost through the window.
- The lower the U-value, the greater a window's resistance to heat flow and the better its insulating value, which is indicated by the R-value.

Thus, the U-value is the inverse of the R-value or:

$$U = \frac{1}{R} \tag{10.2.1}$$

Some manufacturers rate thermal performance using R-Value. For example, an R-factor of 4.0 is the same as a U-Factor of 0.25.

The overall, "total," or "whole window" U-Factor of any window depends on the type of glazing, frame materials and size, glazing coatings, and type of gas (air, or inert argon or krypton) between the panes. Some typical U-, and R- Factor ranges for different window assemblies are shown in Table 10.2.1.

Table 10.2.1. U- and R-factor ranges

Window assembly	U-factor	R-factor
Single glazed	0.91 to 1.11	1.1 to 0.9
Double glazed	0.43 to 0.57	2.3 to 1.7
Triple glazed	0.15 to 0.33	6.7 to 3.3

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10.3: Factors in Window Selection (II)

Solar Heat Gain Coefficient

Solar Heat Gain Coefficient (SHGC) measures how well a window blocks heat from the sunlight.

- The SHGC is the fraction of incident solar radiation admitted through a window, both directly transmitted, and absorbed and subsequently released inward.
- SHGC is expressed as a number between 0 and 1.
- The lower a window's solar heat gain coefficient, the less solar heat it transmits.

Visible Transmittance

Visible Transmittance (VT) measures how much visible light comes through a window.

- The visible transmittance is an optical property that indicates the amount of visible light transmitted.
- VT is expressed as a number between 0 and 1.
- The higher the VT, the more light is transmitted.

The following video explains more about VT.

YouTube Video

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The **light-to-solar gain ratio(LSGR)** provides a gauge of the relative efficiency of different glass types in transmitting daylight while blocking heat gains. It is determined by the ratio between VT and SHGC, i.e.,

$$LSGR = \frac{VT}{SHGC} \tag{10.3.1}$$

The higher the ratio number, the brighter the room is without adding excessive amounts of heat.

Table 10.3.1 lists typical SHG, VT, and LSG values for different types of glass according to:

- Total Window
- Center of Glass (in parentheses)

Table 10.3.1. Typical SHG, VT, and LSG values

Window and glazing types	SHG (0 to 1 scale)	VT (0 to 1 scale)	LSG (VT / SHG)
Single glazed, clear	0.79 (0.86)	0.69 (0.90)	0.87 (1.04)
Double glazed, clear	0.58 (0.76)	0.57 (0.81)	0.98 (1.07)
Double glazed, bronze	0.48 (0.62)	0.43 (0.61)	0.89 (0.98)
Double glazed, spectrally selective	0.31 (0.41)	0.51 (0.72)	1.65 (1.75)

Window and glazing types	SHG (0 to 1 scale)	VT (0 to 1 scale)	LSG (VT / SHG)
Double glazed, spectrally selective	0.26 (0.32)	0.31 (0.44)	1.19 (1.38)
Triple glazed, new low-e	0.37 (0.49)	0.48 (0.68)	1.29 (1.39)

The following two parameters are not required to be reported on NFRC label but are optional:

- **Air leakage**
  - Indicated by an air leakage rating expressed as the equivalent cubic feet of air passing through a square foot of window area (cfm/ft^2).
  - Heat loss and gain occur by infiltration through cracks in the window assembly by convection.
  - The lower the AL, the less air will pass through cracks in the window assembly.
- **Condensation resistance**
  - Measures the ability of a product to resist the formation of condensation on the interior surface of that product.
  - The higher the CR rating, the better that product is at resisting condensation formation.
  - While this rating cannot predict condensation, it can provide a credible method of comparing the potential of various products for condensation formation.
  - CR is expressed as a number between 0 and 100.

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10.4: Shading Devices

Before innovations in glass, films, and coatings in the past decade, a typical residential window with one or two layers of glazing allowed roughly 75 to 85% of the solar energy to enter a building, which has a negative impact on summertime comfort and cooling bills, especially in hot climates.

External Window Shading

External window shading devices such as awnings, roof overhangs, shutters, and solar screens, and internal shading devices such as curtains and blinds, can control the entry of solar heat. Although external window shading devices are about 50 percent more effective than internal devices at blocking solar heat, they do have some disadvantages.

