Chapter 7

Sustainable Population and Use of Energy

The discovery of vast amounts of concentrated energy in the form of fossil fuels and other factors such as medical discoveries and use of the scientific method of thinking have resulted in a dramatic increase in human population. In the last 100 years the earth's population has risen from 1.6 billion to 7 billion. This dramatic increase in population will not continue for another 100 years. It might level out or it might change dramatically in the opposite direction. In this chapter we consider options for transitioning into a pattern of energy use and population size that can be sustained.

Why Do I Need to Know This?

If you are a young person, you might expect to live another sixty to eighty years, perhaps even longer if medical advances keep extending life expectancy. If present trends could continue, the energy, air, land, and water available in the later part of your life would have to be shared with an additional four or five billion people. That probably wouldn't happen peacefully. To achieve transition to a stable and sustainable future without major wars and widespread starvation, each of us must do our part and make important decisions in the near future. To make the best decisions possible, you need to prepare yourself by learning about the options because they all have significant limitations.

1 Science behind Sustainability

Learning Objectives

1. Identify the characteristics of isolated, closed, and open systems and identify an example of each. [7.1.1]
2. Identify the characteristics of the first and second laws of thermodynamics and how they apply to perpetual motion machines. [7.1.2]
3. Identify the steps of the scientific method, the difference between a hypothesis and a theory and the difference between inductive and deductive reasoning. [7.1.3]
4. Identify the inputs, outputs, and stored resources of the Earth as a system. [7.1.4]
5. Identify examples of linear and exponential growth. [7.1.5]
6. Identify the type of chart used to show exponential growth as a straight line and make predictions from it. [7.1.6]
7. Identify characteristic growth charts for organisms in open and closed systems. [7.1.7]

The earth and its inhabitants form a complicated ecosystem that is difficult to understand and predict.

Fortunately, scientists and mathematicians have developed tools that make it easier. Physicists use a technique that ignores the complexity of the internal workings of a system and just consider how it interacts with its surroundings and mathematicians have a way to turn charts with dramatic curves into simple straight lines that can be easily extended to predict the future.

Systems Theory

One way to look at a complicated situation is to mentally draw a dotted line around it and examine what goes in and what comes out. If the dotted line represents a boundary that is a barrier which does not allow anything to cross, it is an isolated system, as shown in Figure 7.1. For example, if a coal mine collapses and traps the miners deep underground, they might be cut off from fresh air, communication, heat, drinking water or a way to dispose of their waste products.

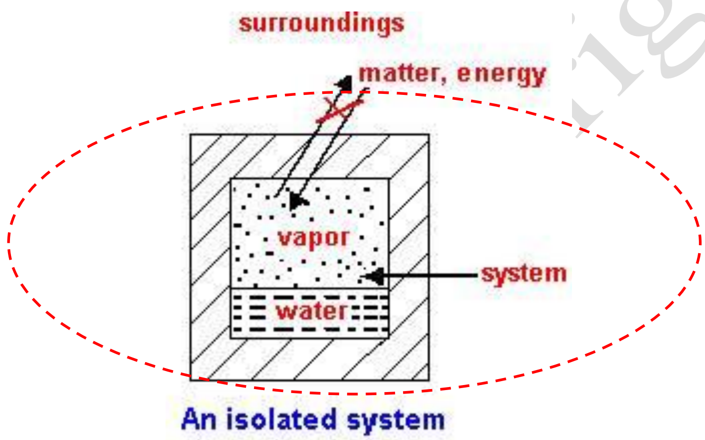


Figure 7.1.An isolated system does not allow matter or energy to cross the boundary

If the barrier allows energy to cross but not matter, it is a closed system, as shown in Figure 7.2.

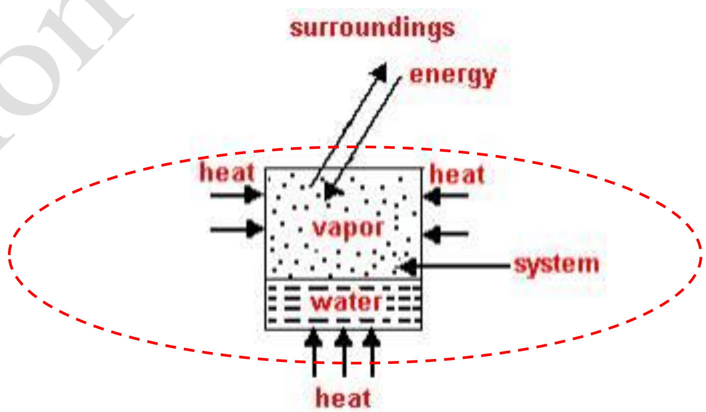


Figure 7.2. A closed system allows energy to come and go but not matter

If the miners in the previous example could still communicate or still had electricity, they would be in a closed system.

Most systems have boundaries that allow matter and energy into and out of the system. These are open systems as shown in Figure 7.3.

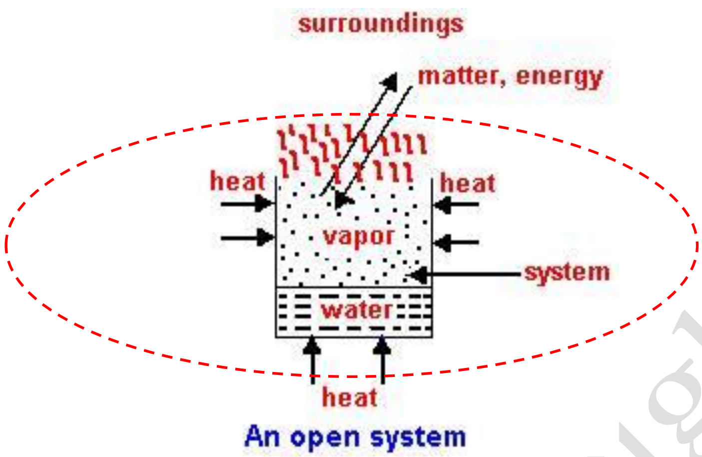


Figure 7.3. An open system allows energy and matter to come and go

If we keep careful accounts of the energy and matter that cross the boundary in both directions and compare them, we can estimate what change has taken place in the amount of matter or energy that is stored inside the system within our dotted line. For example, if we mentally draw a dotted line around a person and weigh the amount of food, water, and air they take in and the amount of gaseous, solid, and liquid waste they excrete, we should be able to estimate how much the person's weight changed if the total weight of the outputs was different than the inputs.

Systems behave according to certain rules that have been tested repeatedly, which are called Laws of Thermodynamics. The First Law of Thermodynamics states that energy cannot be created or destroyed but it may change form. If someone suggests that they have a device that will produce more energy than it takes in, a scientist will assume that the device must have some energy stored inside that will be consumed, after which it will stop. Devices that are supposed to keep moving and producing useful energy without any apparent energy input or which would produce more energy than it takes in are called perpetual motion machines of the first type. In simple terms, *You can't get something for nothing!*

The Second Law of Thermodynamics is best defined using mathematics but it can be understood using simple analogies. The second law has to do with the concentration of energy. One way to think of it is that the concentration of energy always becomes less concentrated with time in an isolated system. Think of a windup clock. If someone twists the mechanism to store energy in its spring and starts the clock, it will use that concentrated energy to move the hands of the clock until its concentrated energy is used up. Its energy is spread out in the room as slightly faster motion of the other molecules in the room. Consider an hour glass. If someone adds energy to the system by turning it over so the sand is in the upper half, that concentrated energy will slowly dissipate when the sand falls to the bottom half. Concentrated energy like the energy in the spring or the energy in the sand can move other objects and do useful work. The ability of concentrated energy to do work is called is quality. The quality of the energy goes down with time. We know that wind-up clocks run down, sand flows downward in an hour glass, water runs downhill, and hot objects cool down. These are all examples of the second law of thermodynamics that can be remembered by the phrase; *Energy becomes less concentrated with time.*

Apparent exceptions are explained by expanding the borders chosen for the system. The earth is full of trees, people, and other concentrations of energy like hurricanes because the earth's boundaries allow energy to enter from the sun. These concentrations are temporary and are part of a larger system (the solar system) where the main source of energy—the sun—is slowly dispersing. The solar energy arriving from the sun is higher quality than the infrared energy leaving the earth at night.

It is important to know both laws when considering new energy sources. For example, if you have a large river moving slowly it might have the same total energy as a small stream falling hundreds of feet. However, the water in the small stream has higher quality energy that can do useful work. It can be diverted to turn a turbine and generate electricity. The large river has low quality energy. If you place the same turbine in the river, and connect it to a generator, the water just flows slowly past the blades without enough force to move them. If the proposed source of energy moves slowly, falls a short distance, or is spread out, it has low quality and will be difficult to use.

The Scientific Method

One of the great developments in human history is the scientific method. It provides a systematic way to explore, test, and refine what we know about the physical world and then utilize that knowledge to discover new, unsuspected truths. It relies on rules of logic that were developed by the Greeks and incorporates experimental evidence. To use the scientific method, one examines a physical process or event and then one proposes a hypothesis—a tentative explanation of an observation. A well-designed hypothesis must be one that can be confirmed or disproven by performing an experiment. If numerous experiments and logical analysis support the hypothesis, it can be used to develop a theory. A theory is a well-established principle that can explain some aspect of the physical world and can often be used to predict the existence of previously unknown facts. (Cherry 2011) This ability of a theory to lead researchers toward discovery of new and previously unsuspected facts is a major accomplishment of the scientific method. For example, the theory of gravity explains how planets and the sun attract each other. By observing the motion of Uranus, astronomers found that some of its motions could not be explained by attraction to the known planets. They were able to calculate where to look for a previously unknown planet and found Pluto. (EarthSky 2010)

The scientific method consists of a sequence of steps:

- Observe a physical phenomenon and take measurements; look for patterns
- Make a guess, called a hypothesis that can be measured that explains the data
- Create an experiment that can confirm or disprove the hypothesis
- Examine the result of the experiment and draw a conclusion
- Report the findings

Scientists do not believe a theory the way that a religion has beliefs. If a theory has worked well for many years and has proven useful for discovering new relationships, scientists have a high degree of confidence that the theory is correct but they are willing to revise it if necessary. New evidence might come along that would require the theory to be revised. Scientists were comfortable with the theory that mass is neither created or destroyed. When radioactivity elements like Radium were discovered, the source of energy of these particles was a mystery. Eventually, Albert Einstein proposed an alteration to the basic theory of the conservation of matter. He showed that energy is conserved and that matter is just a concentrated form of energy. In some situations matter can be converted into energy which explained where the radioactive elements got the energy to emit alpha, beta, and gamma radiation. The theory was revised from conservation of matter to conservation of energy.

Starting with data and attempting to determine an underlying pattern or general principles is called inductive reasoning. Starting with an idea that is believed to be true and then using that belief to explain observed facts is called deductive reasoning.

A famous example of the early days of the scientific method involved a radical thinker named Galileo Galilei during a period of European history known today as the Renaissance. In the 1500's in Europe, colleges run by the Catholic Church taught that heavy objects fall faster than lighter objects in proportion to their weight. For example a cannon ball that weighs ten times as much as a musket ball would fall ten times faster. Because the Roman Catholic Church had adopted many such statements from the Greeks about science as part of their teachings, people were expected to simply take their word for it, particularly because the church claimed to be infallible—without error. Instead, Galileo challenged this belief and disproved it using two methods. First, he disproved it logically and then, according to one of his students, he disproved it experimentally by dropping two balls of different weight from the tower of Pisa which as conveniently tilted, as shown in Figure 7.4. The two balls fell at almost the same speed.

Figure 7.4.Tower from which Galileo tested his hypothesis about falling objects

Because this was a simple experiment that anyone could do and proved that the church was mistaken, people began to question traditional assumptions about the physical world including the causes of diseases and crop failures and began using logic and the scientific method to discover cures for diseases in humans and plants instead of assuming that disease was the result of sin or offending the gods. The results were increased food supply and lower death rates.

The Earth as a System

The earth moves through space around the sun and the sun emits electromagnetic waves that reach the earth. Some of these electromagnetic waves are visible to humans and some are too long (infrared) or too short (ultraviolet) to be seen by humans. Part of the atmosphere of the earth is clear and part of it is filled with clouds, as shown in Figure 7.5.

