9.4: Energy Sources and Carriers

Electricity

Introduction

Over the past century and a half electricity has emerged as a popular and versatile energy carrier. Communication was an early widespread use for electricity following the introduction of the telegraph in the 1840s. In the 1870s and 1880s electric motors and lights joined the telegraph as practical electrical devices, and in the 1890s electricity distribution systems, the forerunners of today's electricity grid, began to appear. The telegraph became wireless with the invention of radio, demonstrated in the laboratory in the 1880s and for transatlantic communication in 1901. Today, electricity is exploited not only for its diverse end uses such as lighting, motion, refrigeration, communication and computation, but also as a primary carrier of energy. Electricity is one of two backbones of the modern energy system (liquid transportation fuels are the other), carrying high density energy over short and long distances for diverse uses. In 2009, electricity consumed the largest share of the United States' primary energy, 38 percent, with transportation a close second at 37 percent (EIA Annual Energy Review, 2009). These two sectors also accounted for the largest shares of U.S. carbon emissions, 38 percent for electricity and 33 percent for transportation (EIA Annual Energy Review, 2009). Figure 9.4.1 shows the growth of electricity as an energy carrier since 1949 and the growing range of its uses.
Figure \(\PageIndex{1}\) United States Electricity Net Generation Since 1949 and Uses The growth of United States electricity generation since 1949 and some of its uses. Source: G. Crabtree using data from EIA Annual Energy Review 2009, Table 8.2a, p 230.; Felix O, U.S. CPSC, Joe Mabel, Marcin Wichary, Samboy, Andrew, Jan Ainali, Lovelac7

Figure Electricity Energy Chain shows the electricity energy chain from generation to use. By far most electricity is generated by combustion of fossil fuels to turn steam or gas turbines. This is the least efficient step in the energy chain, converting only 36 percent of the chemical energy in the fuel to electric energy, when averaged over the present gas and coal generation mix. It also produces all the carbon emissions of the electricity chain. Beyond production, electricity is a remarkably clean and efficient carrier. Conversion from rotary motion of the turbine and generator to electricity, the delivery of electricity through the power grid, and the conversion to motion in motors for use in industry, transportation and refrigeration can be more than 90 percent efficient. None of these steps produces greenhouse gas emissions. It is the post-production versatility, cleanliness, and efficiency of electricity that make it a prime energy carrier for the future. Electricity generation, based on relatively plentiful domestic coal and gas, is free of immediate fuel security concerns. The advent of electric cars promises to increase electricity demand and reduce dependency on foreign oil, while the growth of renewable wind and solar generation reduces carbon emissions. The primary sustainability challenges for electricity as an energy carrier are at the production step: efficiency and emission of carbon dioxide and toxins.

Figure \(\PageIndex{2}\) Electricity Energy Chain Graph shows the electricity energy chain from generation to use. Source: G. Crabtree
The Electricity Grid: Capacity and Reliability

Beyond production, electricity faces challenges of capacity, reliability, and implementing storage and transmission required to accommodate the remoteness and variability of renewables. The largest capacity challenges are in urban areas, where 79 percent of the United States and 50 percent of the world population live. The high population density of urban areas requires a correspondingly high energy and electric power density. In the United States, 33 percent of electric power is used in the top 22 metro areas, and electricity demand is projected to grow 31 percent by 2035 (Annual Energy Outlook, 2011). This creates an "urban power bottleneck" where underground cables become saturated, hampering economic growth and the efficiencies of scale in transportation, energy use and greenhouse gas emission that come with high population density (Owen, 2009). Saturation of existing cable infrastructure requires installation of substantial new capacity, an expensive proposition for digging new underground cable tunnels.

![Superconducting Underground Cables](https://eng.libretexts.org/Bookshelves/Environmental_Engineering_(Sustainability)/Book%3A_Sustainability_-_A_Comprehen...

Figure \(\PageIndex{3}\)) Superconducting Underground Cables The superconducting wires on the right carry the same current as the conventional copper wires on the left. Superconducting cable wound from these wires carries up to five times the current of conventional copper cables. Source: Courtesy, American Superconductor Corporation

The reliability of the electricity grid presents a second challenge. The United States’ grid has grown continuously from origins in the early 20th Century; much of its infrastructure is based on technology and design philosophy dating from the 1950s and 1960s, when the major challenge was extending electrification to new rural and urban areas. Outside urban areas, the grid is mainly above ground, exposing it to weather and temperature extremes that cause most power outages. The response to outages is frustratingly slow and traditional – utilities are often first alerted to outages by telephoned customer complaints, and response requires sending crews to identify and repair damage, much the same as we did 50 years ago. The United States’ grid reliability is significantly lower than for newer grids in Europe and Japan, where the typical customer experiences ten to 20 times less outage time than in the United States. Reliability is especially important in the digital age, when an interruption of even a fraction of a cycle can shut down a digitally controlled data center or fabrication line, requiring hours or days to restart.

Reliability issues can be addressed by implementing a smart grid with two-way communication between utility companies and customers that continuously monitors power delivery, the operational state of the delivery system, and implements demand response measures adjusting power delivered to individual customers in accordance with a previously established unique customer protocol. Such a system requires installing digital sensors that monitor power flows in the delivery system, digital decision and control technology and digital communication capability like that already
standard for communication via the Internet. For customers with on-site solar generation capability, the smart grid would monitor and control selling excess power from the customer to the utility.

Figure \(\PageIndex{4}\) illustrates the two-way communication features of the smart grid. The conventional grid in the upper panel sends power one way, from the generating station to the customer, recording how much power leaves the generator and arrives at the customer. In the smart grid, the power flow is continuously monitored, not only at the generator and the customer, but also at each connection point in between. Information on the real time power flow is sent over the Internet or another special network to the utility and to the customer, allowing real time decisions on adding generation to meet changes in load, opening circuit breakers to reroute power in case of an outage, reducing power delivered to the customer during peak periods to avoid outages (often called "demand response"), and tracking reverse power flows for customers with their own solar or other generation capacity. The conventional power grid was designed in the middle of the last century to meet the simple need of delivering power in one direction. Incorporating modern Internet-style communications and control features could bring the electricity grid to a qualitatively new level of capability and performance required to accommodate local generation and deliver higher reliability.

Smart components incorporated throughout the grid would be able to detect overload currents and open breakers to interrupt them quickly and automatically to avoid unnecessary damage and triggering a domino effect cascade of outages over wide areas as happened in the Northeast Blackout of 2003. For maximum effectiveness, such smart systems require fast automatic response on millisecond time scales commensurate with the cycle time of the grid. Even simple digital communication meets this requirement, but many of the grid components themselves cannot respond so quickly. Conventional mechanical circuit breakers, for example, take many seconds to open and much longer to close. Such long times increase the risk of dangerous overload currents damaging the grid or propagating cascades. Along with digital communications, new breaker technology, such as that based on fast, self-healing superconducting fault current limiters, is needed to bring power grid operation into the modern era.

**Integrating Renewable Electricity on the Grid**

Accommodating renewable electricity generation by wind and solar plants is among the most urgent challenges facing the grid. Leadership in promoting renewable electricity has moved from the federal to the state governments, many of which have legislated Renewable Portfolio Standards (RPS) that require 20 percent of state electricity generation to be renewable by 2020. 30 states and the District of Columbia have such requirements, the most aggressive being...
California with 33 percent renewable electricity required by 2020 and New York with 30 percent by 2015. To put this legal requirement in perspective, wind and solar now account for about 1.6 percent of U.S. electricity production; approximately a factor of ten short of the RPS requirements. (Crabtree & Misewich, 2010).

Renewable Variability

The grid faces major challenges to accommodate the variability of wind and solar electricity. Without significant storage capacity, the grid must precisely balance generation to demand in real time. At present, the variability of demand controls the balancing process: demand varies by as much as a factor of two from night to day as people go through their daily routines. This predictable variability is accommodated by switching reserve generation sources in and out in response to demand variations. With renewable generation, variation can be up to 70 percent for solar electricity due to passing clouds and 100 percent for wind due to calm days, much larger than the variability of demand. At the present level of 1.6 percent wind and solar penetration, the relatively small variation in generation can be accommodated by switching in and out conventional resources to make up for wind and solar fluctuations. At the 20 percent penetration required by state Renewable Portfolio Standards, accommodating the variation in generation requires a significant increase in the conventional reserve capacity. At high penetration levels, each addition of wind or solar capacity requires a nearly equal addition of conventional capacity to provide generation when the renewables are quiescent. This double installation to insure reliability increases the cost of renewable electricity and reduces its effectiveness in lowering greenhouse gas emissions.