Internal Shading Devices

Table 10.4.1 shows the percentages of the radiant energy that different types of internal shading devices transmit, reflect, or absorb.

Table 10.4.1. Percents of radiant energy

Shade type	Transmitted energy (%)	Reflected energy (%)	Absorbed energy (%)
Roller shades	25	15 to 80	20 to 65
Vertical blinds	0	23	77
Venetian blinds	5	40 to 60	35 to 55

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10.5: Advances in Window Technologies (I)

Research in the recent past led to the development of **low-emissivity** or "**low-e,**" glass and films that control heat gain and loss, reduce glare, minimize fabric fading, provide privacy, and occasionally provide added security in wind, seismic, and other high-hazard zones. New construction and window replacement applications commonly use glazing with these coatings.

Some low-e coatings and solar control films reduce solar heat gain without impairing visible light transmission excessively. These include tinted glass and spectrally selective coatings, which transmit visible light while reflecting the infrared portion of sunlight.

Many spectrally selective coatings or glazings also have some low-e properties as well.

Types of Glazing

Modern window glazing falls into three categories:

- Chemically or physically altered glass
- Coated glass or films
- Multiple-layered assemblies with or without either of the first two items.

Chemically or Physically Altered Glass

Tinting – One of the oldest of all the modern window technologies. Under favorable conditions, tinting can reduce solar heat gain during the cooling season by 25 percent to 55 percent. Tinted glass is made by alteration of the chemical properties of the glass. Both glass and plastic laminate may be tinted.

The tints absorb a portion of the sunlight and solar heat before it can pass all the way through the window to the room. Tinted glazings reduce the latter by 25 to 55 percent. "Heat absorbing" tinted glass maximizes its absorption across some, or all, of the solar spectrum. Unfortunately, the absorbed energy often transfers by radiation and convection to the inside.

Coated Glass or Films

Spectrally Selective Coatings

Spectrally selective coatings or tints reduce infrared light (heat) transmission while allowing relatively more visible light to pass through (compared to bronze- or gray-tinted glass).

For buildings that use daylight for lighting, a spectrally selective window is a good choice. Spectrally selective glass also absorbs much of the ultraviolet (UV) portion of the solar spectrum.

In a multi-paned window, they function best as the outermost sheet of glazing. Thermal performance is increased when combined with a low-e coating. Spectrally selective coatings often have a light blue or green tint.

Low-e Coatings

Low-e and reflective coatings usually consist of a layer of metal a few molecules thick. The thickness and reflectivity of the metal layer (Low-E coating) and the location of the glass it is attached to directly affects the amount of solar heat gain in the room.

Most window manufacturers now use one or more layers of low-e coatings in their product lines. Any low-e coating is roughly equivalent to adding an additional pane of glass to a window.

Low-e coatings reduce IR heat transfer by 5 to 10 times. The lower the emissivity value (a measure of the amount of heat transmission through the glazing or coating), the better the material reduces the heat transfer from the inside to the outside.

Most low-e coatings also slightly reduce the amount of visible light transmitted through the glazing relative to clear glass. Table 10.5.1 gives the emissivity values for different types of glass.

Table 10.5.1. Emissivity values for various low-e coatings

Type of coating	Emissivity
Clear glass, uncoated	0.84
Glass with single hard coat low-e	0.15
Glass with single soft coat low-e	0.10

There are three types of low-e coating available: Soft, hard coatings, and Heat Mirror.

- *Soft coat* is applied to the surface of a glass at lower temperatures. It's not durable enough to be exposed to the elements, so it's only used on the inner surfaces of windows which are not exposed to the elements.
- *Hard coat* is produced by fusing metallic oxide to the hot surface of glass during manufacture and is found primarily on storm windows and removable energy panels. Hard coat is applied on the glass surface at a high temperature. One layer is about 1/10,000 the diameter of a human hair. Hard coat is not quite as energy efficient as soft coat, but is tough enough to be used on surfaces exposed to the elements. Both types of low-e coatings (within insulated glazing assemblies) typically last for 10 to 50 years.
- *Heat Mirror* is a proprietary product that's applied to a thin polyester sheet suspended between the two panes of dual pane window. The coating reflects radiant heat while the sheet decreases heat loss by splitting the air space in two.