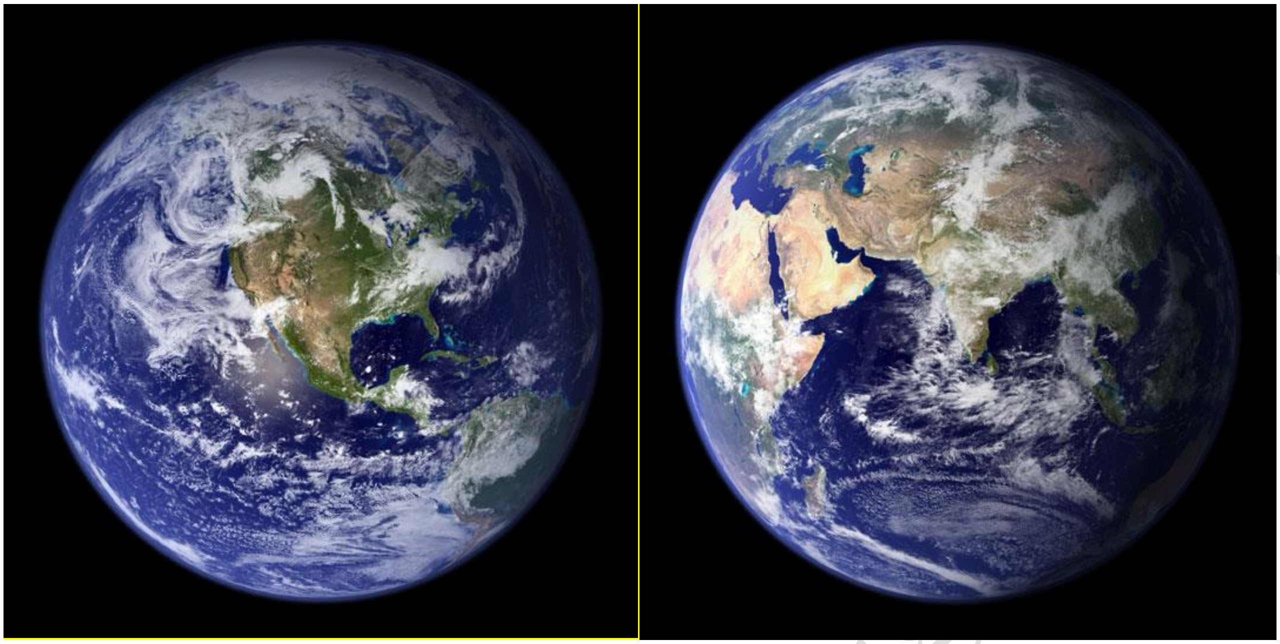


Figure 7.5. Light reaches the surface or reflects from clouds

Some of this light reaches the surface of the earth where its energy is absorbed by the land, plants, and oceans. Some of it is reflected back into space from the clouds. The amount of cloudiness affects how much of the sun's energy reaches the surface. As the earth turns, the land and oceans that were exposed to sunlight face away from the sun. Some of the heat energy of the warm land and oceans is radiated into space as infrared light. The earth is not an isolated system because energy from the sun enters as electromagnetic waves of many different lengths and then energy is emitted into space on the side away from the sun as infrared light.

The sun also emits charged particles such as protons which are called the solar wind. When these protons reach the earth they are deflected by the earth's magnetic field toward the north or south poles. When they strike the gasses in the atmosphere the interaction cause the gasses to emit light. When the sun is especially active and produces stronger than normal solar wind, the lights are much brighter and can be seen further south. They are called the Northern or Southern lights and appear as moving curtains of color, as shown in Figure 7.6.

Figure 7.6. Northern lights

The earth is also struck by meteors that are pieces of rock or metal that usually vaporize in the atmosphere but sometimes reach the ground where they might leave a crater such as the one shown in Figure 7.7.

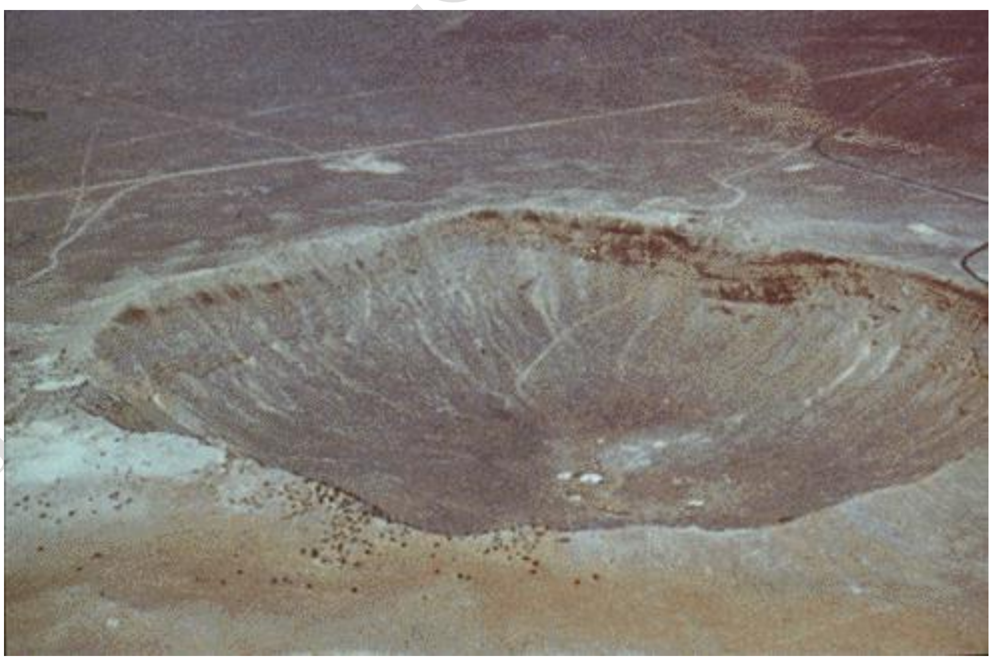


Figure 7.7. Barringer crater in Arizona

Very little mass leaves the earth. Hydrogen gas can make its way to the upper atmosphere and the fastest molecules can escape but the earth's gravity holds almost everything else too strongly to escape. The earth is an open system but the amount of matter that enters the system is relatively small.

The earth has been receiving energy from the sun since it formed about 4.5 billion years ago. Some of that sunlight has been stored as fossil fuels in the form of natural gas, oil, and coal.

Exponential Growth

If an organism is capable of reproducing itself by dividing into two new organisms, the number of individuals could double each generation if none of them die. For example, the number of individuals after three divisions would be eight (1x2x2x2). Another way to write this is 2^3 where the superscript 3 is the exponent which indicates the number of times the base (2) is multiplied by itself. This type of growth is called exponential growth. Linear growth increases by addition. An example of linear growth would be 2, 4, 6, 8, 10, 12. Figure 7.8 shows a table of data where the value in the second column doubles each generation and next to it is a line chart. The values for the 19^{th} and 20^{th} generations are not shown. It would be difficult to extend the curved line of the chart to estimate the populations in the next two generations.

Exponential Growth

Generation	*Linear*	*Exponential*
0		1
1	2	2
2	4	4
3	6	8
4	8	16
5	10	32
6	12	64
7	14	128
8	16	256
9	18	512
10	20	1,024
11	22	2,048
12	24	4,096
13	26	8,192
14	28	16,384
15	30	32,768
16	32	65,536
17	34	131,072
18	36	262,144
19		
20		

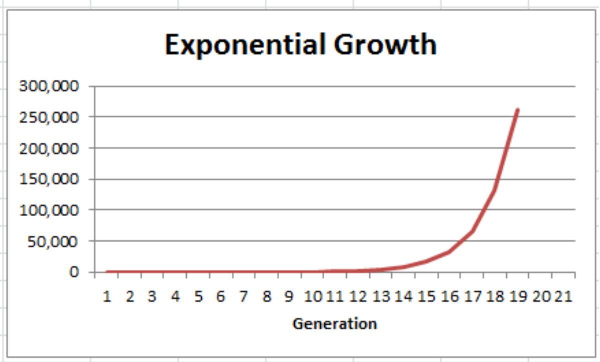
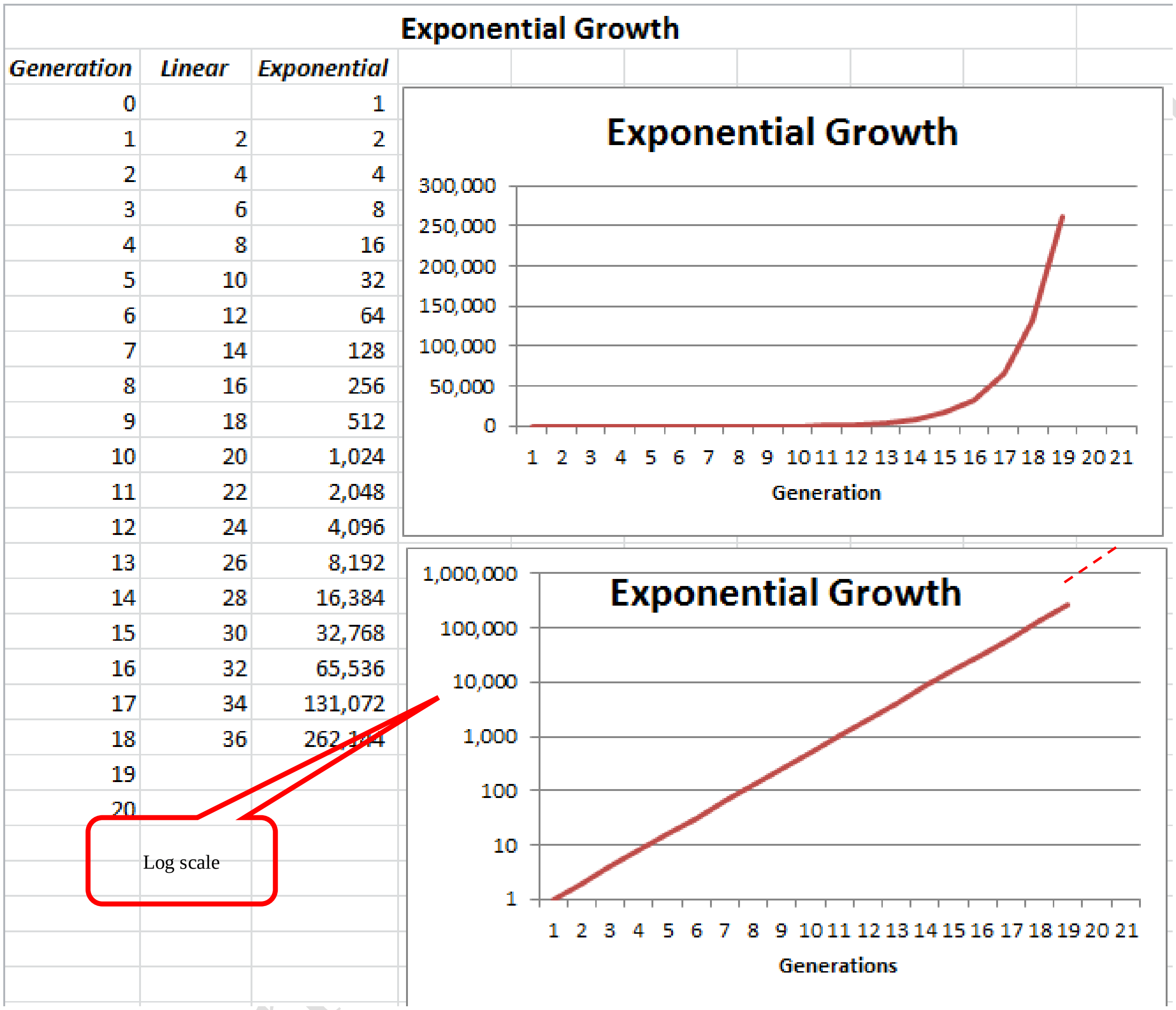


Figure 7.8. Exponential growth with line chart

To make the task of extending the line of the chart easier, scientists change the scale on the vertical axis so that it increases exponentially. This type of scale is called a log scale. If the population being charted is an exponential increase, the chart with a log scale will be a straight line, as shown in the second chart in

Figure 7.9. A straight line is much easier to extend into the future to make predictions. In this example, you can see that in two more generations, the population will increase to about a million.



Generation	Linear	Exponential
0		1
1	2	2
2	4	4
3	6	8
4	8	16
5	10	32
6	12	64
7	14	128
8	16	256
9	18	512
10	20	1,024
11	22	2,048
12	24	4,096
13	26	8,192
14	28	16,384
15	30	32,768
16	32	65,536
17	34	131,072
18	36	262,144
19		
20		

Figure 7.9. Exponential growth with line chart

Although the charts look different, they represent the same thing—exponential growth.

Population Growth in Open and Closed Systems

Biologists know what happens when an organism is put in an environment where it has no competition and food is abundant. If the system is an open system where there is a constant but limited fresh supply of food and waste products are regularly removed, the organism will increase in numbers until it reaches the point where the organism consumes all of the new food or their waste products match the rate of disposal. When that happens, the number of organisms stops increasing and stabilizes. Biologists study this phenomenon using simple organisms like bacteria or yeast that have short lives and short reproductive cycles to demonstrate the concept. This maximum is the carrying capacity of the system, as shown in Figure 7.10.

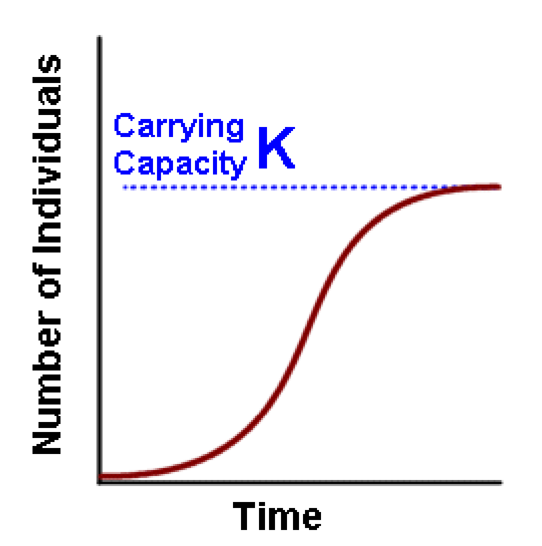


Figure 7.10.Growth of yeast in an open system

If the organism is in a closed system with a fixed amount of food and nowhere else to dispose of waste, the population will increase rapidly until it consumes all the food or it becomes poisoned by its own waste and then most of the organisms will die, as shown in Figure 7.11. Notice that this chart uses a log scale to make the exponential growth look like a straight line.