A major complication of renewable variation is its unpredictability. Unlike demand variability, which is reliably high in the afternoon and low at night, renewable generation depends on weather and does not follow any pattern. Anticipating weather-driven wind and solar generation variability requires more sophisticated forecasts with higher accuracy and greater confidence levels than are now available. Because today’s forecasts often miss the actual performance target, additional conventional reserves must be held at the ready to cover the risk of inaccuracies, adding another increase to the cost of renewable electricity.

Storage of renewable electricity offers a viable route to meeting the variable generation challenge. Grid electricity storage encompasses many more options than portable electricity storage required for electric cars. Unlike vehicle storage, grid storage can occupy a large footprint with little or no restriction on weight or volume. Grid storage can be housed in a controlled environment, eliminating large temperature and humidity variations that affect performance. Grid storage must have much higher capacity than vehicle storage, of order 150 MWh for a wind farm versus 20-50 kWh for a vehicle. Because of these differences, the research strategy for grid and vehicle energy storage is very different. To date, much more attention has been paid to meeting vehicle electricity storage requirements than grid storage requirements.

There are many options for grid storage. Pumped hydroelectric storage, illustrated in Figure \(\PageIndex{5}\), is an established technology appropriate for regions with high and low elevation water resources. Compressed Air Energy Storage (CAES) is a compressed air equivalent of pumped hydro that uses excess electricity to pump air under pressure into underground geologic formations for later release to drive generators. This option has been demonstrated in Huntorf, Germany and in McIntosh, Alabama. High temperature sodium-sulfur batteries operating at 300 °C have high energy density, projected long cycle life, and high round trip efficiency; they are the most mature of the battery technologies suggested for the grid. Flow batteries are an attractive and relatively unexplored option, where energy is...
stored in the high charge state of a liquid electrolyte and removed by electrochemical conversion to a low charge state. Each flow battery requires an electrolyte with a high and low charge state and chemical reaction that takes one into the other. There are many such electrolytes and chemical reactions, of which only a few have been explored, leaving a host of promising opportunities for the future. The energy storage capacity depends only on the size of the storage tank, which can be designed fully independently of the power capacity that depends on the size of the electrochemical reactor. Sodium sulfur and flow batteries store electric charge and can be used at any place in the electricity grid. In contrast, thermal storage applies only to concentrating solar power technologies, where mirrors focus solar radiation to heat a working fluid that drives a conventional turbine and generator. In these systems, heat energy can be stored as a molten salt in a highly insulated enclosure for hours or days, allowing solar electricity to be generated on demand after sunset or on cloudy days. All of these options are promising and require research and development to explore innovations, performance and cost limits.

![Pumped Hydroelectric Storage](image)

**Figure \(\PageIndex{5}\)** Pumped Hydroelectric Storage Upper storage reservoir for pumped hydroelectric storage, an established technology for storing large amounts of grid electricity. Source: Ongrys via Wikimedia Commons

### How to Transmit Electricity Over Long Distances

The final challenge for accommodating renewables is long distance transmission. As Figure \(\PageIndex{6}\) shows, the largest wind resources, located at mid-continent, and the largest solar resources, in the southwest, are far from the population centers east of Mississippi and on the West Coast. If these resources are to be used, higher capacity long distance transmission must be developed to bring the renewable electricity to market. Although such long distance delivery is possible where special high voltage transmission lines have been located, the capacity and number of such lines is limited. The situation is much like automobile transportation before the interstate highway system was built in the 1950s. It was possible to drive coast to coast, but the driving time was long and uncertain and the route indirect. To use renewable electricity resources effectively, we must create a kind of interstate highway system for electricity.
Summary

Electricity and liquid petroleum are the two primary energy carriers in the United States, and in the world. Once produced, electricity is clean and versatile making it an appealing energy carrier for the future. The challenges facing the electricity grid are capacity, reliability, and accommodating renewable sources such as solar and wind whose output is variable and whose location is remote from population centers. Electricity storage and long distance transmission are needed to accommodate these renewable resources.

Fossil Fuels (Coal and Gas)

At present the fossil fuels used for electricity generation are predominantly coal (45 percent) and gas (23 percent); petroleum accounts for approximately 1 percent (see Figure \(\PageIndex{7}\)). Coal electricity traces its origins to the early 20th Century, when it was the natural fuel for steam engines given its abundance, high energy density and low cost. Gas is a later addition to the fossil electricity mix, arriving in significant quantities after World War II and with its greatest growth since 1990 as shown in Figure \(\PageIndex{8}\). Of the two fuels, coal emits almost twice the carbon dioxide as gas for the same heat output, making it significantly greater contributor to global warming and climate change.
The Future of Gas and Coal

The future development of coal and gas depend on the degree of public and regulatory concern for carbon emissions, and the relative price and supply of the two fuels. Supplies of coal are abundant in the United States, and the transportation chain from mines to power plants is well established by long experience. The primary unknown factor is the degree of public and regulatory pressure that will be placed on carbon emissions. Strong regulatory pressure on carbon emissions would favor retirement of coal and addition of gas power plants. This trend is reinforced by the recent dramatic expansion of shale gas reserves in the United States due to technology advances in horizontal drilling and...
hydraulic fracturing ("fracking") of shale gas fields. Shale gas production has increased 48 percent annually in the years 2006 – 2010, with more increases expected (EIA Annual Energy Outlook, 2011). Greater United States production of shale gas will gradually reduce imports and could eventually make the United States a net exporter of natural gas.

The technique of hydraulic fracturing of shale uses high-pressure fluids to fracture the normally hard shale deposits and release gas and oil trapped inside the rock. To promote the flow of gas out of the rock, small particles of solids are included in the fracturing liquids to lodge in the shale cracks and keep them open after the liquids are depressurized. Although hydraulic fracturing has been used since the 1940s, is technologically feasible, economic, and proven to enhance gas and oil recovery, it faces considerable environmental challenges. In aquifers overlying the Marcellus and Utica shale formations of northeastern Pennsylvania and upstate New York, methane contamination of drinking water associated with shale gas extraction has been reported (Osborn, Vengosh, Warner, & Jackson, 2011). The public reaction to these reports has been strong and negative, prompting calls for greater transparency, scientific investigation and regulatory control to clearly establish the safety, sustainability and public confidence in the technique. See Module 10.2 for more on the process of hydraulic fracturing and its associated risks.

Figure \(\PageIndex{9}\)) Global Carbon Cycle, 1990s The global carbon cycle for the 1990s, showing the main annual fluxes in GtC yr\(^{-1}\): pre-industrial ‘natural’ fluxes in black and ‘anthropogenic’ fluxes in red. Source: Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Cambridge University Press, figure 7.3

Beyond a trend from coal to gas for electricity generation, there is a need to deal with the carbon emissions from the fossil production of electricity. Figure Global Carbon Cycle, 1990s shows the size of these emissions compared to natural fluxes between ocean and atmosphere and from vegetation and land use. The anthropogenic fluxes are small by comparison, yet have a large effect on the concentration of carbon dioxide in the atmosphere. The reason is the step-wise dynamics of the carbon cycle. The ultimate storage repository for carbon emissions is the deep ocean, with abundant capacity to absorb the relatively small flux from fossil fuel combustion. Transfer to the deep ocean, however, occurs in three steps: first to the atmosphere, then to the shallow ocean, and finally to the deep ocean. The bottleneck is the slow transfer of carbon dioxide from the shallow ocean to the deep ocean, governed by the great ocean conveyor belt or thermohaline circulation illustrated in Figure Great Ocean Conveyor Belt. The great ocean conveyor belt takes 400 – 1000 years to complete one cycle. While carbon dioxide waits to be transported to the deep ocean, it saturates the shallow ocean and "backs up" in the atmosphere causing global warming and threatening climate change. If carbon emissions are to be captured and stored (or "sequestered") they must be trapped for thousands of years while the atmosphere adjusts to past and future carbon emissions (Lenton, 2006).
Figure 10 Great Ocean Conveyor Belt The great ocean conveyor belt (or thermohaline current) sends warm surface currents from the Pacific to Atlantic oceans and cold deep currents in the opposite direction. The conveyor belt is responsible for transporting dissolved carbon dioxide from the relatively small reservoir of the shallow ocean to much larger reservoir of the deep ocean. It takes 400 - 1000 years to complete one cycle. Source: Argonne National Laboratory

Sequestration of carbon dioxide in underground geologic formations is one process that, in principle, has the capacity to handle fossil fuel carbon emissions (Olajire, 2010); chemical reaction of carbon dioxide to a stable solid form is another (Stephens & Keith, 2008). For sequestration, there are fundamental challenges that must be understood and resolved before the process can be implemented on a wide scale.