Additional information

The only spectrally selective coatings now available are modified soft coat low-e coatings. The selective properties of the coatings are determined by modifying the coating's thickness and number of layers. A spectrally selective tinted glazing with a pyrolytic hard coat serves a similar purpose. These spectrally selective hard coats are currently under development.

Aftermarket Films - "Aftermarket" films are available for application on existing windows. They are relatively easy to apply on glazing up to 36 square inches. They are often applied to the glass with a water-soluble adhesive. To reduce the possibility of bubbles and wrinkles on large windows, have the film installed professionally. Most films should be applied to the inside surface of the glass since they can be damaged easily by weather.

If you plan to install the film yourself, be careful to select the appropriate film for your needs, and understand all directions before beginning. Plastic films generally last about 8 to 10 years before they start looking worn.

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10.6: Advances in Window Technologies (II)

Types of Glazing Continued: Multiple Layered Assemblies

The third type of modern window glazing is multiple-layered assemblies with or without either of the first two items.

Gas Fills

Filling the space with a less conductive, more viscous, or slow-moving gas minimizes the convection currents within the space, conduction through the gas is reduced, and the overall transfer of heat between the inside and outside is reduced. This is illustrated in Figure 10.6.1.

Illustration of a gas-filled window. Refer to text above.

Figure 10.6.1. Gas-filled windows

Argon and krypton gases with measurable improvement in thermal performance have been used. A mixture of krypton and argon gases is also used as a compromise between thermal performance and cost. Table 10.6.1 compares the two gases.

Table 10.6.1. Comparison of argon and krypton gases

	Argon	Krypton
Cost	Inexpensive	More expensive
Miscellaneous	Nontoxic, nonreactive, clear, odorless	

Xenon gas may also be used and provides R-20 per inch.

Layers of Glass and Air Spaces

Layers of Glass and Air Spaces may be either single-pane, double-pane, triple-pane or multi-pane.

- *Standard single-pane glass* has very little insulating value (approximately R-1). It provides only a thin barrier to the outside and can account for considerable heat loss and gain. Traditionally, the approach to improve a window's energy efficiency has been to increase the number of glass panes in the unit, because multiple layers of glass increase the window's ability to resist heat flow.
- *Double-pane or triple-pane* windows have insulating air-filled or gas-filled spaces between each pane. Each layer of glass and the air spaces resist heat flow. The width of the air spaces between the panes is important, because air spaces that are too wide (more than 5/8 inch) or too narrow (less than 1/2 inch) have lower R-values (i.e., they allow too much heat transfer).
- Advanced, multi-pane windows are now manufactured with inert gases (argon or krypton) in the spaces between the panes because these gases transfer less heat than does air. Multi-pane windows are considerably more expensive than single-pane windows and limit framing options because of their increased weight.

Note

During the late 1980s, manufacturers combined the technology of multiple glazing, low-E coatings, and gas-filling to create "super windows." These windows are highly insulated with R-values that can go as high as R-9.

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10.7: Advances in Window Technologies (III)

Frame and Spacer Materials

Window frames are available in a variety of materials including aluminum, wood, vinyl, and fiberglass. Frames may be primarily composed of one material, or they may be a combination of different materials such as wood clad with vinyl or aluminum-clad wood. Each frame material has its advantages and disadvantages, as shown in Table 10.7.1.

Table 10.7.1. Comparison of various window frame materials

	Advantages	Disadvantages	How to improve
Aluminum	Ideal for strength and customized window design	Conduct heat and therefore lose heat faster and are prone to moisture condensation.	Anodizing or coating will prevent corrosion and electro-galvanic deterioration of aluminum frames; thermal resistance can be improved by placing continuous insulating plastic strips between the interior and exterior frame.
Wood	Have higher R-values, are not affected by temperature extremes, and do not generally promote moisture condensation.	Require considerable maintenance in the form of periodic painting or staining. If not properly protected, wood frames can swell, which leads to rot, warping, and sticking.	
Vinyl (typically polyvinyl chloride, i.e., PVC)	Available in a wide range of styles and shapes, have moderate to high R-values, are easily customized, are competitively priced, and require very low maintenance.	Do not possess the inherent strength of metal or wood	Larger-sized windows are often strengthened with aluminum or steel reinforcing bars.
Fiberglass	Some of the highest R-values; excellent for insulating; will not warp, shrink, swell, rot, or corrode.	Relatively new and are not yet widely available. Unprotected fiberglass does not hold up to the weather and therefore is always painted.	