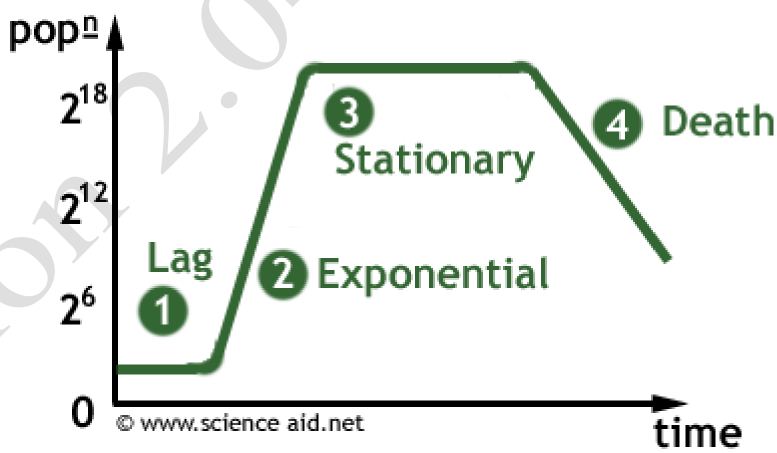


Figure 7.11.Bacteria in a closed system

In real life, most systems aren't completely open or closed. More commonly, the production of food is slow but it might have a long time to accumulate a surplus. If a new organism is introduced that uses the food, its population growth can resemble a closed system where the population expands until the excess food is consumed and then dies back to a sustainable level that matches the continuous flow. This process is demonstrated by what happened when biologists transferred a small herd (29) of reindeer to an island in Alaska in 1944 that had no predators and a plentiful supply of slow-growing lichen that had accumulated for many years. The lichen served as food for the reindeer in the winter. The population of the herd grew rapidly. In twenty years the number increased from 29 to 6,000 but by 1963, they had eaten almost all of the available lichen. That winter, all but 42 of the reindeer died of starvation, as shown in Figure 7.12. (Klein n.d.)

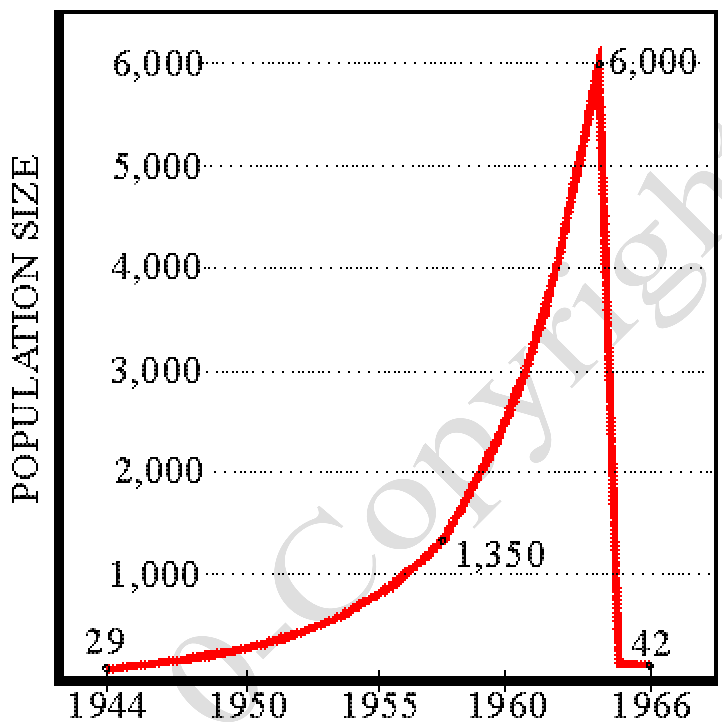


Figure 7.12.Reindeer population on St. Matthews Island

Key Takeaways

An isolated system does not allow energy or matter to cross the boundary. An example would be trapped miners that are cut off from communication and supplies. A closed system allows energy to come and go but not matter. An example might be miners trapped in a tunnel that still had working telephone and electricity. An open system allows energy and matter to come and go. An example might be a fishing village by a river. [7.1.1]

The first two laws of thermodynamics: [7.1.2]

- First law – energy is neither created nor destroyed but it can change form. A perpetual motion machine of the first type claims to be able to produce more energy than its inputs.
- Second law — the quality of energy (its ability to do useful work, its concentration, or its organization) always decreases with time. Perpetual motion machines of the second type claim to be able to extract energy from diffuse, low quality sources

and concentrate it into a more useful form.

The steps of the scientific method are: [7.1.3]

- Observe a physical phenomenon and take measurements; look for patterns
- Make a guess, called a hypothesis that can be measured that explains the data
- Create an experiment that can confirm or disprove the hypothesis
- Examine the result of the experiment and draw a conclusion
- Report the findings

A theory is based on repeated testing of hypothesis and it can often be used to predict previously unknown facts. Inductive reasoning seeks to find explanations for observed facts while deductive reasoning explains observed facts as examples of a belief.

The earth receives energy from the sun and emits energy as infrared light. It receives matter in the form of protons from the sun and stone or metal from meteors. [7.1.4]

Exponential growth increases by multiples such as 2,4,8,16,32 while linear growth increases by additional amounts, e.g. 2,4,6,8,10,12. [7.1.5]

Exponential growth appears to be a straight line if the vertical axis uses a log scale. This type of chart is called a log chart. Predictions can be made by extending the straight line. [7.1.6]

The growth chart of an organism in an open system can look like an S curve where it reaches a stable upper limit. The growth chart of an organism in a closed system can rise rapidly and then drop abruptly if a limited source of food has been exhausted or if the waste builds up and poisons the organisms. [7.1.7]

2 Human Population

Learning Objectives

1. Identify the dates and intervals for each billion of human population increase. [7.2.1]
2. Identify resource(s) that became available that spurred exponential growth of the human population. [7.2.2]
3. Identify the four stages of population growth in a developing society. [7.2.3]
4. Describe Malthus' hypothesis regarding the future of human population. [7.2.4]
5. Identify carrying capacity estimates based on current U.S. standard of living for the world. [7.2.5]
6. Identify stored resources that might be exhausted which could cause a population crash. [7.2.6]

If we look back at the history of humankind, we observe a dramatic change that began in the late 1700s CE that resulted in a sudden increase in world population. A chart of the world's human population shows exponential growth that is characteristic of a population that has suddenly found a new, large supply of a previously limited resource, as shown in Figure 7.13.

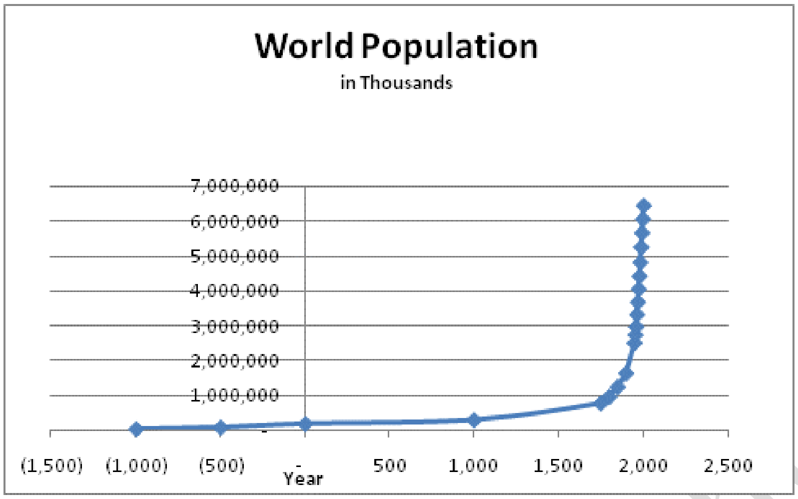


Figure 7.13. World population from 1,000 BCE to 2000 CE

If we take a closer look at the period from 1900 to 1950 in Figure 7.14, we see that world population continued to increase in spite of two world wars in the early 1900s that killed almost 100 million people. The growth rate accelerated in 1950 and has been rising exponentially for the last sixty years.

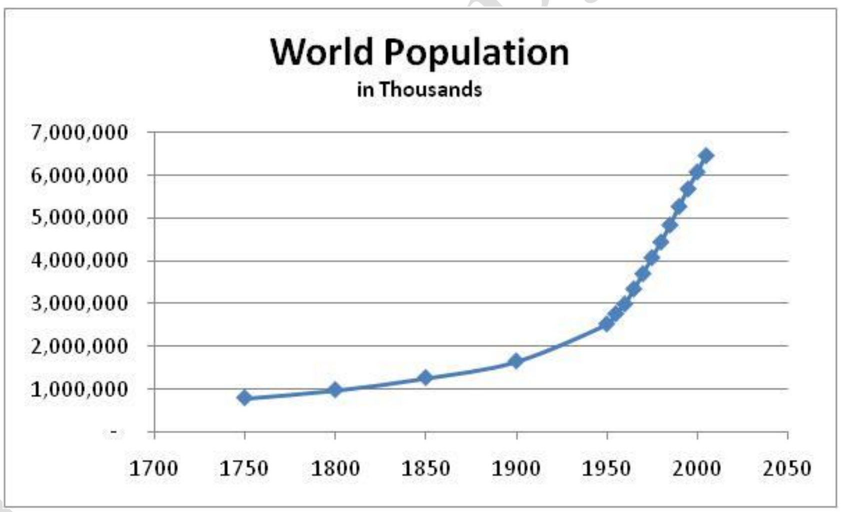


Figure 7.14.World population from 1750 to 2000

Something is going on that has changed world population even more than wars that killed millions of people. The big question that faces humanity is how the world population will change in the next fifty years. If the system behaves like an open system with a new resource, the curve could flatten out as it nears the carrying capacity of the open system. If this growth is caused by the consumption of a limited resource, the population could crash like the reindeer population on St. Mathews Island.

Another way to get a sense of how fast the population is increasing is to consider how many years it takes to add one billion people. Consider the table in Figure 7.15.

Population in Billions	Range	Years
1	First humans to 1804	>1,000,000 years
2	1804-1927	123 years
3	1927-1960	33 years
4	1960-1975	15 years
5	1975-1987	12 years
6	1987-1999	12 years
7	1999-2012	13 years

Figure 7.15. World population from 1950 to 2050

Notice the most recent interval is slightly longer. Experts expect the trend to begin to flatten out in the next forty years as you would expect of an open system as shown in Figure 7.16. (World Population 2008) [Link]

World Population: 1950-2050

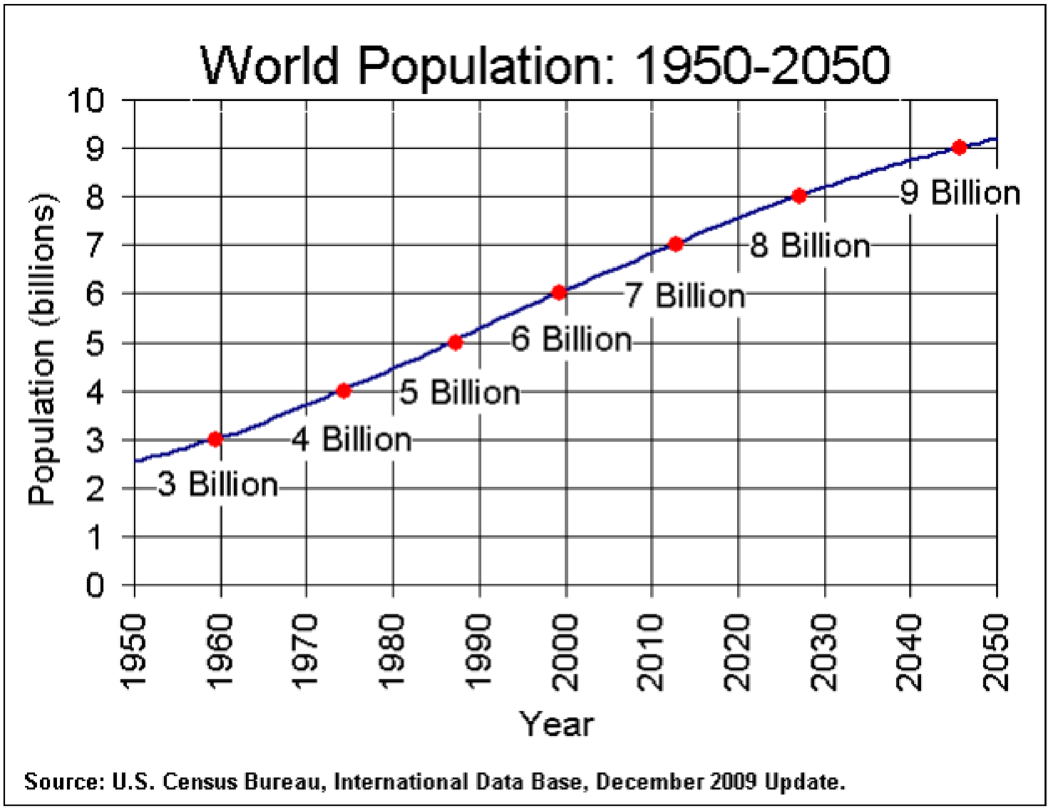


Figure 7.16. World population from 1950 to 2050

The slowdown is expected because humans behave differently in some ways than bacteria or deer to an increased supply of food. One of the differences is that people are aware of their condition and the likelihood that they will have enough surplus resource to support themselves in their old age. In undeveloped countries where the death rate is high due to starvation and illness, people have more children to assure that some of them survive to take care of them in their old age. In developed countries, more people live in cities where extra children are an added cost and women have more choices. Population experts have observed societies that have developed and adapted to their higher standard of living and developed a hypothesis to explain the growth called the Demographic Transition Model. The model has four phases; undeveloped, early development, urbanization, and stability. (Demographic Transition Model 2011)

Undeveloped

In undeveloped countries, the birth rate is high (five or more children per female) but so is the death rate. Most families live on farms and they depend upon the labor provided by their children. Older people depend on survival of their children for care in old age. In countries where many children die within the first five years, high birth rates are necessary to assure that enough children survive to produce food and care for the elderly.