The chemical reactions and migration routes through the porous rocks in which carbon dioxide is stored underground are largely unknown. Depending on the rock environment, stable solid compounds could form that would effectively remove the sequestered carbon dioxide from the environment. Alternatively, it could remain as carbon dioxide or transform to a mobile species and migrate long distances, finally finding an escape route to the atmosphere where it could resume its contribution to greenhouse warming or cause new environmental damage. The requirement on long term sequestration is severe: a leak rate of 1 percent means that all the carbon dioxide sequestered in the first year escapes in a century, a blink of the eye on the timescale of climate change.

Summary

Coal (45 percent) and gas (23 percent) are the two primary fossil fuels for electricity production in the United States. Coal combustion produces nearly twice the carbon emissions of gas combustion. Increasing public opinion and regulatory pressure to lower carbon emissions are shifting electricity generation toward gas and away from coal. The domestic supply of gas is increasing rapidly due to shale gas released by hydraulic fracturing, a technology with significant potential for harmful environmental impact. Reducing the greenhouse gas impact of electricity production requires capturing and sequestering the carbon dioxide emitted from power plants. Storing carbon dioxide in underground geologic formations faces challenges of chemical transformation, migration, and longevity.
Nuclear Energy

From a sustainability perspective, nuclear electricity presents an interesting dilemma. On the one hand, nuclear electricity produces no carbon emissions, a major sustainable advantage in a world facing human induced global warming and potential climate change. On the other hand, nuclear electricity produces spent fuel that must be stored out of the environment for tens or hundreds of thousands of years, it produces bomb-grade plutonium and uranium that could be diverted by terrorists or others to destroy cities and poison the environment, and it threatens the natural and built environment through accidental leaks of long lived radiation. Thoughtful scientists, policy makers and citizens must weigh the benefit of this source of carbon free electricity against the environmental risk of storing spent fuel for thousands or hundreds of thousands of years, the societal risk of nuclear proliferation, and the impact of accidental releases of radiation from operating reactors. There are very few examples of humans having the power to permanently change the dynamics of the earth. Global warming and climate change from carbon emissions is one example, and radiation from the explosion of a sufficient number of nuclear weapons is another. Nuclear electricity touches both of these opportunities, on the positive side for reducing carbon emissions and on the negative side for the risk of nuclear proliferation.

Debating Nuclear Energy

Nuclear electricity came on the energy scene remarkably quickly. Following the development of nuclear technology at the end of World War II for military ends, nuclear energy quickly acquired a new peacetime path for inexpensive production of electricity. Eleven years after the end of World War II, in 1956, a very short time in energy terms, the first commercial nuclear reactor produced electricity at Calder Hall in Sellafield, England. The number of nuclear reactors grew steadily to more than 400 by 1990, four years after the Chernobyl disaster in 1986 and eleven years following Three Mile Island in 1979. Since 1990, the number of operating reactors has remained approximately flat, with new construction balancing decommissioning, due to public and government reluctance to proceed with nuclear electricity expansion plans. Figure Growth of Fuels Used to Produce Electricity in the United States and Figure Nuclear Share of United States Electricity Generation show the development and status of nuclear power in the United States, a reflection of its worldwide growth.

![Growth of Fuels Used to Produce Electricity in the United States](image1)


The outcome of this debate (Ferguson, Marburger, & Farmer, 2010) will determine whether the world experiences a
nuclear renaissance that has been in the making for several years (Grimes & Nuttall, 2010). The global discussion has been strongly impacted by the unlikely nuclear accident in Fukushima, Japan in March 2011. The Fukushima nuclear disaster was caused by an earthquake and tsunami that disabled the cooling system for a nuclear energy complex consisting of operating nuclear reactors and storage pools for underwater storage of spent nuclear fuel ultimately causing a partial meltdown of some of the reactor cores and release of significant radiation. This event, 25 years after Chernobyl, reminds us that safety and public confidence are especially important in nuclear energy; without them expansion of nuclear energy will not happen.

![Operating and Decommissioned Nuclear Power Plants in the United States](https://eng.libretexts.org/Bookshelves/Environmental_Engineering_(Sustainability)/Book%3A_Sustainability_-_A_Comprehen...)

Figure (\(\PageIndex{12}\)) Operating and Decommissioned Nuclear Power Plants in the United States Graph shows the number of operating versus decommissioned nuclear power plants in the United States. Source: U.S. Energy Information Agency, Annual Energy Review 2009, p. 274 (Aug. 2010)

There are two basic routes for handling the spent fuel of nuclear reactors: once through and reprocessing (World Nuclear Association; Kazimi, Moniz, & Forsberg, 2010). Once through stores spent fuel following a single pass through the reactor, first in pools at the reactor site while it cools radioactively and thermally, then in a long-term geologic storage site, where it must remain for hundreds of thousands of years. Reprocessing separates the useable fraction of spent fuel and recycles it through the reactor, using a greater fraction of its energy content for electricity production, and sends the remaining high-level waste to permanent geologic storage. The primary motivation for recycling is greater use of fuel resources, extracting ~ 25 percent more energy than the once through cycle. A secondary motivation for recycling is a significant reduction of the permanent geologic storage space (by a factor of ~ 5 or more) and time (from hundreds of thousands of years to thousands of years). While these advantages seem natural and appealing from a sustainability perspective, they are complicated by the risk of theft of nuclear material from the reprocessing cycle for use in illicit weapons production or other non-sustainable ends. At present, France, the United Kingdom, Russia, Japan and China engage in some form of reprocessing; the United States, Sweden and Finland do not reprocess.

**Summary**

Nuclear electricity offers the sustainable benefit of low carbon electricity at the cost of storing spent fuel out of the environment for up to hundreds of thousands of years. Nuclear energy developed in only 11 years, unusually quickly for a major energy technology, and slowed equally quickly due to public concerns about safety following Three Mile Island and Chernobyl. The Fukushima reactor accident in March 2011 has raised further serious concerns about safety; its impact on public opinion could dramatically affect the future course of nuclear electricity. Reprocessing spent fuel offers...
the advantages of higher energy efficiency and reduced spent fuel storage requirements with the disadvantage of higher risk of weapons proliferation through diversion of the reprocessed fuel stream.

Renewable Energy: Solar, Wind, Hydro and Biomass

Strong interest in renewable energy in the modern era arose in response to the oil shocks of the 1970s, when the Organization of Petroleum Exporting Countries (OPEC) imposed oil embargos and raised prices in pursuit of geopolitical objectives. The shortages of oil, especially gasoline for transportation, and the eventual rise in the price of oil by a factor of approximately 10 from 1973 to 1981 disrupted the social and economic operation of many developed countries and emphasized their precarious dependence on foreign energy supplies. The reaction in the United States was a shift away from oil and gas to plentiful domestic coal for electricity production and the imposition of fuel economy standards for vehicles to reduce consumption of oil for transportation. Other developed countries without large fossil reserves, such as France and Japan, chose to emphasize nuclear (France to the 80 percent level and Japan to 30 percent) or to develop domestic renewable resources such as hydropower and wind (Scandinavia), geothermal (Iceland), solar, biomass and for electricity and heat. As oil prices collapsed in the late 1980s interest in renewables, such as wind and solar that faced significant technical and cost barriers, declined in many countries, while other renewables, such as hydro and biomass, continued to experience growth.