Spacers are used to separate multiple panes of glass within the windows. Although metal (usually aluminum) spacers are commonly installed to separate glass in multi-pane windows, they conduct heat.

During cold weather, the thermal resistance around the edge of a window is lower than that in the center; thus, heat can escape, and condensation can occur along the edges.

Figure 10.7.1 shows a window with spacers.

Figure 10.7.1. Window with spacers

Problems with Spacers

The following have been done to alleviate the problems associated with spacers:

- One manufacturer has developed a multi-pane window using a 1/8-inch-wide (0.32 centimeters-wide) PVC foam separator placed along the edges of the frame. Like other multi-pane windows, these use metal spacers for support, but because the

foam separator is secured on top of the spacer between the panes, heat loss and condensation are reduced.
- Several window manufacturers now sandwich foam separators, nylon spacers, and insulation materials such as polystyrene and rockwool between the glasses inside their windows.
- A new type of spacer product called warm-edge technology has evolved in the industry to overcome the thermal inefficiency of conventional aluminum spacers. Warm-edge refers to the type of spacer material used to separate the panes of glass (or glazing) in an insulated window unit. If the material conducts less heat or cold than a conventional aluminum spacer at the edge of the glass, it is said to be "warm-edge." Most of these newer spacers are less conductive and outperform pure aluminum. But still they all contain some kind of metal. And metal is highly conductive.
- Available in the market is a NO-metal Super Spacer, which uses no metal and is made up of 100 percent polymer structural foam. Therefore, it is believed to improve the R-Value of the whole window and reduce moisture condensation problems.

Selecting Main Parameters of Windows

General guidelines for selecting the main parameters of windows based on the climate are provided in Table 10.7.2.

Table 10.7.2. Recommended minimum values for window parameters

	Colder climate	Moderate climate	Warm climate
U-factor	<0.33	0.33	0.33
Visual transmittance	50%	>50%	>60%
SHGC	0.4 to 0.55	>0.55	<0.4
UV-protection	>75%	75%	75%
Edge spacers	Super spacers	Warm edge spacers	Warm edge spacers
Frame	Non-conductive	Non-conductive	Non-conductive
Air leakage	<0.3 cfm/ft^2	<0.3 cfm/ft^2	<0.3 cfm/ft^2

Improvement in Window Performance

Figure 10.7.2 shows the improvement in window performance (R-value) with advanced window glazing. It can be seen from the figure that the super windows are losing less heat and are even making progress to gain heat instead of losing heat because of solar heat gains.

Graph showing window performance improvement 1970-2006. Described in text above.

Figure 10.7.2. Window glazing and performance

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10.8: Smart Windows

Smart windows use a new technology called **suspended particle devices (SPDs)**. They are small, light-absorbing microscopic particles or light valves. In smart windows, millions of the SPDs are placed between two panes of glass that are coated with conductive material.

- When the smart windows are turned "on," electricity from the control switch travels through the conductive coating and causes the SPDs to line up and allow the passage of light.
- When the smart windows are turned "off," no electricity travels through the conductive coating, so the particles float freely between the glass, causing it to appear darkened or tinted.

A similar technology using electrochromics is also being developed to improve windows.

The video below shows how the SPDs react.

YouTube Video

This interactive element is not available in this format. Visit the link or scan the QR code to access it online.

View this YouTube Video online

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10.9: Calculating Heat Loss of Windows

As you may recall from Chapter 7, heat loss is calculated using the formula

$$Heat\ Loss = \frac{Area * HDD * 24}{R - value} \tag{10.9.1}$$

Using equation 10.9.1, you can calculate the heat loss for windows.

Example 1

A house in State College, PA has 380 ft ^{2} of windows (R-value = 1.1), 2750 ft ^{2} of walls and 1920 ft ^{2} of roof (R = 30). The composite R-value of the walls is 19. Calculate the heating requirement for the house for the heating season. What is the percentage of heat that is lost through the windows? Let HDD be 6000 °F days.