Early Development

When a society develops—usually by utilizing fossil fuel—the first effect is a reduced death rate. For example, during the industrial revolution in Europe, fossil fuels were used to reduce illness due to indoor smoke, increase food production, and decrease starvation from localized crop failure. During this stage, birth rates remain high which results in a large increase in population.

Urbanization

Greater food production by fewer farmers allows people to congregate in cities where medical technology can reduce deaths by disease. When most of the population moves into cities, large families are not needed to raise crops. Instead, the cost of educating and caring for numerous children becomes burdensome. Females become more educated regarding their options and fertility control measures are more available. As a result, the birth rate drops during this stage.

Stability

A new stability is attained when the birth rate and death rate become balanced at much lower levels. For example, Europe now has a stable population. The four stages are shown in Figure 7.17.

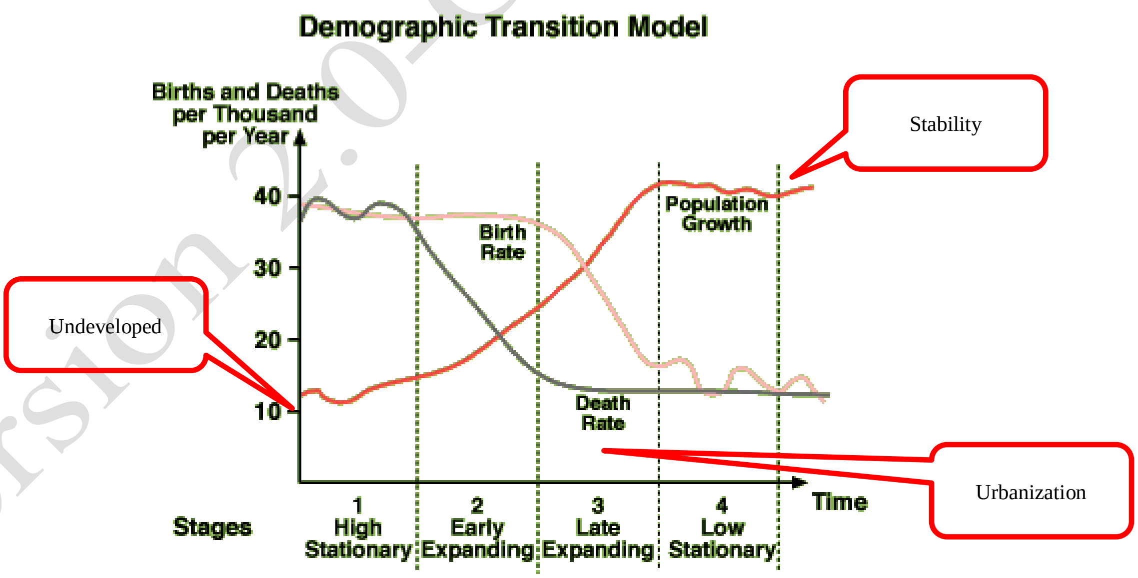


Figure 7.17.Population and stages of development

This model matches the population curve observed for Europe which stabilized in 1990, as shown in figure 7.18.

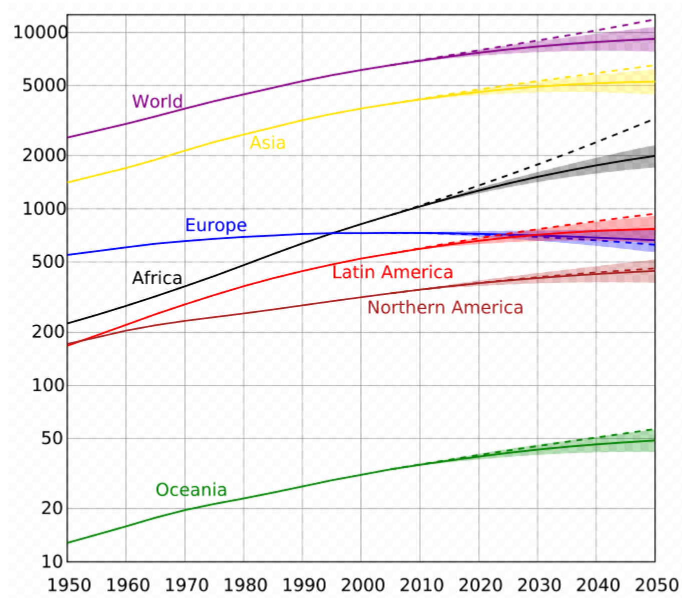


Figure 7.18.Population projections by region

In figure 7.18, the known data ends near the middle of the chart. The dotted lines are extensions of the known trends. Notice the scale on the left is a log scale. The lines fan out to show the range of high and low estimates through 2050. They assume that the development model will apply to undeveloped regions which will all grow more slowly than the dotted lines that are extensions of previous exponential growth. If the development model does not apply to currently undeveloped countries and world population continues to increase at its present rate, it would reach 11 billion by 2050.

Carrying Capacity Estimates

If the development hypothesis is appropriate, the world's population will stabilize at the carrying capacity of the system—the earth. The carrying capacity is determined by the steady inflow of energy and food and outflow of waste at a sustainable level. To estimate the carrying capacity of the earth we need to identify the most limiting factor. It might be a resource like land, energy, food, or fresh water or a waste disposal problem where putting waste into the oceans or atmosphere exceeds their limits to absorb them. This is a difficult estimate to make because there are several factors and measurements are hard to obtain in undeveloped countries.

In the 1700s, philosophers were optimistic that humans could perfect their world with better forms of government and new technologies would create a better material life. A British economist—Robert Malthus, shown in Figure 7.19—observed the beginnings of a rapid rise of population in England and warned that humans could reproduce "geometrically" (exponentially) while food production could only be increased "arithmetically" (linearly). Instead of a perfect world there would eventually be a point where there would not be enough food.

Figure 7.19.Robert Malthus

In the 1800s, the only method available for increasing food production was to increase the amount of land used for growing crops, which Malthus recognized as a limiting factor. Malthus' hypothesis assumed that farmland could be cleared and brought into production by approximately the same amount each year—linear increase. (Malthus 1798)

> *I think I may fairly make two postulata.*
>
> *First, That food is necessary to the existence of man.*
>
> *Secondly, That the passion between the sexes is necessary and will remain nearly in its present state.*
>
> *Assuming then my postulata as granted, I say, that the power of population is indefinitely greater than the power in the earth to produce subsistence for man.*
>
> *Population, when unchecked, increases in a geometrical ratio. Subsistence increases only in an arithmetical ratio. A slight acquaintance with numbers will shew the immensity of the first power in comparison of the second.*
>
> *By that law of our nature which makes food necessary to the life of man, the effects of these two unequal powers must be kept equal.*
>
> *This implies a strong and constantly operating check on population from the difficulty of subsistence. This difficulty must fall somewhere and must necessarily be severely felt by a large portion of mankind.*

The Green Revolution

Malthus did not anticipate the impact of the use of fossil fuels on food production combined with the scientific method applied to plant yields. Charitable foundations in the U.S. such as the Rockefeller and Ford foundations sponsored scientific research to discover new ways to increase food production from a fixed amount of land. Scientists discovered and developed new varieties of wheat, rice, sorghum, millet, maize, cassava, and beans that were much more productive. When combined with fertilizers—plant food—and pesticides—insect killers—made from natural gas and petroleum, and the use of fossil fuels to pump water and run farm equipment, food production increased much faster than population. (Hazell 2002) [Link] New varieties of grain crops like the rice shown in Figure 7.20 increased food production in developing countries like India.

Figure 7.20. Scientifically developed rice triples food output

The production per acre was tripled for most basic food crops in less than 40 years. This dramatic increase in productivity was called the green revolution which increased the carrying capacity of the earth. Many considered it a disproof of Malthus' hypothesis because his critics assumed that similar scientific discoveries will continue to increase crop yields to keep ahead of population increase.

The Ecological Footprint

A more recent estimate of the earth's carrying capacity based on post-green revolution crop yields per acre was made in 1999 by A.R Palmer. He estimated how much land it takes to provide food, wood products, and living space for one person who is living a particular lifestyle. (Palmer 1999) Palmer called this amount of land a person's ecological footprint. He estimated that it takes 1.5 acres of land to grow the food we eat, 1.6 acres to grow the forest products, and .4 acres of land on which we reside or otherwise take out of food production for a total of 3.5 acres per person. (An acre is a square of land that is about 209 feet on each side.) Palmer divided the available amount of land that is useful for growing crops, grazing animals, or growing forests by the ecological footprint of an American and estimated that the carrying capacity of the earth is about 4 billion people living and eating the way Americans do now. Given improvements in efficient use of energy and reducing the ecological footprint from 3.5 acres to 2.5 acres (1 hectare), Palmer estimated that the carrying capacity could be as high as 9 billion.

A similar estimate was performed by William Rees (Rees 1996) that had a similar result of 4 to 6 billion. He argued that developed countries are acting like open systems by taking resources from other countries and exporting waste to the ocean and atmosphere. Rees makes two important arguments regarding technology and trade; [Link]

> *…technology can directly reduce carrying capacity while creating the illusion of increasing it! We often use technology to increase the short-term energy and material flux through exploited ecosystems. This seems to enhance systems productivity while actually permanently eroding the resource base. For example, the effectiveness of electronic fish-finding devices and high-tech catching technology has overwhelmed the reproductive capacity of fish stocks; energy-subsidized intensive agriculture may be more productive than low-input practices in the short term, but it also increases the rate of soil and water depletion.*
>
> *While commodity trade may release a local population from carrying capacity constraints in its own home territory, this merely displaces some fraction of that population's environmental load to distant export regions. In effect, local populations import others' "surplus" carrying capacity.*

Some people say that the carrying capacity of the earth is much higher at 40 billion. This estimate assumes that all of one person's needs could be met using ¼ of an acre of land that is suitable for growing food. (Armstrong n.d.) A quarter acre is a square of land that is about 104 feet on a side compared to the 3.5 acres presently used by Americans. It also assumes that land is the limiting factor and does not consider waste disposal, fresh water supply, or energy so the carrying capacity is likely to be much closer to a smaller number.

Limited Resources that Might Cause a Crash When Exhausted

Like an island that has a large reserve of resources, it is possible for our rapidly increasing population to consume the stored resources—like the Reindeer ate the lichen—and then crash to a much smaller population. Alternatively, we can adjust our consumption of resources and size of population intentionally to a sustainable level that matches the flow of energy into the system and its ability to process the waste. Some experts are predicting that the undeveloped countries will develop and that world population will stabilize at ten to twelve billion people. This argument assumes that food, fresh water, and waste disposal will be available at least at present levels and would be shared more equally. This assumption is not warranted if we are consuming a stored resource or if waste products are accumulating. Consider some of the limiting factors to sustainable population levels:

Fresh Water

Food might not be the limiting factor. Humans also need fresh drinking water. Even though the earth is covered with oceans, sea water is too salty for humans to drink. The energy from the sun evaporates water from the oceans leaving the salt behind. The water returns to the surface as rain. Some of the water flows along the surface and some seeps into the ground where it is called ground water, as shown in Figure 7.21.