The increasing price and volatility of oil since 1998, and the increasing dependence of many developed countries on foreign oil (60 percent of United States and 97 percent of Japanese oil was imported in 2008) spurred renewed interest in renewable alternatives to ensure energy security. A new concern, not known in previous oil crises, added further motivation: our knowledge of the emission of greenhouse gases and their growing contribution to global warming, and the threat of climate change. An additional economic motivation, the high cost of foreign oil payments to supplier countries (approximately $350 billion/year for the United States at 2011 prices), grew increasingly important as developed countries struggled to recover from the economic recession of 2008. These energy security, carbon emission, and climate change concerns drive significant increases in fuel economy standards, fuel switching of transportation from uncertain and volatile foreign oil to domestic electricity and biofuels, and production of electricity from low carbon sources.

Physical Origin of Renewable Energy

Although renewable energy is often classified as hydro, solar, wind, biomass, geothermal, wave and tide, all forms of renewable energy arise from only three sources: the light of the sun, the heat of the earth’s crust, and the gravitational attraction of the moon and sun. Sunlight provides by far the largest contribution to renewable energy, illustrated in Figure 1. The sun provides the heat that drives the weather, including the formation of high- and low-pressure areas in the atmosphere that make wind. The sun also generates the heat required for vaporization of ocean water that ultimately falls over land creating rivers that drive hydropower, and the sun is the energy source for photosynthesis, which creates biomass. Solar energy can be directly captured for water and space heating, for driving conventional turbines that generate electricity, and as excitation energy for electrons in semiconductors that drive photovoltaics. The sun is also responsible for the energy of fossil fuels, created from the organic remains of plants and sea organisms compressed and heated in the absence of oxygen in the earth’s crust for tens to hundreds of millions of years. The time scale for fossil fuel regeneration, however, is too long to consider them renewable in human terms.
Geothermal energy originates from heat rising to the surface from earth’s molten iron core created during the formation and compression of the early earth as well as from heat produced continuously by radioactive decay of uranium, thorium and potassium in the earth’s crust. Tidal energy arises from the gravitational attraction of the moon and the more distant sun on the earth’s oceans, combined with rotation of the earth. These three sources – sunlight, the heat trapped in earth’s core and continuously generated in its crust, and gravitational force of the moon and sun on the oceans – account for all renewable energy.

![Image](https://eng.libretexts.org/Bookshelves/Environmental_Engineering_(Sustainability)/Book%3A_Sustainability_-_A_Comprehen…)

**Figure 13** Forms of Renewable Energy Provided by the Sun

The sun is the ultimate source for many forms of renewable energy: wind and running water that can be used for power generation without heat or combustion, and photosynthesis of green plants (biomass) for combustion to provide heat and power generation and for conversion to biofuels (upper panels). Solar energy can be directly captured for water and space heating in buildings, after concentration by mirrors in large plants for utility-scale power generation by conventional turbines, and without concentration in photovoltaic cells that produce power without heat or combustion (lower panels). Source: G. Crabtree using images from Linuxerist, Mor plus, Richard Dorrell, Hermantron, BSMPS, Cachogaray, and Andy F.

As relative newcomers to energy production, renewable energy typically operates at lower efficiency than its conventional counterparts. For example, the best commercial solar photovoltaic modules operate at about 20 percent efficiency, compared to nearly 60 percent efficiency for the best combined cycle natural gas turbines. Photovoltaic modules in the laboratory operate above 40 percent efficiency but are too expensive for general use, showing that there is ample headroom for performance improvements and cost reductions. Wind turbines are closer to their theoretical limit of 59 percent (known as Betz's law) often achieving 35 – 40 percent efficiency. Biomass is notoriously inefficient, typically converting less than one percent of incident sunlight to energy stored in the chemical bonds of its roots, stalks and leaves. Breeding and genetic modification may improve this poor energy efficiency, though hundreds of millions of years of evolution since the appearance of multicelled organisms have not produced a significant advance. Geothermal energy is already in the form of heat and temperature gradients, so that standard techniques of thermal engineering can be applied to improve efficiency. Wave and tidal energy, though demonstrated in several working plants, are at early stages of development and their technological development remains largely unexplored.

**Capacity and Geographical Distribution**

Although renewable energies such as wind and solar have experienced strong growth in recent years, they still make up...
a small fraction of the world’s total energy needs. Figure Renewable Energy Share of Global Final Energy Consumption, 2008 shows the contribution of fossil, nuclear and renewable energy to final global energy consumption in 2008. The largest share comes from traditional biomass, mostly fuel wood gathered in traditional societies for household cooking and heating, often without regard for sustainable replacement. Hydropower is the next largest contributor, an established technology that experienced significant growth in the 20th Century. The other contributors are more recent and smaller in contribution: water and space heating by biomass combustion or harvesting solar and geothermal heat, biofuels derived from corn or sugar cane, and electricity generated from wind, solar and geothermal energy. Wind and solar electricity, despite their large capacity and significant recent growth, still contributed less than one percent of total energy in 2008.

The potential of renewable energy resources varies dramatically. Solar energy is by far the most plentiful, delivered to the surface of the earth at a rate of 120,000 Terawatts (TW), compared to the global human use of 15 TW. To put this in perspective, covering 100x100 km$^2$ of desert with 10 percent efficient solar cells would produce 0.29 TW of power, about 12 percent of the global human demand for electricity. To supply all of the earth’s electricity needs (2.4 TW in 2007) would require 7.5 such squares, an area about the size of Panama (0.05 percent of the earth’s total land area). The world’s conventional oil reserves are estimated at three trillion barrels, including all the oil that has already been recovered and that remain for future recovery. The solar energy equivalent of these oil reserves is delivered to the earth by the sun in 1.5 days.

The global potential for producing electricity and transportation fuels from solar, wind and biomass is limited by geographical availability of land suitable for generating each kind of energy (described as the geographical potential), the technical efficiency of the conversion process (reducing the geographical potential to the technical potential), and the economic cost of construction and operation of the conversion technology (reducing the technical potential to the economic potential). The degree to which the global potential of renewable resources is actually developed depends on many unknown factors such as the future extent of economic and technological advancement in the developing and developed worlds, the degree of globalization through business, intellectual and social links among countries and regions, and the relative importance of environmental and social agendas compared to economic and material objectives. Scenarios evaluating the development of renewable energy resources under various assumptions about the world’s economic, technological and social trajectories show that solar energy has 20-50 times the potential of wind or biomass for producing electricity, and that each separately has sufficient potential to provide the world’s electricity needs in 2050 (de Vries, 2007).

The geographical distribution of useable renewable energy is quite uneven. Sunlight, often thought to be relatively

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evenly distributed, is concentrated in deserts where cloud cover is rare. Winds are up to 50 percent stronger and steadier offshore than on land. Hydroelectric potential is concentrated in mountainous regions with high rainfall and snowmelt. Biomass requires available land that does not compete with food production, and adequate sun and rain to support growth. Figure \(\PageIndex{15}\) shows the geographical distribution of renewable electricity opportunities that are likely to be economically attractive in 2050 under an aggressive world development scenario.

![Renewable Electricity Opportunities Map](https://eng.libretexts.org/Bookshelves/Environmental_Engineering_(Sustainability)/Book%3A_Sustainability_-_A_Comprehen...)

**Figure \(\PageIndex{15}\)** Renewable Electricity Opportunities Map shows areas where one or more of the wind, solar, and biomass options of renewable electricity is estimated to be able to produce electricity in 2050 at costs below 10 b kWh. Source: de Vries, B.J.M., van Vuuren, D.P., & Hoogwijk, M.M. (2007). A hyper-text must be included to the Homepage of the journal from which you are licensing at [http://www.sciencedirect.com/science.../03014215/35/4](http://www.sciencedirect.com/science.../03014215/35/4). Permission for reuse must be obtained from Elsevier.

**Wind and Solar Resources in the United States**

The United States has abundant renewable resources. The solar resources of the United States, Germany and Spain are compared in Figure \(\PageIndex{16}\)). The solar irradiation in the southwestern United States is exceptional, equivalent to that of Africa and Australia, which contain the best solar resources in the world. Much of the United States has solar irradiation as good or better than Spain, considered the best in Europe, and much higher than Germany. The variation in irradiation over the United States is about a factor two, quite homogeneous compared to other renewable resources. The size of the United States adds to its resource, making it a prime opportunity for solar development.