Answer available at the end of this section.

Example 2

Windows in the house described in Example 1 are upgraded at a cost of $1,550. The upgraded windows have an R-value of 4.0.

(a) What is the percent savings in the energy and the heating bill if the energy cost is $11.15/MMBTUs?

(b) What is the payback period for this modification?

Answer available at the end of this section.

Table 10.9.1 shows the cost effectiveness of replacing old windows with new and improved windows. The costs are calculated using a computer program called RESFEN developed by US Department of Energy.

Table 10.9.1. Cost effectiveness of using improved windows

Performance	Base Model	Recommended Level	Best Available
Window description	Double-paned, clear glass, aluminum frame	Double-paned, low-e coating, wood or vinyl frame	Triple-paned, tinted, two spectrally selective low-e coatings, krypton-filled, wood or vinyl frame
SHGC[a]	0.61	0.55	0.20
U-factor[b]	0.87	0.40	0.15
Annual heating energy use	547 therms	429 therms	426 therms
Annual cooling energy use	1,134 kWh	1,103 kWh	588 kWh
Annual energy cost	$290	$240	$210
Lifetime energy cost	$4,700	$3,900	$3,400
Lifetime energy cost savings		$800	$1,300

[a] SHGC, or Solar Heat Gain Coefficient, is a measure of the solar radiation admitted through a window. SHGC ranges between 0 and 1; the lower the number, the lower the transmission of solar heat. SHGC has replaced shading coefficient (SC) as the standard indicator of a window's shading ability. SHGC is approximately equal to the SC multiplied by 0.87.

[b] U-factor is a measure of the rate of heat flow through a window. The U-factor is the inverse of the R-value, or resistance, the common measure of insulation.

[c] Lifetime energy cost savings is the sum of the discounted value of annual energy cost savings, based on average usage and an assumed window life of 25 years. Future energy price trends and a discount rate of 3.4 percent are based on Federal guidelines (effective from April 2000 to March 2001). Assumed electricity price: $0.06/kWh, the Federal average electricity price in the U.S.Assumed gas price: $0.40/therm, the Federal average gas price in the U.S.

Cost-Effectiveness Assumptions: The model shown above is the result of a simulation using a residential windows modeling program called RESFEN. Calculations are based on a prototype house: 1,540 ft^2, two stories, a standard efficiency gas furnace and central air conditioner, and window area covering 15 percent of the exterior wall surface area.

Answers

Example 1

Heat loss through the windows is

$$Heat\ Loss = \frac{380 * 6000 * 24}{1.1} = 49,745,455\ BTUs = 49.74\ MMBTUs$$

Heat loss through the walls is

$$Heat\ Loss = \frac{2750 * 6000 * 24}{19} = 20,842,105\ BTUs$$

Heat loss through the roof is

$$Heat\ Loss = \frac{1920 * 6000 * 24}{30} = 9,216,000\ BTUs$$

The total heat loss is then the sum of the heat losses, which is 79,803,560 BTUs = 79.80 MMBTUs.

The percentage of heat loss through the windows is

$$\%\ Heat\ Loss = \frac{49.74}{79.80} * 100 = 62.3\%$$

Example 2

Part (a):

The new heat loss for the same window size with the new R-value is

$$New\ Heat\ Loss = \frac{380 * 6000 * 24}{4.0} = 13,680,000\ BTUs = 13.68\ MMBTUs$$

The annual energy savings is

$$Annual\ Savings = 49.74 - 13.68 = 36.06\ MMBTUs$$

The percent savings is

$$\%\ Savings = \frac{36.06}{79.84} * 100 = 45.1\%$$

Part (b):

The old heating bill is

$$Old\ Bill = 79.80\ MMBTUs * \frac{\$11.15}{MMBTU} = \$889.90$$

The new heating bill is

$$New\ Bill = 43.74\ MMBTUs * \frac{\$11.15}{MMBTU} = \$487.73$$

The monetary savings is thus

$$889.90 - 487.73 = \$402.06\ per\ year$$

The payback period is

$$Payback\ Period = \frac{Additional\ Investment}{Annual\ Savings} = \frac{1550}{402.06} = 3.85\ years$$

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GLOSSARY

S

Sample Word 1 | Sample Definition 1

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