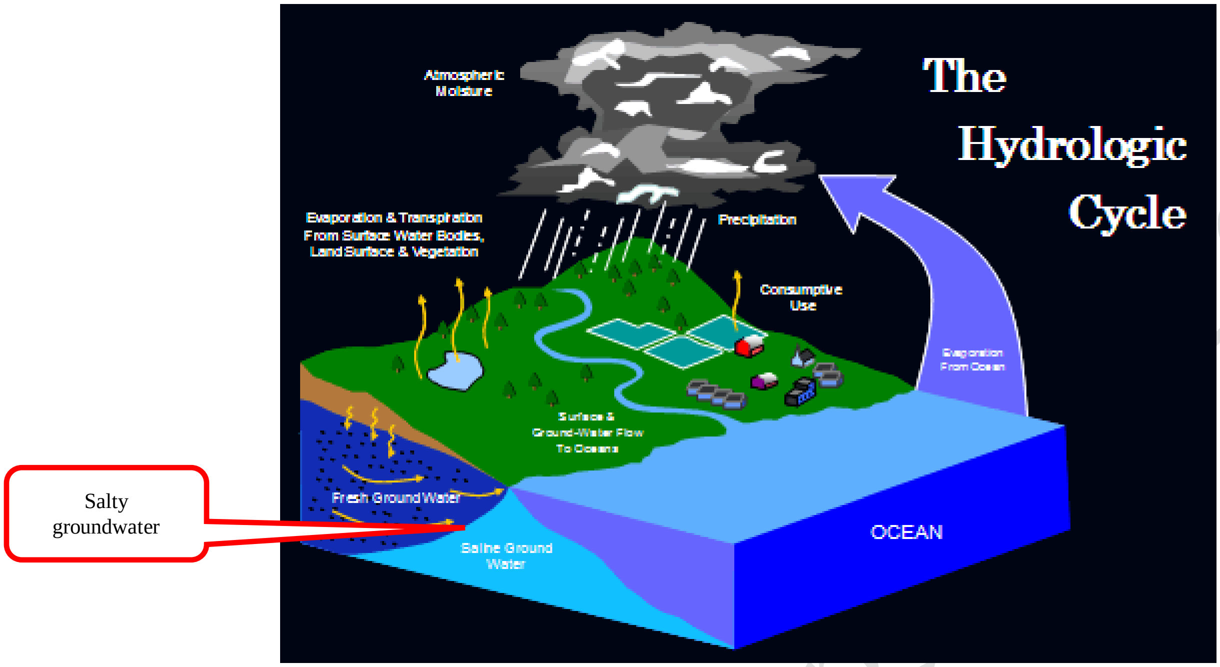


Figure 7.21.Fresh water from the oceans

Near the coast, there is a region where the fresh ground water mixes with the ocean saltwater as shown in Figure 7.21. If freshwater is pumped from the ground faster than it is replenished from inland supplies, the saltwater moves in and makes those wells unusable for many years.

Sometimes the fresh water is trapped below ground above layers of rock through which it cannot pass. Over time, large amounts of water collect. These resources are called aquifers. Part of the green revolution was created by using fossil fuels to pump water from aquifers to the surface where it was used for irrigation. In most regions, the rate at which the water is being removed is faster than it can be restored by annual rainfall and the levels of water in the aquifer are falling. When the water level reaches the bottom layer of rock, wells in the areas where the aquifer is shallow will dry up and productivity will start to fall. For example, water from the Ogallala aquifer provides water to eight states for irrigating crops, as shown in Figure 7.22. It supports nearly one-fifth of the wheat, corn, cotton, and cattle produced in the United States.

Figure 7.22.Irrigated crops

The aquifer has about as much water in it as Lake Huron. Water is being removed more rapidly than rainfall is replacing it and the water level in the aquifer is falling. It has dropped about 100 feet since the 1940s and is still dropping at a rate of 2.7 feet per year. If water use continues at the present rate, it could be depleted in a few decades. (Water Encyclopedia 2011) It may be difficult to imagine a body of water as large as Lake Huron disappearing due to irrigation projects but it has already happened. The former Soviet Union diverted entire rivers for irrigation from the Aral Sea and doubled the land area using irrigation. The Aral Sea was the world's fourth largest fresh water lake. The Soviets diverted the fresh water for irrigation and the lake lost 90% of its volume, as shown in Figure 7.23. After the Soviet Union broke up, the Russians still benefit from the diverted water while the people of Kazakhstan and Uzbekistan have lost their lake and its fish. (Kazakhstan Discovery 2011)

Figure 7.23.Irrigation projects caused world's fourth largest lake to disappear

India relies heavily on groundwater from aquifers to irrigate its crops. The World Bank estimates that in 20 years, 60% of India's aquifers will be in critical condition. (World Bank 2010)

Water that is contaminated with human waste can be processed to remove solid material and kill harmful bacteria in waste water treatment plants in cities. The waste water can be used for crop irrigation or returned to a river. Cities can also reclaim waste water by forcing it through fine filters using a process called reverse osmosis.

In rural areas waste water is cleaned by using septic tanks—a concrete tank that collects solids—and septic fields—an array of porous pipes in sandy soil where waste water evaporates upward into the air or filters downward into the ground water.

Salt is much harder to remove from water than most human waste products. If there is enough energy available, fresh water can be extracted from ocean water in a process called desalinization which removes salt. Reverse osmosis and desalinization require large amounts of energy so most population centers rely on rainfall or groundwater.

Waste Disposal

Scientists observe that there is another reason for a population crash in a closed system besides running out of food and water. In a closed system, an organism can die when its own waste products pollute the source of food or water to toxic levels. In developed countries, energy is used to transport and bury solid waste and to remove pollutants from exhaust gasses and water sources to keep the levels below a toxic limit. In undeveloped countries, waste products are dumped in rivers or burned or exhausted into the air. Because the earth is almost a closed system, the practices in the undeveloped world affect the air and water everywhere.

Most people in the U.S. are aware of waste from cities called municipal waste and how it is handled but municipal waste is only 5% of the waste created in the U.S. The other 95% of the 4.5 billion tons of solid waste is from agriculture, mining, or industry. (World of Earth Science 2003) The handling of the waste from agriculture, mining, and industry is usually out of sight of the public and economic forces often encourage dumping waste rather than processing it safely. Some argue that it is the appropriate role of government agencies to check on this type of waste management.

The United Nations is concerned that adding carbon dioxide to the atmosphere by burning fossil fuels is causing global temperature increases. (Intergovernmental Panel on Climate Change 2011) This hypothesis is based on the observation that world temperatures are going up at the same time that extra carbon dioxide is being emitted by burning fossil fuels (observation of events). The hypothesis is that the extra carbon dioxide is restricting the outflow of heat by blocking some of the infrared light resulting in a net increase of energy within the system. This hypothesis cannot be tested in a controlled experiment because it involves the whole planet but it can be used to make predictions. One of those predictions is that the earth's temperature will rise by several degrees which would be enough to adversely affect climate and the growth of crops.

The United States' population has not stabilized in spite of being a developed country due to rising life expectancy, fertility treatments, and immigration. David Pimentel and Mario Giampietro estimated in 1994 that the U.S. population would grow to 520 million by 2050 but the amount of water for irrigation and fossil fuel would decrease. (Pimentel and Giampietro, Food, Land, Population and the U.S. Economy 1994) They argued that the population at the time they wrote the article (260 million) could not be sustainable due to reduced land, water, and energy, let alone twice that many people. Pementel and Giampietro made the following predictions in 1994:

> ***Land:*** *On-going soil erosion and expanding urbanization contribute to the continuous loss of cropland in the U.S. Annually, more than two million acres of prime cropland are lost to erosion, salinization, and waterlogging. In addition, more than one million acres are removed from cultivation as America's limited arable land is overwhelmed by the demands of urbanization, transportation networks, and industry. As a result of arable land shortages, U.S. meat consumption may be reduced.*
>
> ***Water:*** *The groundwater that provides 31% of the water used in agriculture is being depleted up to 160% faster than its recharge rate. The vast U.S. Ogallala aquifer (under Nebraska, Oklahoma, and Texas) will likely become non-productive within the next 40 years. Even if water management is substantially improved, the projected 520 million Americans in 2050 would have about 700 gallons/day/capita, considered the minimum for all human needs, including agriculture.*
>
> ***Energy:*** *The availability of non-renewable fossil energy explains in part the historically high productivity of U.S. agriculture. Currently the 400 gallons of oil equivalents expended to feed each American amount to about 17% of all energy used in this country each year. Yet given current use levels, only 15 to 20 years of oil resources remain in the U.S. Although imports now account for 58% of oil used in the U.S., these international reserves are expected to be exhausted within the next 30 to 50 years.*

Like the predictions made by Malthus, this prediction did not take into account increases in resources from improved technologies. Notice under Energy that they predicted in 1994 that U.S. oil resources would be depleted in 15 to 20 years which has not happened because oil and gas are being recovered from deeper and less easily extracted sources using more advanced technologies.

Uranium

The U.S. generates about 20% of its electricity from the fission of U-235. Because nuclear fission produces a million times more energy per atom than a chemical reaction like burning fossil fuel, it is an attractive option for generating energy in the future. However, U-235 is less than 1% of the Uranium. The other 99% is U-238. U-238 can be converted into Pu-239 in a breeder reactor for use as fuel but it takes the neutrons from the fission of U-235 to do the job. If we use up most of the U-235 to generate energy in non-breeder reactors, we might run out of it and then it would be too late to use it to breed U-238 into Pu-239. At present rates of and methods of consumption, known Uranium reserves could last 80 years. Little exploration has been done with advanced technologies to find new Uranium deposits or to extract it from low-grade ore so that estimate is probably low. If breeder reactors are used, it would increase the life of the resource to thousands of years. (World Nuclear Association 2010) To be effective, a switch to breeder reactors would have to be done before we use up the U-235. If the world decided to use nuclear reactors as the main source of energy but only used the U-235, it could run out in a few decades and then there would not be enough to breed U-238 into Pu-239.

The most likely carrying capacity estimates are probably somewhere between the most pessimistic and the most optimistic predictions. This does not mean that the problems can be ignored—it means that there is time to do something about them.

Key Takeaways

First billion: prehistory to 1804; Second billion 1927, 123 yrs.; Third billion 1960, 33 yrs.; Fourth billion 1975, 15 yrs.; Fifth billion 1987 12 yrs.; Sixth billion 1999 12 yrs.; Seventh billion 2012 13 yrs. [7.2.1]

Growth was the result of increased food that was produced by using fossil fuels and water from aquifers. [7.2.2]

Populations go through four phases: [7.2.3]

- Undeveloped: high death rate high birth rate
- Early development: falling death rate, high birth rate
- Urbanization: low death rate, falling birth rate
- Stability: low death rate, low birth rate

Malthus explained that population could increase geometrically which is called exponentially in modern terms, but cropland could only be increased arithmetically or linearly. [7.2.4]

Given the present use of land and energy by U.S. citizens, there would be enough to support 4 billion. [7.2.5]

Fossil fuels like coal, oil, and natural gas are forms of stored solar energy that could be used up. Water trapped in underground aquifers is another stored resource that could be depleted. Uranium is a resource that is used up making power or exploding weapons but it is plentiful if utilized in breeder reactors. [7.2.6]

3 Sustainable Production and Use of Energy

Learning Objectives

1. Identify the four major categories of energy sources for the Earth as a system. [7.3.1]

2. Identify the difference between annual energy output and peak power production of a device and the units of measure for each. [7.3.2]

3. Explain why the time that electricity is produced affects its value and price. [7.3.3]

4. Describe the capacity factor and how it is calculated and used to compare energy sources. [7.3.4]

5. Identify the desired characteristics of energy sources for transportation. [7.3.5]

6. Identify the most significant limitation of each of the following alternative energy production methods: [7.3.6]

- Geothermal
- Groundwater Heat Pump
- Tidal
- Hydrogen Fusion
- Fission U235
- Fission Pu239
- Hydroelectric
- Wind
- PV on Earth
- PV in Space
- Ethanol from Corn
- Ethanol from Cellulose
- Biodiesel from Algae

To provide enough food, energy, and material goods to a world population of about 9 billion people will require more food production from the available land and new methods of food production from the oceans without poisoning them with waste. This will take far more energy and fresh water than we are using now but it will have to come from sources that do not depend upon stored reserves that will run out any time soon. Some people expect that additional amounts of fossil fuels will continued to be discovered at sufficient rates to continue to support the U.S. lifestyle. This is probably true for a while if the U.S. behaves like an open system where it can import fuel from other countries and export its waste. This policy will deprive those countries of the resources they need to develop and will lock them into an undeveloped state of high birth and death rates. It may also poison our own air and water or cause global temperatures to increase.

Alternatives to burning fossil fuels are being considered and developed. Because fossil fuels are concentrated solar energy that accumulated for millions of years, it is very high quality energy from a thermodynamics point of view. It is inherently harder to get energy from lower quality energy sources that are less concentrated like solar, wind, and tides and the cost of those forms of energy will be higher than fossil fuels until fossil fuels become scarce.

Once the cost of finding and drilling for oil is paid for, the cost of producing and refining additional oil is low. It costs Saudi Arabia about $5 to produce an extra barrel of oil (44 gallons). (Smith 2009) Because Saudi Arabia has the world's largest proven reserves of oil, it can control the world price by choosing how much oil to produce each year. One of the factors that they consider when setting the price is how much an alternative source costs to produce. This price is called the replacement cost. The Saudi government can keep the price of oil below the price at which replacements will be economically competitive. This makes it difficult for companies that make alternatives to obtain financing and keeps the U.S. dependent on foreign oil.