The wind resource of the United States, while abundant, is less homogeneous. Strong winds require steady gradients of temperature and pressure to drive and sustain them, and these are frequently associated with topological features such as mountain ranges or coastlines. The onshore wind map of the United States shows this pattern, with the best wind along a north-south corridor roughly at mid-continent (Figure \(\PageIndex{16}\))). Offshore winds over the Great Lakes and the east and west coasts are stronger and steadier though they cover smaller areas. The technical potential for...
onshore wind is over 8000 GW of capacity (Lu, 2009; Black & Veatch, 2007) and offshore is 800 – 3000 GW (Lu, 2009; Schwartz, Heimiller, Haymes, & Musial, 2010). For comparison, the United States used electricity in 2009 at the rate of 450 GW averaged over the day-night and summer-winter peaks and valleys.

Figure \(\PageIndex{16}\) 80 Meter Wind Resource Map Figure shows the average wind speeds in the United States at 80 meters. Also see offshore wind resource maps. Source: U.S. Department of Energy, National Renewable Energy Laboratory and AWS Truepower LLC

### Barriers to Deployment

Renewable energy faces several barriers to its widespread deployment. Cost is one of the most serious, illustrated in Figure \(\PageIndex{17}\). Although the cost of renewables has declined significantly in recent years, most are still higher in cost than traditional fossil alternatives. Fossil energy technologies have a longer experience in streamlining manufacturing, incorporating new materials, taking advantage of economies of scale and understanding the underlying physical and chemical phenomena of the energy conversion process. As Figure \(\PageIndex{17}\) shows, the lowest cost electricity is generated by natural gas and coal, with hydro and wind among the renewable challengers. Cost, however, is not an isolated metric; it must be compared with the alternatives. One of the uncertainties of the present business environment is the ultimate cost of carbon emissions. If governments put a price on carbon emission to compensate the social cost of global warming and the threat of climate change, the relative cost of renewables will become more appealing even if their absolute cost does not change. This policy uncertainty in the eventual cost of carbon-based power generation is a major factor in the future economic appeal of renewable energy.
Figure 17 Production Cost of Electricity - 2020 Projection Estimates of the cost of electricity in 2020 by fossil, nuclear and renewable generation. Source: European Commission, Strategic Energy Technologies Information System

A second barrier to widespread deployment of renewable energy is public opinion. In the consumer market, sales directly sample public opinion and the connection between deployment and public acceptance is immediate. Renewable energy is not a choice that individual consumers make. Instead, energy choices are made by government policy makers at city, state and federal levels, who balance concerns for the common good, for “fairness” to stakeholders, and for economic cost. Nevertheless, public acceptance is a major factor in balancing these concerns: a strongly favored or disfavored energy option will be reflected in government decisions through representatives elected by or responding to the public. Figure 18 shows the public acceptance of renewable and fossil electricity options. The range of acceptance goes from strongly positive for solar to strongly negative for nuclear. The disparity in the public acceptance and economic cost of these two energy alternatives is striking: solar is at once the most expensive alternative and the most acceptable to the public.

The importance of public opinion is illustrated by the Fukushima nuclear disaster of 2011. The earthquake and tsunami that ultimately caused meltdown of fuel in several reactors of the Fukushima complex and release of radiation in a populated area caused many of the public in many countries to question the safety of reactors and of the nuclear electricity enterprise generally. The response was rapid, with some countries registering public consensus for drastic action such as shutting down nuclear electricity when the licenses for the presently operating reactors expire. Although its ultimate resolution is uncertain, the sudden and serious impact of the Fukushima event on public opinion shows the key role that social acceptance plays in determining our energy trajectory.
Figure \((\PageIndex{18})\) Acceptance of Different Sources of Energy Figure shows the European Union citizens’ public acceptance of renewable and fossil electricity generation technologies. Source: European Commission, Eurobarometer on Energy Technologies: Knowledge-Perception-Measures, p. 33

Summary

Strong interest in renewable energy arose in the 1970s as a response to the shortage and high price of imported oil, which disrupted the orderly operation of the economies and societies of many developed countries. Today there are new motivations, including the realization that growing greenhouse gas emission accelerates global warming and threatens climate change, the growing dependence of many countries on foreign oil, and the economic drain of foreign oil payments that slow economic growth and job creation. There are three ultimate sources of all renewable and fossil energies: sunlight, the heat in the earth’s core and crust, and the gravitational pull of the moon and sun on the oceans. Renewable energies are relatively recently developed and typically operate at lower efficiencies than mature fossil technologies. Like early fossil technologies, however, renewables can be expected to improve their efficiency and lower their cost over time, promoting their economic competitiveness and widespread deployment.

The future deployment of renewable energies depends on many factors, including the availability of suitable land, the technological cost of conversion to electricity or other uses, the costs of competing energy technologies, and the future need for energy. Scenario analyses indicate that renewable energies are likely to be technically and economically capable of supplying the world’s electricity needs in 2050. In addition to cost, public acceptance is a key factor in the widespread deployment of renewable energy.

Fossil Fuel (Oil)

Liquid petroleum fuels and electricity are the two dominant energy carriers in the United States, oil accounting for 37 percent of primary energy and electricity for 38 percent. These two energy carriers account for a similar fraction of carbon emissions, 36 percent and 38 percent, respectively. Two thirds of oil consumption is devoted to transportation, providing fuel for cars, trucks, trains and airplanes. For the United States and most developed societies, transportation is woven into the fabric of our lives, a necessity as central to daily operations as food or shelter. The concentration of oil reserves in a few regions or the world (Figure Crude Oil Reserves) makes much of the world dependent on imported energy for transportation.

The rise in the price of oil in the last decade makes dependence on imported energy for transportation an economic as well as an energy issue. The United States, for example, now spends upwards of $350 billion annually on imported oil, a drain of economic resources that could be used to stimulate growth, create jobs, build infrastructure and promote social
advances at home.

From a sustainability perspective, oil presents several challenges. First is the length of time over which the world's finite oil reserves can continue to supply rising demand. Second is the impact on global warming and climate change that carbon emissions from oil combustion will have, and third is the challenge of finding a sustainable replacement for oil for transportation. The first challenge, how much oil is left and when its production will peak, was discussed in Module Sustainable Energy Systems - Chapter Introduction. The bottom line is that, as Yogi Berra famously said, making predictions is difficult, especially about the future. Although we know the general course of initial rise and ultimate fall that global oil production must take, we do not know with confidence the time scale over which it will play out.

The uncertainty of the timing of the peak in global oil production encourages us to find other issues and motivations for dealing with an inevitably unsustainable supply. A prime motivation is energy security, the threat that oil supplies could be interrupted by any of several events including weather, natural disaster, terrorism and geopolitics. Much of the world feels these threats are good reasons for concerted effort to find replacements for oil as our primary transportation fuel. A second motivation is the environmental damage and accumulation of greenhouse gases in the atmosphere due to transportation emissions. Unlike electricity generation, transportation emissions arise from millions of tiny sources, e.g. the tailpipes of cars and trucks and the exhaust of trains and airplanes. The challenge of capturing and sequestering carbon dioxide from these distributed and moving sources is dramatically greater than from the large fixed sources of power plants. A more achievable objective may be replacing oil as a transportation fuel with biofuel that recycles naturally each year from tailpipes of cars to biofuel crops that do not compete with food crops. Other options include replacing liquid fuels with electricity produced domestically, or increasing the efficiency of vehicles by reducing their weight, regeneratively capturing braking energy, and improving engine efficiency. Each of these options has promise and each must overcome challenges.

Changes in the energy system are inevitably slow, because of the time needed to develop new technologies and the operational inertia of phasing out the infrastructure of an existing technology to make room for a successor. The transportation system exhibits this operational inertia, governed by the turnover time for the fleet of vehicles, about 15 years. Although that time scale is long compared to economic cycles, the profit horizon of corporations and the political horizon of elected officials, it is important to begin now to identify and develop sustainable alternatives to oil as a transportation fuel. The timescale from innovation of new approaches and materials to market deployment is typically 20 years or more, well matched to the operational inertia of the transportation system. The challenge is to initiate innovative research and development for alternative transportation systems and sustain it continuously until the alternatives are established.

Summary

Oil for transportation and electricity generation are the two biggest users of primary energy and producers of carbon emissions in the United States. Transportation is almost completely dependent on oil and internal combustion engines for its energy. The concentration of oil in a few regions of the world creates a transportation energy security issue. Unlike electricity generation emissions, carbon emissions from transportation are difficult to capture because their sources, the tailpipes of vehicles, are many and moving. The challenges of oil energy security and capturing the carbon emissions of vehicles motivate the search for an oil replacement, such as biofuels, electricity or greater energy efficiency of vehicles.
The Conversion of Biomass into Biofuels

Biofuels are fuels made from biomass. The best known example is ethanol, which can be easily fermented from sugar cane juice, as is done in Brazil. Ethanol can also be fermented from broken down (saccharified) corn starch, as is mainly done in the United States. Most recently, efforts have been devoted to making drop-in replacement hydrocarbon biofuels called green gasoline, green diesel, or green jet fuel. This chapter discusses the need for biofuels, the types of biofuels that can be produced from the various available biomass feedstocks, and the advantages and disadvantages of each fuel and feedstock. The various ways of producing biofuels are also reviewed.

The Need for Renewable Transportation Fuels

In crude oil, coal, and natural gas, (collectively called fossil fuels) our planet has provided us with sources of energy that have been easy to obtain and convert into useful fuels and chemicals. That situation will soon change, however, in a few decades for petroleum crude and in a few centuries for coal and natural gas. Peak Oil refers to the peak in oil production that must occur as petroleum crude runs out. As shown in Figure \(\PageIndex{19}\), the main discoveries of crude oil occurred prior to 1980.

Since oil is getting harder and harder to find, we now have to obtain it from less accessible places such as far under the ocean, which has led to hard-to-repair accidents such as the Deepwater Horizon oil spill in May, 2010. An additional effect is the higher cost of refining the petroleum since it comes from more remote locations or in less desirable forms such as thick, rocky “tar sand” or “oil sand” found in Canada or Venezuela. Overall, the use of petroleum crude cannot exceed the amount of petroleum that has been discovered, and assuming that no major oil discoveries lie ahead, the production of oil from crude must start to decrease. Some analysts think that this peak has already happened.

An additional aspect of oil scarcity is energy independence. The United States currently imports about two thirds of its petroleum, making it dependent on the beneficence of countries that possess large amounts of oil. These countries are shown in Figure \(\PageIndex{20}\), a world map rescaled with the area of each country proportional to its oil reserves. Middle Eastern countries are among those with the highest oil reserves. With its economy and standard of living so
based on imported petroleum crude it is easy to see why the United States is deeply involved in Middle East politics. It should be noted that Figure \(\PageIndex{19}\) corresponds to the entire world and even currently oil-rich countries such as Saudi Arabia will soon experience peak oil.

![Who has the oil?](https://eng.libretexts.org/Bookshelves/Environmental_Engineering_(Sustainability)/Book%3A_Sustainability_-_A_Comprehens...)

**Figure \(\PageIndex{19}\)** The World According to Oil World map redrawn with country area proportional to oil resources. Source: Rep. Roscoe Bartlett, Maryland

A second major motivation to move away from petroleum crude is global climate change. While the correlation of carbon dioxide (CO2) concentration in the atmosphere to average global temperature is presently being debated, the rise of CO2 in our atmosphere that has come from burning fossil fuel since the industrial revolution is from about 280 ppm to about 390 ppm at present, and cannot be denied. Energy sources such as wind, solar, nuclear, and biomass are needed that minimize or eliminate the release of atmospheric CO2. Biomass is included in this list since the carbon that makes up plant fiber is taken from the atmosphere in the process of photosynthesis. Burning fuel derived from biomass releases the CO2 back into the atmosphere, where it can again be incorporated into plant mass. The Energy Independence and Security Act (EISA) of 2007 defines an advanced biofuel as one that lowers lifecycle greenhouse gas emissions (emissions from all processes involved in obtaining, refining, and finally burning the fuel) by 60% relative to the baseline of 2005 petroleum crude.

**First Generation Biofuels**

First generation biofuels are commonly considered to be ethanol, as has been produced in Brazil for over 30 years from sugar cane, and biodiesel produced by breaking down, in a process called transesterification, vegetable oil. Brazil can efficiently harvest the juice from its sugar cane and make ethanol, which is price-competitive with gasoline at cost per mile.
Figure \(\PageIndex{20}\)) Gas/Ethanol Fuel Pump A fuel pump in Brazil offering either ethanol alcohol (A) or gasoline (G). Source: Natecull

There, if the cost of alcohol (as it is known colloquially) is less than 70% than the cost of gasoline, tanks are filled with ethanol. If the cost of alcohol is more than 70% of the cost of gasoline, people fill up with gasoline since there is about a 30% penalty in gas mileage with ethanol. This comes about simply because the chemical structure of ethanol has less energy per volume (about 76,000 Btu/gallon or 5,100 kcal/liter) than gasoline (115 Btu/gallon or 7,600 kcal/liter) or diesel (132,000 Btu/gallon or 8,800 kcal/liter). Cane ethanol qualifies, per EISA 2007, as an advanced biofuel.

In the United States, for a cost of about twice that of cane-derived ethanol, corn starch is saccharified and fermented into ethanol. Ethanol is used predominantly as a high octane, oxygenated blend at 10% to improve the combustion in gasoline engines. The distribution of ethanol as E85 flex fuel (85% ethanol and 15% gasoline) has faltered probably because the price, even with a 50 cents/gallon federal subsidy, does not make up for the 25 – 30% decrease in gas mileage (see Figure \(\PageIndex{21}\)).
First generation biodiesel is made via the base catalyzed transesterification of plant oils such as soy and palm. The main disadvantage with plant oil-based biofuels is the high cost of the plant oil, owing to the relatively little oil that can be produced per acre of farmland compared to other biofuel sources. The problem with transesterification is that it produces a fuel relatively high in oxygen, which a) causes the biodiesel to become cloudy (partially freeze) at relatively high temperature, and makes the biodiesel b) less stable, and c) less energy dense than petroleum-derived diesel.

Cane ethanol qualifies as an advanced biofuel, as its production lowers greenhouse gas emissions more than 60% relative to the 2005 petroleum baseline (per EISA 2007). Corn ethanol is far from this energy efficiency. However, ethanol made from lignocellulose – the non-food part of plants - comes close, at a 50% reduction. This brings us to the second generation of biofuels.

Second Generations Biofuels

Second generation biofuels are shown in Figure 22. In anticipation of the “food versus fuel” debate, EISA 2007 placed a cap on the production of corn ethanol (at 15 billion gallons/year, close to what is now produced), with the bulk of biofuels to be derived from agricultural residues such as corn stover (the parts of the corn plant left over from the ears of corn – the stalk and leaves) and wheat straw, forest waste (wood trimmings) and energy crops such as switchgrass and short rotation poplar trees which can be grown on abandoned or marginal farmland with minimal irrigation and fertilization. A U.S. Department of Agriculture study commissioned in 2005 called the Billion Ton Study estimated that approximately one billion tons per year of biomass could be sustainably produced in the United States each year; the energy in this biomass equals to the amount of oil we import. If the energy contained in this biomass can be recovered at an efficiency of 50 percent, we can replace half of our imported oil with domestically produced biofuels.
Collectively termed “lignocellulose,” this material consists of three main components: cellulose, hemicellulose, and lignin. Chemical or biological pretreatments are required to separate the whole biomass into these fractions. Hemicellulose and cellulose, with the appropriate enzymes or inorganic acids, can be deconstructed into simple sugars and the sugars fermented into ethanol, or with some newer strains of microbes, into butanol. Butanol has only 10% less energy density than gasoline. The lignin fraction of biomass is the most resistant to deconstruction by biological or chemical means and is often burned for heat or power recovery.

At the same time attention turned toward cellulosic ethanol, petroleum refining companies set about to improve biodiesel. A petroleum refining process called hydrotreating was used to upgrade plant oil. In this process, the oil is reacted with hydrogen in the presence of inorganic catalysts, and the plant oil is converted into a much higher quality, oxygen-free “green diesel” and jet fuel. This type of biofuel is in fact a “drop in replacement” to petroleum-derived diesel and jet fuel and passes all of the stringent regulations demanded by the automobile and defense industries. It has been tested in a number of commercial and military aircraft.