Some argue that we should not wait until the fossil fuels are gone or become so scarce that the price rises above the replacement cost before we look for an alternative because once the fossil fuels are almost gone there is a risk of a population crash. Instead, they argue that we should use some of the fossil fuel while it is relatively cheap and abundant to build devices that can extract enough energy from other sources to support billions of people. In this section, we explore those alternatives.

Available Energy Sources

In simple terms, there are only four long-term sources of energy that are available to use for a sustainable future. They are:

- Extracting heat from the interior of the planet
- Extracting energy from the motion of the earth and moon
- Converting mass into energy using fission or fusion
- Solar energy that arrives each day from the sun

Although they are not sources, conservation and recycling should also be considered. Conservation is using less by wasting less. For example, when you turn off lights when you are not in the room, it is much easier than generating that much electricity. Many products such as aluminum cans, paper, or glass bottles take a significant amount of energy to make from ore or trees. They can be reused which takes less energy.

Types of Energy Use

Energy use can be divided into two broad categories; stationary and mobile. If energy is used in a particular location, it can be delivered by fixed systems like pipelines and wires. Providing energy to moving vehicles presents problems that are unique to the transportation industry. The energy must be high quality and have the minimum possible volume and weight. The energy must be in a form that does not need to be connected to a pipe or wire while the vehicle is moving.

If we convert our automobiles to electricity, they could charge at night thereby increasing the capacity factor of the extra generating equipment without reducing the capability of meeting daytime peak demands. Automobiles that run primarily on electricity with a gas engine backup are called Plug-in Hybrid Electric Vehicles (PHEVs), as shown in Figure 7.24.

Figure 7.24. Electricity may be used to power vehicles

If we replace 50% of our automobiles with PHEVs we would only have to increase the number of electric power plants by about 7% (Letendre 2006) Another advantage of concentrating the source of energy for transportation in a few sites instead of on millions of individual vehicles is that expensive pollution control measures can be used effectively. If millions of cars with rechargeable batteries were connected to the electric system, they could be used to smooth out the variability of alternatives like wind power. According to Professor Frank at UC Davis, Hawaii could use a combination of wind and hybrid cars to replace all of its petroleum imports that are presently used to generate electricity and operate vehicles. (Gage 2010)

Energy Measurements

Energy can be measured in a variety of units that have developed over time for use in particular industries or applications. Fortunately, websites exist that make it convenient to convert from one unit of measure into another. This is particularly important when considering alternative forms of energy where the energy in one form is used to replace energy in another form. For example, if you wanted to compare the energy in a gallon of gasoline to electrical energy you could go to onlineconversion.com to find the multiplier, as shown in Figure 7.25.

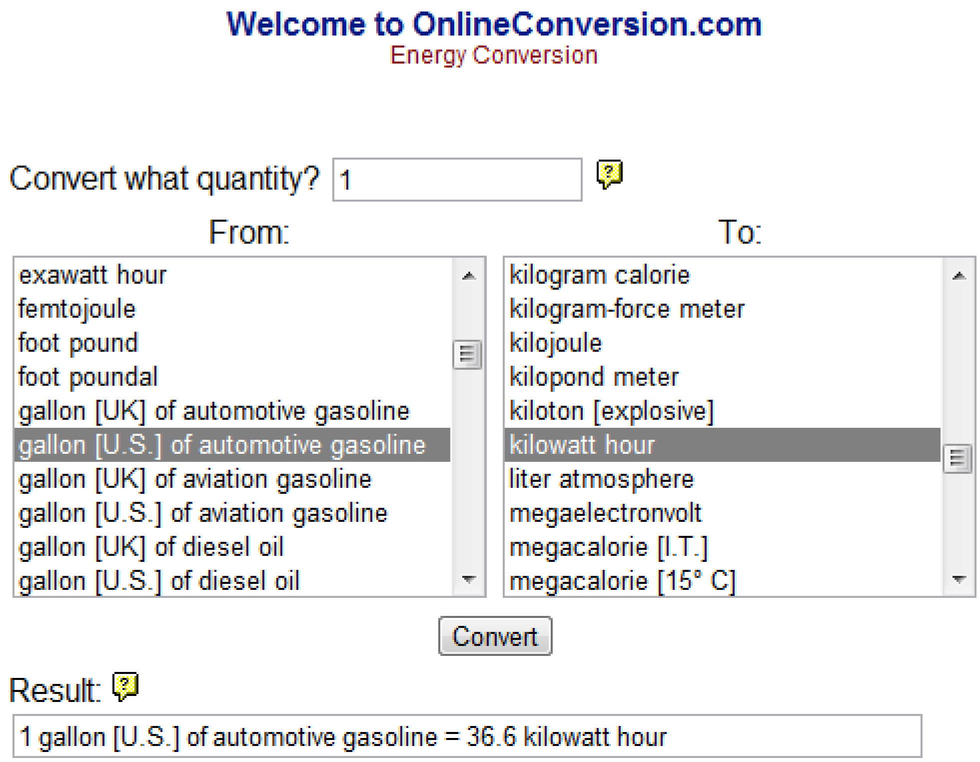


Figure 7.25.Conversion factors for units of energy

The international unit of energy which is also commonly used for electrical energy is the kilowatt·hour which is often abbreviated as kWh. When comparing energy sources, it is important to convert them to the same unit of measure so we will use the kilowatt·hour. Because electricity is a form of energy that is common to most stationary uses of energy and it is becoming more common in transportation, the kWh will be used as the unit of energy measurement in this text.

Unlike solid or liquid fuels, electricity is difficult to store in large quantities. Instead of storing large quantities of electricity, most countries build extra generating equipment to use during times of peak demand—when the need for electrical energy is greatest. The maximum output of a generating device is rated in kilowatts which are often abbreviated as kW.

When comparing electricity generating sources, it is very important to compare both measurements. For example, a plant that burns coal to generate electricity might have a maximum output of 800,000 kilowatts and a large wind turbine might have a maximum output of 1,000 kilowatts. It would appear that 800 wind turbines could match the output of the coal plant. This is true when both are running at maximum power. However, the coal plant can run at maximum all day and all night seven days a week except for a few weeks per year when it is shut down for maintenance. The wind turbine only puts out its maximum when the wind is blowing at 20 miles per hour or faster. Most of the time the wind speed is less than that and many times it is zero. To make a meaningful comparison of energy sources, it is necessary to compare the total energy over a longer period such as a year.

For example, consider the coal-fired power plant at Monroe Michigan shown in Figure 7.26.

Figure 7.26.Conversion factors for units of energy

This plant has a power rating of 3,014,000 kilowatts. If it could run at that capacity continuously 24 hours a day for 365 days, it would produce 26,402,640,000 kilowatt-hours of energy. It normally produces about 22,000,000,000 kilowatt-hours. If we divide the actual energy output by the maximum possible we get .83 or 83% which is the capacity factor.

$$\frac{22{,}000{,}000{,}000\ kWh}{3{,}014{,}000 kW\ X\ 24 \frac{hr}{day} X\ 365\ days/yr} = \frac{22{,}000{,}000{,}000\ kWh}{26{,}402{,}640{,}000\ kWh} = 83\%$$

There are two large wind turbines in Michigan near Mackinaw City where winds have a higher average speed than most of the rest of the state, as shown in Figure 7.27.

Figure 7.27.Wind turbines in Michigan

They are rated at 900 kilowatts each and they each produce about 2,000,000 kilowatt-hours per year. The capacity factor for these wind turbines is:

$$\frac{2{,}000{,}000\ kWh}{900kw\ X\ 24\frac{hr}{day} X\ 365\ days/yr} = \frac{2{,}000{,}000\ kWh}{7{,}884{,}000\ kWh} = 25\%$$

Manufacturers of alternative energy systems often provide the maximum output but seldom provide the annual energy output. Both numbers are necessary to make meaningful comparisons. In this example, it would take 800 wind turbines to match the power output but 11,000 wind turbines to match the annual energy output of the Monroe plant. The wind turbines would also need a massive storage or transportation system to provide power when the wind speed was low.

Electricity Value and Price

Because electrical energy is difficult to store in large quantities, electric utilities run their largest and most efficient plants as much as possible and hold older and smaller, less efficient generating facilities on standby to meet peak demands. Because electricity is used to cool buildings, the peak demand often occurs during the day on the hot days of the year. During peak demand periods the cost to generate the electricity is greatest because it takes additional equipment to generate it and they are often older or smaller units. Most hydroelectric facilities like the Grand Coulee Powerplant shown in Figure 7.28 store water behind a dam during the night and weekends and then let most of it flow through the generators during peak demand periods.

Figure 7.28.Grand Coulee Powerplant in Washington State

It has a vertical drop of 350 feet which provides high quality energy that can be converted into electricity. The dam and power plant generate 21,000,000,000 kWh per year. It has a maximum rating of 6,809,000 kW. (U.S. Department of the Interior 2010) It has a capacity factor of 35%.

$$\frac{21{,}000{,}000{,}000\ kWh}{6{,}809{,}000 kW\ X\ 24\,\frac{hr}{day}\,X\ 365\ days/yr} = \frac{21{,}000{,}000{,}000\ kWh}{59{,}646{,}840{,}000\ kWh} = 35\%$$

This is typical of most hydroelectric facilities. The generating capacity is greater than the average flow of the river so that the water can be stored and then used during peak demand periods. This variation in water flow can cause problems in the river downstream of the dam but it is an integral part of the design of the system.

Most large customers of electrical energy have two parts of their bill; a charge for energy measured in kilowatt·hours and a charge based on the maximum power demand measured in kilowatts. For example, in Michigan a large customer like a school, office building, or factory pays about 5¢ per kWh of energy and an additional $16 per kw based on the highest demand of the month. For most large buildings, the bill is about half energy and half demand charge. To make things simpler for residential customers, they only get billed about 12¢ per kWh based on energy which masks the wide variation in its value from peak demand periods to off-peak periods.

The difference in value of electricity by season and time of day is important when considering alternatives. For example, the electricity generated by a solar panel is likely to be worth twice as much as the energy produced by a wind turbine because the solar panel will reliably produce electricity during the parts of the day and the season when it is needed for cooling buildings. Having a supplemental solar panel on a building would reduce the monthly demand charge more months of the year than a wind turbine making its electricity almost twice as valuable.

Comparison of Sustainable Energy Sources

Like buying a car, there are several factors to consider when choosing which sources of energy to develop. The choices are important because the system must be ready to go before we run low on fossil fuels, or air pollution reaches toxic levels, or we need large amounts of energy to desalinate sea water. If we choose incorrectly, there might not be enough time or additional resources to start over and avoid a population crash.

Criteria

In this text, the author has used the following comparison criteria. They are based on use in the United States.

- Quality: Concentrated form of energy with the ability to do useful work
- Domestic supply: The source is within the boundaries of the U.S.
- Available during peak demand periods (Peak)
- Renewable or very long term (Renew)
- Clean: minimum waste which can be recycled or absorbed
- Scalable: Can be increased to produce large amounts of energy
- Known technology (Known): no significant scientific breakthroughs are needed
- Infrastructure (Infra): compatible with existing delivery systems like pipelines and electricity transmission and distribution systems
- Safe: Minimal environmental impact or risk of human life to extract, transport, and use
- Transportation (Trans): Useable in vehicles, high quality, low volume and weight

Several energy sources will be considered. They will be given a grade from A to E that indicates the author's opinion of each type of energy source. Recall that there are four basic sources of energy from which to choose; Daily solar, converting mass to energy, converting planetary motion to energy, extracting heat from the earth's interior. Electricity can be stored in batteries for mobile use. Batteries tend to be heavy, large, and of medium energy quality. In the following analysis, sources of energy that are used to make electricity are rated as a C under transportation. Breakthroughs in mobile electricity storage could change that rating if alternatives to batteries are found that store more energy using less weight and volume.

Energy from Inside the Earth

If you draw a large circle on a piece of paper to represent a cross section of the earth, the thickness of the line would be proportional to the thickness of the earth's crust and the interior of the circle would be proportional to the part of the earth that is molten with temperatures over 1600 °F as shown in Figure 7.29.