The various routes to drop-in replacement hydrocarbon biofuels are shown in Figure Routes to Advanced Biofuels. On the left side of the figure, feedstocks are ordered relative to their abundance and cost. The most abundant and,
therefore, cheapest feedstock is lignocellulose from sources such as agricultural residue, forest waste, and energy crops such as switch grass and short rotation poplar trees. Of lesser abundance and higher expense are the sugars and starches – corn and sugar cane. The least abundant and most expensive biofuels, lipid-based feedstocks from plant oil or animal fat, are shown at the bottom. Efforts are underway to mass produce oil-laden algae. The oils harvested from algae are relatively easy to convert to hydrocarbon biofuels, by using processing similar to hydrotreating. The main set of problems associated with algae lie in its mass production. Algal feedstocks are easy to convert to hydrocarbons but algae itself is difficult to mass produce, whereas lignocellulose is very abundant but more difficult to convert into hydrocarbons.

Two of the routes to hydrocarbon biofuels compete directly with fermentation of sugars to ethanol. The same sugars can be treated with inorganic catalysts, via the blue liquid phase processing routes seen in the center of Figure \(\PageIndex{23}\), or with microbial routes to yield hydrocarbons as the fermentation product (pink routes). Microbes are examples of biocatalysts; enzymes within the microbe act in basically the same way that inorganic catalysts act in inorganic solutions. The field of research in which enzymes are engineered to alter biological reaction pathways is called synthetic biology.

A flow sheet of an inorganic catalytic set of processes to hydrocarbon biofuels, from a leading biofuel startup company (Virent Energy Systems of Madison, Wisconsin) is shown in Figure \(\PageIndex{24}\). Both of the biocatalytic and the inorganic catalytic processes involve an intrinsic separation of the hydrocarbon product from water, which eliminates the energy intensive distillation step needed for alcohol fuels. For the microbial route the added benefit of this self-separation is that the microbes are not poisoned by the accumulation of product as occurs in fermentation to alcohol.

Two other main routes to hydrocarbon biofuels are seen in the upper section of Figure \(\PageIndex{23}\): gasification and pyrolysis. An advantage of both of these routes is that they process whole biomass, including the energy-rich lignin fraction of it. Gasification produces a mixture of carbon monoxide and hydrogen called synthesis gas, which can be converted to hydrocarbon fuels by a number of currently commercialized catalytic routes including Fischer-Tropsch synthesis and methanol-to-gasoline. The challenge with biomass is to make these processes economically viable at small scale. The second process is pyrolysis, which yields a crude-like intermediate called pyrolysis oil or bio-oil. This intermediate must be further treated to remove oxygen; once this is done it can be inserted into an existing petroleum refinery for further processing.
Summary

The motivations for hydrocarbon biofuels are energy independence and a reduction in greenhouse gas emissions. The first renewable biofuels were biodiesel and bioethanol. With inorganic catalysis and synthetic biology, these have been supplanted with drop-in replacement gasoline, diesel, and jet fuels. These can be made in the United States in a number of ways from presently available, sustainably produced lignocellulosic feedstocks such as corn stover, wood chips, and switchgrass, and in the future, from mass-produced algae. It is too early to tell which production method will prevail, if in fact one does. Some processes might end up being particularly advantageous for a particular feedstock such as wood or switchgrass. What we do know is that something has to be done; our supply of inexpensive, easily accessible oil is running out. Biofuels will be a big part of the country's long-term energy independence. A great deal of scientific and engineering research is currently underway; it's an exciting time for biofuels.

Geothermal Heating and Cooling

With limited supplies of fossil fuels in the coming decades and increasing awareness of environmental concerns related to combustions of fossil fuels, alternate energy sources such as geothermal are becoming increasingly attractive. Geothermal energy is energy that comes from the earth. In this section we describe the basic principles of geothermal energy systems and the energy savings that can result from their use.

The Heat Pump

The key to understanding a geothermal energy system is the heat pump. Normally heat goes from a hot area to a cold area, but a heat pump is a device that enables heat to be transferred from a lower temperature to a higher temperature with minimal consumption of energy (see Figure 25). The condensed steam in a geothermal heat pump will thus provide heat at a much higher temperature to the area being heated than the original heat source. Finally a throttle, similar to a water faucet at home, is used to lower the pressure (See Expansion Valve in Figure 26) to complete the closed system cycle, which is then repeated. By switching the direction of the heat pump, the geothermal system can be used for cooling as well.
Geothermal Heating and Cooling

Geothermal systems are suited to locations with somewhat extreme temperature ranges. Areas with moderate temperature ranges (e.g. some areas of California) can use ordinary heat pumps with similar energy savings by adding or removing heat to/from the outside air directly. Areas that experience somewhat extreme temperatures (e.g. the Midwest and East Coast) are ideal target locations for geothermal systems. For regions with moderate climates, such as many parts of the South or the West Coast, conventional heat pumps, that exchange energy generally with the outside air, can still be used with similar energy savings. Geothermal heat pumps (GHPs) use the almost constant temperatures (7°C to 8°C, or 45°F to 48°F) of soil beneath the frost line as an energy source to provide efficient heating and cooling all year long. The installation cost of GHPs is higher than conventional systems due to additional drilling and excavation expenses, but the added cost is quickly offset by GHPs’ higher efficiency. It is possible to gain up to 50 percent savings over conventional heating and cooling systems (see Figure \(\PageIndex{26}\)), which allows the additional capital costs from installation to be recovered, on average, in less than 5 years. GHP’s have an average lifespan of over 30 years, leaving 25 years or more of heating/cooling savings for those willing to make the investment. In addition, GHPs are space efficient and, because they contain fewer moving components, they also have lower maintenance costs.

Types of Geothermal Systems

There are two major types of geothermal systems: in ground and pond systems. In ground geothermal systems can be vertical and horizontal as shown in Figure \(\PageIndex{27}\)). The excavation cost of vertical systems is generally higher and they require more land area for installation, which is generally not an option in urban locations. Other than excavation costs, vertical and horizontal GHPs have similar efficiencies since the ground temperature below the frost line is essentially constant.
Pond geothermal systems are generally preferable if there is water available in the vicinity at almost constant temperature year round. These systems are especially suited to industrial units (e.g. oil refineries) with water treatment facilities to treat processed water before it is discharged. The temperature of treated water from these facilities is essentially constant throughout the year and is an ideal location for a pond system. Pond geothermal systems are constructed with either open loops or closed loops (see Figure \(\PageIndex{28}\)). Open loop systems actually remove water from the pond, while the close loop systems only remove energy in the form of heat from the pond water. Of course, in open pond system this water is again returned to the pond, albeit at a lower temperature when used for heating.
Ecothermics of Geothermal Systems

As stated earlier, depending upon the type of system, the capital and installation cost of a geothermal system is about twice the cost of a traditional heating, ventilation, air conditioning (HVAC) system. However, both the operating and maintenance costs are much lower and switching from heating to cooling is effortless. A typical return of investment (ROI) plot for a ground geothermal system for a multi-unit building is favorable (see Figure 29). A geothermal system that had an additional $500,000 in capital costs but lower operating and maintenance costs allowed the added cost to be recouped in 5 to 8 years. Since the average lifespan of a geothermal system is at least 30 years, the savings over the lifetime of the system can be substantial. The efficiency of ground geothermal systems is fairly constant since there are no large variations in ground temperature. The efficiency for pond systems would, in general, be much higher than those shown in Figure 29 if, during the winter months, the pond water temperature is higher than typical ground temperatures below the frost line (7°C - 8°C, or 44°F - 48°F) because the efficiency of heat pumps increases with higher heat source temperature. Another reason for higher efficiency of pond systems is the much higher heat transfer rate between a fluid and the outer surface of the geothermal pipes, especially if the water is flowing.

![Return of Investment in Geothermal System](https://eng.libretexts.org/Bookshelves/Environmental_Engineering_(Sustainability)/Book%3A_Sustainability_-_A_Comprehensive...)  

Increasing Efficiency of Geothermal Systems

Several strategies are available to increase the efficiency of geothermal systems. One of the most promising possibilities is to use it in conjunction with phase change materials (PCM) (see also Module 10.6), particularly to handle peak loads of energy consumptions. Phase change materials are materials that can absorb and deliver much larger amounts of energy compared to typical building materials. The cost of geothermal systems unlike other HVAC systems increases almost linearly with system size (approximately $1000/ton). Thus, building larger systems to account for peak loads can significantly add to both the capital and installation costs. PCM can be incorporated into all four geothermal systems described earlier. The best approach is to incorporate PCMs with geothermal systems for applications in systems with non-uniform energy requirements, or systems with short but significant swings and peaks in energy needs. For example, designers may include snow melting heating systems for train platforms or they may build a buffer energy reservoir...
using PCMs to satisfy peak needs of cooling on a hot summer afternoon. The advantages in the former application would be to avoid running the geothermal system for heat loads at low temperatures over prolonged periods, which would not be as energy efficient and would require specially designed systems.

Using phase change materials allows for the use of standard geothermal systems, which would then store energy in a PCM unit to supply heat at a constant temperature and at a uniform heat rate to, for example, melt the snow on train platforms. Once the energy in the PCM is nearly used the geothermal system would repower the PCM storage. The extra energy needs for peak periods could be stored in PCM Storage Tanks and then used to address such needs. For example, on a hot summer day, the PCM unit can be used to remove additional heat above the designed capacity of the geothermal system during temperature spikes, which generally last only a few hours. This then reduces the load on the geothermal system during peak hours when electricity cost is generally the highest.

PCM Storage Tanks reduce the overall cost of the geothermal heat pump system significantly since it does not have to be designed to address peak heating/cooling needs. In addition, it also shifts energy loads from peak hours to non-peak hours. Figure 1 shows temperature variations for a typical summer day in July 2010 in Chicago. The high temperature of 90 degrees lasted only for a short period of about 4 hours, and then returned to below 85 degrees rapidly. These relatively short temperature peaks can be easily managed by PCMs.

Figure 1 Temperature Variation Temperature variation during a typical July day in Chicago. Source: Sohail Murad produced figure using data from Great Lakes Environmental Research Laboratory

In conclusion, geothermal heat pumps are a very attractive, cost efficient sustainable energy source for both heating and cooling with a minimal carbon print. It is a well-developed technology that can be easily incorporated into both residential and commercial buildings at either the design stage or by retrofitting buildings.

References


Review Questions

1. Electricity is the fastest growing energy carrier in the world, trailed by liquid fuels for transportation. Why is electricity more appealing than liquid fuels?

2. A primary challenge for the electricity grid is capacity to handle the "urban power bottleneck" in cities and suburbs. How can superconducting cables address urban capacity issues?

3. Renewable wind and solar electricity is plentiful in the United States, but they are located remotely from high population centers and their output is variable in time. How can these two issues be addressed?

4. The United States’ electricity supply is provided primarily by coal, natural gas, nuclear, and hydropower. How safe are these fuel supplies from interruption by international disasters, weather events or geopolitical tension?

5. Natural gas reserves from shale are increasing rapidly due to increased use of hydrofracturing technology ("fracking"). The increased domestic resource of shale gas has the potential to provide greater energy security at the expense of greater environmental impact. What are the long-term costs, benefits, and outlook for tapping into domestic shale gas reserves?

6. Anthropogenic carbon emissions are small compared to natural exchange between ocean and atmosphere and fluxes from vegetation and land use. Why do anthropogenic emissions have such a large effect on the concentration of carbon dioxide in the atmosphere?

7. One proposal for mitigating carbon emissions is capturing and storing them in underground geologic formations (sequestration). What scientific, technological and policy challenges must be overcome before sequestration can be deployed widely?

8. Nuclear electricity came on the scene remarkably quickly following the end of World War II, and its development stagnated quickly following the Three Mile Island and Chernobyl accidents. The Fukushima disaster of 2011 adds a third cautionary note. What conditions must be fulfilled if the world is to experience an expansion of nuclear electricity, often called a nuclear renaissance?

9. Nuclear fuel can be used once and committed to storage or reprocessed after its initial use to recover unused nuclear fuel for re-use. What are the arguments for and against reprocessing?

10. Storage of spent nuclear fuel for tens to hundreds of thousands of years is a major sustainability challenge for nuclear electricity. Further development of the Yucca Mountain storage facility has been halted. What are some of the alternatives for storing spent nuclear fuel going forward?

11. What events in the 1970s and late 1990s motivated the modern interest in renewable energy?
12. Renewable energy is often divided into solar, wind, hydropower, biomass, geothermal, wave and tide. What are the ultimate sources of each of these renewable energies? What is the ultimate source of fossil fuel and why is it not classified as renewable?

13. Renewable energy has the technical potential to supply global electricity needs in 2050. What factors determine whether renewable energy will actually be deployed to meet this need? How can unknowns, such as the rate of technological and economic advances, the economic, intellectual and social connections among countries, and the relative importance of environmental and social agendas be taken into account in determining the course of deployment of renewable energy?

14. Public acceptance is a key factor in the growth of renewable energy options. What is the public acceptance of various energy options, and how might these change over the next few decades?

15. The almost exclusive dependence of the transportation system on liquid fuels makes oil an essential commodity for the orderly operation of many societies. What are some alternatives to oil as a transportation fuel?

16. There are many reasons to reduce consumption of oil, including an ultimately finite supply, the high cost and lost economic stimulus of payments to foreign producers, the threat of interruption of supply due to weather, natural disaster, terrorism or geopolitical decisions, and the threat of climate change due to greenhouse gas emissions. Which of these reasons are the most important? Will their relative importance change with time?

17. The transportation system changes slowly, governed by the lifetime of the fleet of vehicles. Compare the time required for change in the transportation system with the timescale of economic cycles, the profit horizon of business, the political horizon of elected officials and the time required to develop new transportation technologies such as electric cars or biofuels. What challenges do these time scales present for changing the transportation system?

18. What are the potential advantages of hydrocarbon biofuels over alcohol biofuels?

19. How could biofuels be used with other alternate energy forms to help the United States become energy independent?

20. On what principle does a geothermal heat pump work?

21. What makes it more cost efficient than electrical heating or conventional furnaces?

22. Are geothermal heat pumps suitable for moderate climates (e.g. Miami, FL)? Are conventional electrical or gas furnaces the only choices in these areas?

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**Glossary**

**Energy Carrier**

A medium, such as electricity, gasoline or hydrogen, that can move energy from one place to another, usually from the point of production (e.g. an electrical generator or petroleum refinery) to the point of use (e.g. an electric light or motor or a gasoline engine).

**Biocatalysis**

Catalysis conducted by enzymes – catalysis within the body, for example.
Energy Density

The amount of energy contained in a given volume (say a gas tank). The higher the energy density of a fuel, the farther the car will go on a tank of the fuel.

Fermentation

The conversion of sugars into alcohols or hydrocarbons by microbes.

Fischer-Tropsch synthesis

The inorganic catalytic reaction between CO and H₂ (synthesis gas), which produces diesel and jet fuel.

Gasification

The conversion of biomass at very high temperature (1000 – 1200°C) in an oxygen atmosphere that results in a “synthesis gas” intermediate – a mixture of carbon monoxide (CO) and hydrogen (H₂).

Hydrotreating

Reaction in the presence of hydrogen.

Infrastructure Compatible

Compatible with existing oil pipelines, storage tanks, petroleum refineries, and internal combustion engines.

Inorganic Catalysis

Solid, inorganic materials such as platinum nanoparticles deposited onto activated carbon, which accelerate the rate of chemical reactions without being consumed in the process.

Lignocellulose

The non-food portion of plants such as the stalks and leaves of corn plants (corn stover).

Peak Oil

The peak in world oil production that must come about as oil consumption surpasses the discovery of new oil.

Pyrolysis

The conversion of biomass at moderately high temperature (500 – 800°C) in an inert atmosphere that results in a “bio-oil” intermediate.
Synthetic Biology

The field of biology in which microbes are engineered to control metabolic pathways.

Transesterification

The base catalyzed reaction of plant oil with methanol with breaks the oil into long fatty acid chains, which can be used as a low quality diesel fuel.

Geothermal Energy

Energy from the earth.

Heat Pump

A device that allows heat to be removed at a lower temperature and supplied at a higher temperature, for example an air conditioner.

Heat, Ventilation and Air Conditioning Systems (HVAC)

Systems such as furnaces and air conditioners that are commonly used in homes and commercial buildings.

Phase Change Materials

Materials that can absorb and deliver larger amount of heat than common building materials because they can change their state (solid or liquid).