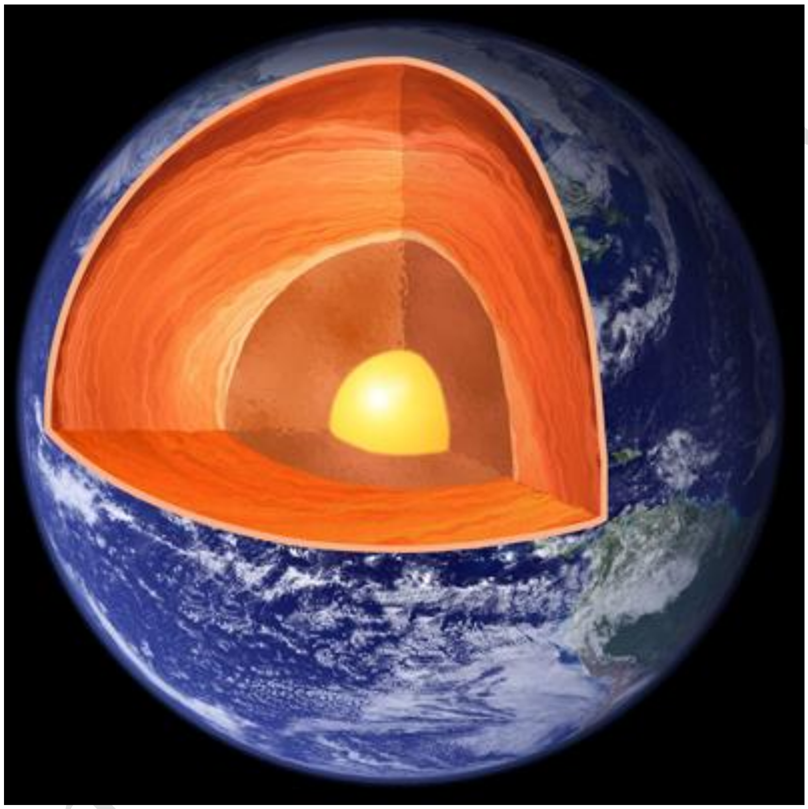


Figure 7.29. Interior of the Earth

There is a vast amount of heat energy a few miles beneath our feet if we only knew how to get to it. The heat of the earth is called geothermal—earth heat.

Geothermal Steam

If we could drill holes through ten or fifteen miles of rock, we could reach levels where the rocks were hot enough to boil water into steam that could be used to generate electricity. Oil well drilling rigs are capable of drilling holes that are about seven or eight miles deep. The oil from these wells is hot with temperatures between 180 and 250 degrees Fahrenheit. The oil from Alaska's north slope comes from wells that are about two to four miles deep and the oil comes out at 145 to 180 degrees. Because this is not hot enough to make steam and generate electricity, the only places where geothermal heat is great enough to use for electricity generation are areas where the earth's crust is cracked or unusually thin like Iceland or Yellowstone National Park. The limitations of extracting heat from holes in hot rocks are:

- cold water can cool the rock below useful temperatures if the rock doesn't conduct heat well and;
- dissolved minerals in the steam are corrosive.

The biggest problem with geothermal energy is that it isn't scalable unless we discover how to penetrate fifteen to twenty miles of rock.

Scorecard:

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
Geothermal	A	A	A	A	B	A	E	A	B	C

Groundwater Heat Pumps

Some of the earth's internal heat reaches the surface. A few feet below the surface it is warm enough to prevent the ground from freezing in the winter. If you go down thirty or forty feet into a layer of soil that has ground water in it the water will be about 55 degrees year round. This is low quality energy and it cannot be used as a source. However, it can be used in combination with a source of electricity to multiply its effect for heating a home. A heat pump uses electricity to move heat. For example, a window air conditioner is a heat pump that moves heat from cool to warm in the opposite direction it would normally flow. A heat pump has a coefficient of performance (COP) that is a ratio of the amount of heat it can move to the amount of electricity it takes to move it. For example, a typical heat pump can be connected to pipes that circulate a liquid into the ground, as shown in Figure 7.30. These systems are also called geothermal but they are not high quality heat that can be used as an energy source.

Figure 7.30.Groundwater heat pump

A ground water heat pump concentrates heat from the 55 degree ground water and sends it into the home as 95 degree warm air. For one unit of electrical energy, it will move three units of heat into the home which means it has a COP of 3:1.

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
Groundwater Heat Pump	D	A	A	A	B	C	A	A	A	E

Energy from the Motion of the Earth, Moon, and Sun

The energy of motion depends on the mass of an object and its speed. The earth is very massive and it is moving through space around the sun at 67,000 miles per hour. It also rotates on its axis once a day which produces speeds up to 1,000 miles per hour at the equator. The moon revolves around the earth at 2,288 miles per hour.

Tidal Energy

One of the effects of the motion of the moon relative to the earth it its effects on the earth's oceans. In most coastal areas the tide rises and falls several feet each day. Because there is a lot of water involved the amount of energy is large but it is very low quality. In some locations the shape of the coast concentrates the tide and it rises as much as 50 feet but these locations are rare. Recall that the Grand Coulee Dam had a drop of 350 feet. To make use of the difference in water height would take a dam across the entire width of a bay or inlet as shown in Figure 7.31. This is very expensive and it only produces energy for a few hours a day and those hours would not necessarily coincide with peak demand for electricity.

Figure 7.31.Tidal power

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
Tidal	D	A	D	A	A	D	A	A	A	C

Energy from Converting Mass into Energy

We know that mass is a very concentrated form of energy. There are only a few types of atoms that can be manipulated into releasing these enormous amounts of energy.

Fusion of Hydrogen Atoms

We know that the nuclei of Hydrogen atoms can be forced together to produce Helium atoms and that the process converts some of the mass into energy. The problem is that the hydrogen nuclei are both positively charged and they repel each other. They can only be made to join under extreme pressure or if they collide at very high speed. A hydrogen bomb uses the shock wave of a Uranium or Plutonium bomb to force Hydrogen atoms together and they are forced together inside the sun by its immense gravity. Efforts have been underway for decades to make a fusion reaction that could produce useable amounts of power slowly so it could be used to produce electric power but scientists and engineers have not been able to overcome the basic problem of the mutual repulsion of the hydrogen atoms. This source would take a major scientific discovery to make it practical. If it could be done, the equipment necessary could be much more expensive than the electricity was worth.

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
Hydrogen Fusion	A	A	A	A	B	E	E	A	B	C

Fission of U-235

Power from Uranium fission is consuming a stored resource but there is enough to last a long time. It is the only alternative to fossil fuels that is already up and running and capable of producing large quantities of energy. It doesn't pollute the air when operating normally. Reactors can malfunction and release radioactive daughter products into the atmosphere that can contaminate crops.

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
Fission U235	A	C	A	C	B	A	A	A	B	C

Fission of Pu-239 and Breeder Reactors

Using U-235 for power and throwing away the other 99% of the Uranium that is U-238 is very inefficient. By using a differently designed reactor, some of the U-238 can be converted to Plutonium which can be extracted from the used fuel rods and concentrated to make new fuel rods. This method could extend the lifetime of the Uranium sources from decades to thousands of years. The biggest drawback to this plan is that Plutonium can be easily concentrated into weapons grade material.

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
Fission Pu239	A	C	A	A-	B	A	A	A	D	C

Energy from Sunshine for Stationary Use

The energy that arrives daily from the sun can be converted into many other forms that can be used to generate electricity or power vehicles.

Hydroelectric

When the sun warms the oceans, some of the water vaporizes and rises into the atmosphere where the wind carries it over land. The water condenses and falls as rain that gathers in rivers. The shape of the land gives the water its high quality as an energy source if large amount of it have a large vertical fall. If a dam is constructed, the water can be trapped in the lake that forms upstream of the dam. If there is enough water flow and the height of the dam is high enough to provide high quality energy, the water can be diverted through turbines to generate electricity.

Almost all of the best dam sites that have high quality energy for the production of electricity are already in use. Many dams were built in the 1930s in the U.S. during the depression to provide work and to provide electricity to rural areas and to control flooding. The Tennessee Valley Authority (TVA) is a good example, as shown in Figure 7.32.

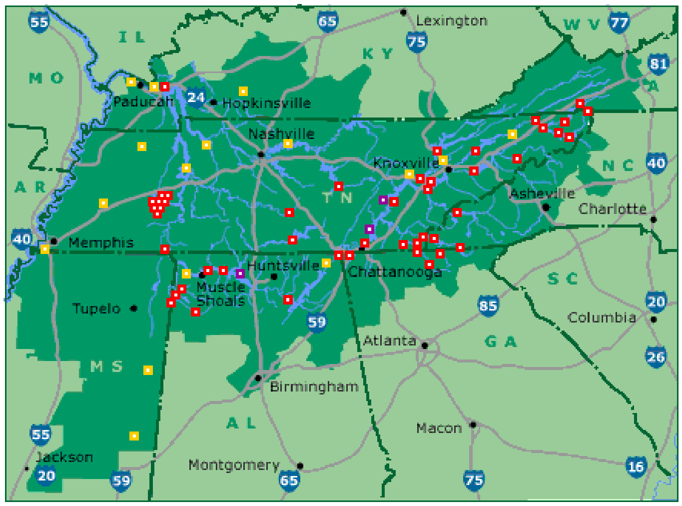


Figure 7.32.Dam sites in the Tennessee Valley Authority

Building new dams is difficult in countries like China where the river valleys are full of people or like Egypt where the river valleys have historical value. This is a source to consider for developing countries that are still sparsely settled and that have suitable locations but it is not scalable to meet additional needs.

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
Hydroelectric	C	A	A	A	B	D	A	A	A	C

Wind

A wind generator is a relatively simple device. Long blades that look like airplane propellers are attached to the shaft of a generator. One of the factors that is poorly understood by the public is how variable the output of a wind generator really is. The power output of a wind generator depends upon the cube of the wind speed. For example, if the wind is blowing at 5 mph and you can get 1 kilowatt out of the generator and then the wind speed doubles to 10 mph the power output goes up to 8 kilowatts. The math looks like this:

$$\left(\frac{10mph^3}{5mph^3}\right) \text{X 1kW} = \frac{1000}{125} \text{ X 1 kW} = 8 \text{ kW}$$

This variability poses a real problem for power generation networks whose job it is to maintain a constant flow of power. Wind systems cannot be more than a small percentage of the total system unless the system also has the ability to store its variable power or distribute it over a wide area of different wind conditions to reduce the variability.

The literature about wind generators usually describes the maximum power of the generator but often does not mention the wind speed at which that power is achieved. For example, the manufacturer says that the wind generator has a maximum output of 1,200 kilowatts but doesn't tell you that they assumed a 20 mph wind speed. If the local wind speed averages about 10 mph, which is typical of many states in the U.S., you will only get 150 kilowatts out of it at 10 mph, not 1,200 as advertised.

$$\left(\frac{10^3}{20^3}\right) \text{X } 1200\text{kW} = \frac{1000}{8000} \text{ X } 1200 \text{ kW} = 150 \text{ kW}$$

To compare wind generators with other sources of electricity, you need to know their capacity factor. California is a leader in wind power and gets 1.5% of its electrical energy from wind energy. In has 13,000 turbines rated at 1,697,000 kilowatts that produced 4,258,000,000 kilowatt-hours of energy. (California Energy Commission 2011) This is a capacity factor of:

$$\frac{4{,}258{,}000{,}000\ kWh}{1{,}697{,}000 kW\ X\ 24 \dfrac{hr}{day} X\ 365\ days/yr} = \frac{4{,}258{,}000{,}000\ kWh}{14{,}865{,}720{,}000\ kWh} = 28\%$$

California's wind generators have a better capacity factor than Michigan's because they are in valleys near the ocean that funnel the wind, which increases its speed. Location is another problem of scalability of wind generators. Because the power output is so sensitive to wind speed, location is critically important. The first generators will be placed at the best sites but the output from these generators is a best-case situation. Wind power is limited by location and variability and needs new storage systems. The costs are well known.

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
Wind	C	A	D	A	A	B	A	A	A-	C

Photovoltaic (PV) on Earth

The energy from the sun reaches the surface of the earth in the form of photons of light. Each of these photons is a tiny bundle of energy. Devices called photovoltaic (PV) cells consist of layers of materials that are designed so that a photon can transfer its energy to an electron on one layer of material that causes it to jump onto the adjacent layer. The layers are made so that it isn't easy for the electron to return directly to its original position. As more photons hit the device, the surplus of energized electrons builds up on one layer and a potential of a few volts is generated with no moving parts. If the cells are used on earth, they produce no power at night and limited power on cloudy days. For example, an installation in Ann Arbor Michigan of 120 PV panels that are 6 feet by 4 feet has a combined rating of 28.4 kilowatts. They produce 38,000 kilowatt-hours in a year. The capacity factor is:

$$\frac{38{,}000\ kWh}{28.4 kW\ X\ 24 \dfrac{hr}{day} X\ 365\ days/yr} = \frac{38{,}000\ kWh}{248{,}784\ kWh} = 15\%$$

One of the natural resources of the U.S. is a large arid region in the Southwest with few cloudy days. A PV installation of 72,000 PV panels at Nellis Air Force Base in Nevada, shown in Figure 7.33, has a much better capacity factor.

$$\frac{30{,}000{,}000\ kWh}{14{,}000kW\ X\ 24\frac{hr}{day}X\ 365\ days/yr} = \frac{30{,}000{,}000\ kWh}{122{,}640{,}000\ kWh} = 24\%$$

Figure 7.33.Photovoltaic cells at Nellis AFB in Nevada

Location is important for PV systems and the best sites in deserts are far from population centers that have normal rainfall with the accompanying clouds. Long-distance electrical power transmission lines would have to be installed from the desert south-west to the East. The amount of land that would be required to provide about half of our electric power is about 46,000 square miles (a square of land 214 miles on a side). To provide all of the electric power needed in the world, the areas indicated by black circles in Figure 7.34 could be covered by PV cells:

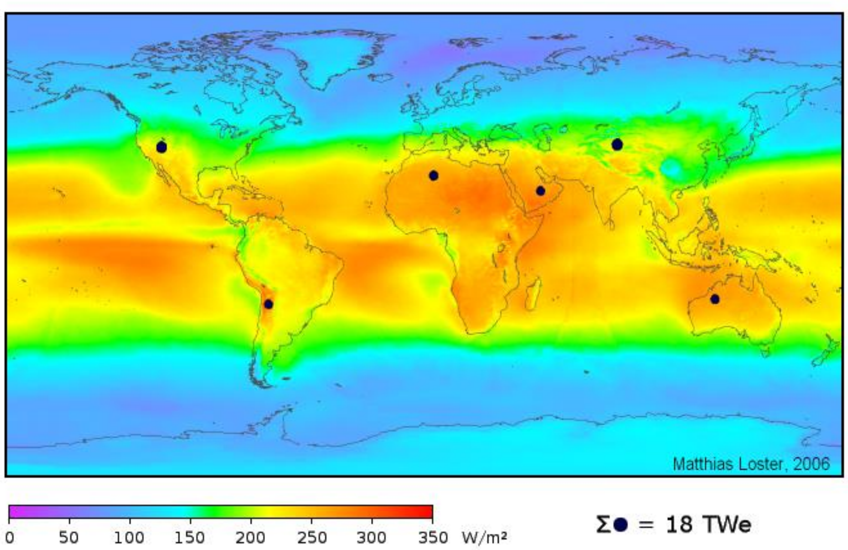


Figure 7.34.Land needed to provide solar energy

The biggest limitation of PV systems is the low capacity factor. Unlike wind, the solar power in desert regions is predictable. To make PV the only solution would require large amounts of storage, which is new, unknown technology. One idea is to use the electricity to run compressors and compress air in underground caverns during the day and then let the compressed air generate electricity at night. (Qweibel, Mason and Fthenakis 2008)

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
PV on Earth	C	A	B	A	A	A	C	A	A	C

Photovoltaic (PV) in Space

Photocells on the ground have an inherent upper limitation on their capacity factor of 50% because they are on the night side of the planet at least half the time. If solar cells are placed in space in an orbit that stays out of the earth's shadow, they could collect solar energy continuously. Large, lightweight mirrors made of aluminized plastic like Mylar balloons could reflect and concentrate sunlight on PV cells to increase the quality of the energy where it would be converted to electricity, as shown in Figure 7.35.

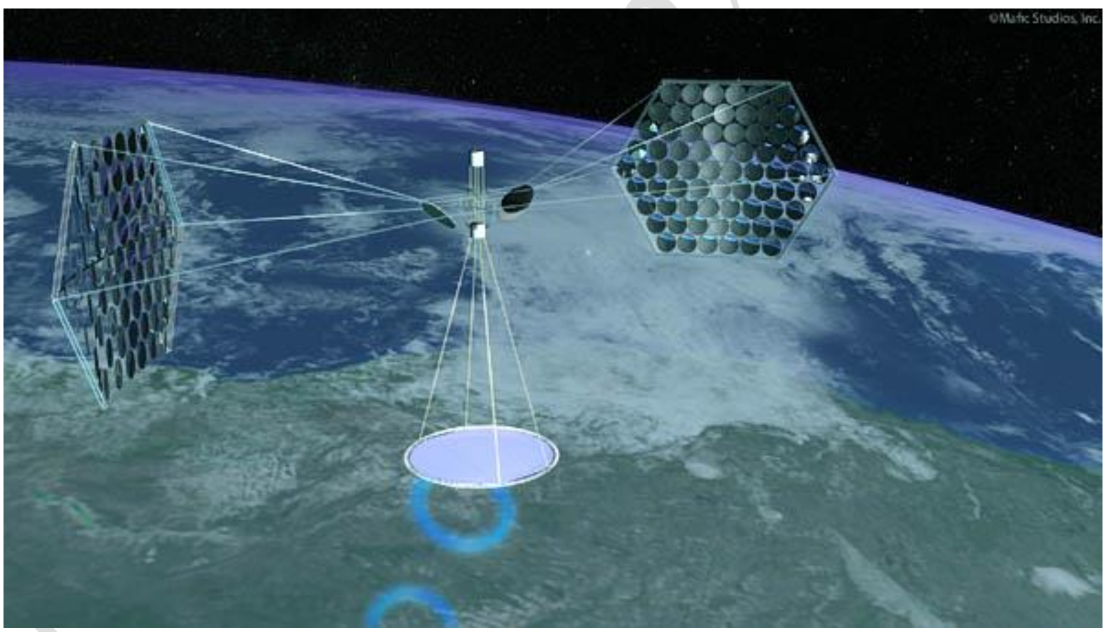


Figure 7.35.Artistic concept of space-based PV system

The energy would be converted into electromagnetic waves and transmitted to antennas on the ground that would be connected to the electrical transmission system. The area of the antennas would be several square miles to reduce the power density so it would be safe for birds. The initial cost of transporting the materials into space would be high. Safety is a concern during normal operation when large amounts of power are transmitted by EM waves through the atmosphere. The potential exists for a system like this to be turned into a weapon if the beam is concentrated which raises safety concerns from the countries that do not control the satellites.

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
PV in Space	A	D	A	A	A	A	C	A	D	C

Energy from Sunshine for Mobile Use

The energy that arrives daily from the sun can be converted into liquids or compressed gasses that can be used to supplement or replace oil.

Ethanol from Corn

Recall that plants use sunlight to make cellulose ($C_6H_{10}O_5$) and dextrose ($C_6H_{12}O_6$). Ethanol is produced when yeast digests dextrose in a water solution. When the concentration of ethanol reaches about 5%, it kills the yeast. To make high concentrations of ethanol, the water/yeast/ethanol mixture is heated below the boiling point of water but above the vaporization temperature of alcohol. The vapor is collected and cooled and the alcohol condenses. This process is called distillation and requires significant amounts of energy.

At first glance, burning corn for transportation sounds like a good idea because it provides high quality energy, is domestic, available, well known, and safe. However, it is not as renewable, clean, or scalable as most people might think and it is not easy to transport in oil pipelines. The production of ethanol requires large amounts of natural gas to make the fertilizer, distill the alcohol, and transport it to gas stations. The net result is that almost as much natural gas energy is consumed to make ethanol as you get back from the fuel. (Pimentel, Ethanol Fuels: Energy Balance, Econiomics, and Environmental Impacts are Negative 2003) [Link] The short-term benefit is that it will work in many new cars but this is also a limitation because it still causes air pollution. The real limitation of ethanol is that it isn't scalable. We cannot grow that much corn. If all of the corn crop in the U.S. was diverted to ethanol production, it would only replace 7% of our oil imports. Additionally, if we ramped up the production of ethanol we would have to decrease our exports of corn causing world food shortages. Finally, alcohol cannot be transported in the pipelines that were designed for oil or natural gas. These lines are buried and not water tight. This isn't a problem with oil but water mixes well with alcohol and ruins its heating value. (Wald 2007)

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
Ethanol from Corn	A	A	A	C	B	D	A	B	A	A

Ethanol from Cellulose

Although cellulose ($C_6H_{10}O_5$) and dextrose ($C_6H_{12}O_6$) are similar chemically, yeast cells do not digest cellulose. This is unfortunate because cellulose forms the woody portions of the plant and there is much more of it than dextrose, which is found in the fruits and seeds. Scientists are looking for something that will break the cellulose down into ethanol—ideally without the presence of much water to reduce the cost of distillation. If we could make ethanol from cellulose then plant fibers like corn stalks, straw, grass, and wood chips could produce ethanol. If the process did not have to take place in a mixture of water, and the ethanol could be concentrated without distillation, this could be a significant source of liquid fuel. Pilot plants are being built to test new bacteria and enzymes that can convert cellulose into ethanol in small quantities. Production in commercial quantities is expected to begin in 2012 in Italy and Spain with four plants in the U.S. to follow. (Fickett 2011)

Scorecard:

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
Ethanol from Cellulose	A	A	A	A	A	A	C	B	A	A

Biodiesel

Recall that diesel fuel consists of hydrocarbon chains that are about sixteen carbons long. Most diesel fuel is made by separating this group of hydrocarbons from crude oil. However, there are other ways to make hydrocarbon chains of this length. If the source is a recently living plant, the fuel is called biodiesel. One source is used cooking oil from restaurant deep fryers. This is a valuable recovery technique but it isn't scalable. An option that made its debut in 2008 is biodiesel produced by algae. If algae can produce biodiesel directly from dextrose or cellulose, it would eliminate the costly step of distillation because diesel fuel does not mix with water. The process isn't proven to be scalable yet but it is worth watching. (Solazyme delivers 100% Algal-derived renewable jet fuel to U.S. Navy 2010)

Scorecard:

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
Biodiesel from Algae	A	A	B	A	A	C	C	A	A	A

To compare the options, their individual scorecards are assembled in the table in Figure 7.34.

	Quality	Domestic	Peak	Renew	Clean	Scalable	Known	Infra	Safe	Trans
Geothermal	A	A	A	A	B	A	E	A	B	C
Groundwater Heat Pump	D	A	A	A	B	C	A	A	A	E
Tidal	D	A	D	A	A	D	A	A	A	C
Hydrogen Fusion	A	A	A	A	B	E	E	A	B	C
Fission U235	A	C	A	C	B	A	A	A	B	C
Fission Pu239	A	C	A	A-	B	A	A	A	D	C
Hydroelectric	C	A	A	A	B	D	A	A	A	C
Wind	C	A	D	A	A	B	A	A	A-	C
PV on Earth	C	A	B	A	A	A	A	A	A	C
PV in Space	A	D	A	A	A	A	C	A	D	C
Ethanol from Corn	A	A	A	C	B	D	A	B	A	A
Ethanol from Cellulose	A	A	A	A	A	A	C	B	A	A
Biodiesel from Algae	A	A	B	A	A	C	C	A	A	A

Key Takeaways

Energy may be obtained from sunlight, heat within the earth, converting mass into energy, and extracting energy from the motion of the earth and moon. [7.3.1]

Annual energy output is how much energy a device can produce in a year and it is measured in kilowatt·hours, kWh. The peak production is the maximum output under ideal circumstances and it is measured in kilowatts, kW. [7.3.2]

Customers use different amounts of electricity at different times of the day and different days of the year. Electricity is more valuable if it is produced when it is needed most. [7.3.3]

The capacity factor is the ratio of the amount of energy a device produces in a year to the amount it might produce if it ran at its maximum rated power continuously for a year. It may be used to compare the reliability or availability of two energy sources. [7.3.4]

Energy sources used for transportation must be high quality with low volume and weight. [7.3.5]

The most limiting factor of each of the alternatives for energy production are: [7.3.6]

- Geothermal: we don't know how to drill through 15 to 20 miles of rock
- Groundwater Heat Pump: Cannot be used for transportation, not a real source
- Tidal: Low quality, not available when needed, not scalable to large quantities
- Hydrogen Fusion: We don't know how to do it, it might be too expensive
- Fission U235: Not renewable, limited lifetime
- Fission Pu239: might provide many countries with nuclear weapons
- Hydroelectric: not scalable, the good sites are already taken

- Wind: not available when its needed, low quality energy
- PV on Earth: Low quality energy requires a lot of collectors
- PV in Space: Not on earth, expensive to build, might be used as a weapon
- Ethanol from Corn: not scalable, Uses natural gas for fertilizer and distillation
- Ethanol from Cellulose: close to knowing how to make in large quantities
- Biodiesel from Algae: close to knowing how to make in large quantities

Key Terms

aquifer

reservoir of groundwater

biodiesel

liquid fuel similar to diesel from petroleum but made from recently living plants or animals

capacity factor

ratio of actual annual energy output of a device to the product of its maximum power multiplied by the hours in a year

carrying capacity

maximum population of a system

closed system

boundary passes energy but not matter

coefficient of performance (COP)

ratio of heat moved by a heat pump to the energy consumed to do so

ecological footprint

amount of land need to support one person with a given lifestyle

deductive reasoning

starting with a belief and using it to explain observations

desalinization

removing salt from water

distillation

separating liquids that have different vaporization temperatures like separating alcohol from water

exponential growth

increase by multiples

fertilizer

assists growth of plants

First Law of Thermodynamics

energy cannot be created or destroyed but it may change form

geothermal

heat from the earth

Green Revolution

increase in food production caused by use of fertilizers, pesticides, irrigation, and new crop breeds

groundwater

rainwater that has seeped into the ground

heat pump

device that uses energy to move larger amounts of energy

hypothesis

a tentative explanation of an observation

inductive reasoning

starting with observations and looking for underlying principles

infallible

without error

isolated system

boundary does not pass energy or matter

linear growth

count increases by adding an amount

municipal waste

solid waste from a city

open system

boundary passes energy and matter

peak demand

highest use of electricity at a particular time

pesticide

kills insects

photovoltaic (PV)

electricity from sunlight

quality

ability of energy to do work

replacement cost

price at which alternatives become competitive

reverse osmosis

forcing a liquid through a filter

Second Law of Thermodynamics

quality of energy decreases with time

septic field

array of porous pipes in sandy soil that allow waste water to evaporate or seep into the ground

septic tank

concrete box used to collect solid waste

theory

well established principle

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