Demand-Side Management Guidebook:

Renewable and Distributed Energy Technologies

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Western Area Power Administration

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Western Area Power Administration is a Federal agency under the U.S. Department of Energy that markets and transmits wholesale electrical power across 15 western states. For more than 30 years, Western has been dedicated to providing public service, such as promoting environmental stewardship, energy efficiency and renewable energy, as well as implementing new technologies to ensure our transmission system continues to be the most reliable possible.

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INTRODUCTION

Distributed energy refers to a variety of small, modular power-generating technologies that can be combined with load management and energy storage systems to improve the quality and/or reliability of the electricity supply. They are "distributed" because they are placed at or near the point of energy consumption, unlike traditional "centralized" systems, where electricity is generated at a remotely located, large-scale power plant and then transmitted down power lines to the consumer.

Implementing distributed energy can be as simple as installing a small, stand-alone electricity generator to provide backup power at an electricity consumer's site. Or it can be a more complex system, highly integrated with the electricity grid and consisting of electricity and thermal generation, energy storage, and energy management systems. Consumers sometimes own the small-scale, on-site power generators, or they may be owned and operated by the utility or a third party.

Distributed energy encompasses a wide range of technologies including wind turbines, solar power, fuel cells, microturbines, reciprocating engines, load-reduction technologies, and energy storage systems. The effective use of grid-connected distributed energy resources (DER) can also require power electronic interfaces and communications and control devices for efficient dispatch and operation of generating units.

Diesel- and gasoline-fueled reciprocating engines are one of the most common distributed energy technologies in use today, especially for standby power applications. However, they create significant pollution (in terms of both emissions and noise) relative to natural-gas- and renewable-fueled generators, and their use is actively discouraged by many municipal governments. As a result, they are subject to severe operational limitations not faced by other distributed generating technologies.

Distributed energy technologies are playing an increasingly important role in the nation's energy portfolio. They can be used to meet baseload power, peaking power, backup power, remote power, power quality, as well as cooling and heating needs (the power applications listed here are defined below).

Distributed energy also has the potential to mitigate congestion in transmission lines, reduce the impact of electricity price fluctuations, strengthen energy security, and provide greater stability to the electricity grid.

Distributed power generators are small compared with typical central-station power plants and provide unique benefits that are not available from centralized electricity generation. Many of these benefits stem from the fact that the generating units are inherently modular, which makes distributed power highly flexible. It can provide power where it is needed, when it is needed. And because they typically rely on natural gas or renewable resources, the generators can be quieter and less polluting than large power plants, which make them suitable for on-site installation in some locations.

The use of distributed energy technologies can lead to improved efficiency and lower energy costs, particularly in combined heating and power (CHP) applications. CHP systems provide electricity along with thermal energy that can be used for hot water, heat for industrial processes, space heating and cooling, refrigeration, and humidity control to improve indoor air quality and comfort.

Grid-connected distributed energy resources also support and strengthen the central-station model of electricity generation, transmission, and distribution. While the central generating plant continues to provide most of the power to the grid, the distributed resources can be used to meet the peak demands of local distribution-feeder lines or major customers. Computerized control systems, typically operating over telephone lines or through wireless networks make it possible to operate the distributed generators as dispatchable resources, generating electricity as needed.

The growing popularity of distributed energy is analogous to the historical evolution of computer systems. Whereas we once relied solely on mainframe computers with outlying workstations that had no processing power of their own, we now rely primarily on a small number of powerful servers networked with a larger number of desktop personal computers, all of which help to meet the information processing demands of the end users.

And just as the smaller size and lower cost of computers has enabled individuals to buy and run their own computing power, so the same trend in generating technologies is enabling individual business and residential consumers to purchase and run their own electrical power systems.

Each chapter in this guidebook covers a different topic:

- Renewable power generation — Electricity generation from renewable resources
- Direct use of renewables — Ways to use renewable resources for heating, cooling, and mechanical power without first converting it to electricity
- Nonrenewable distributed energy — Electricity generation, cogeneration, and thermal technologies that do not typically use renewable resources; novel power-generation technologies that are on the horizon
- Energy storage and hybrid power — Ways to store electrical energy; combining various power generators into a hybrid power plant
- Systems integration and load control — Technologies and approaches for connecting distributed power systems to the electricity grid and monitoring and controlling them.

Growing Demand for Distributed Energy

The 1980s witnessed a complete reversal in a 50-year trend of increasing economies of scale in electricity generation, from community-sized systems in the 1930s to large, centralized power plants in the 1970s. Today, economics no longer favor building only large generating units to meet increases in demand. Smaller plant sizes make the ownership of generating capacity possible for a wider group of people, including energy consumers.

In addition, by using the cogeneration capabilities of some distributed power systems located at energy consumers' sites, the overall energy conversion efficiency of such generators can now exceed 80%, considerably higher than the roughly 30% efficiency of traditional, steam-based central power plants (once line losses are taken into account).

The demand for power is growing. Before personal computers arrived in the 1980s, industry pundits could see little prospect for growth in electricity demand. Today, the increasingly widespread use of computers, business machines, and other electronic equipment is creating a resurgence in demand for electricity—high-quality electricity.

For certain types of customers, power reliability is a true business and operations issue, rather than merely an inconvenience. These customers cannot afford to be without power for more than a brief period without significant loss of revenue, critical data/information, operations, or even life.

Some particularly power-sensitive customers include:

- Mission-critical computer systems
- Industrial processing companies
- High-tech manufacturing facilities and clean rooms
- Financial institutions
- Digital communication facilities (e.g., telephone, television, satellite)
- Military operations
- Wastewater treatment facilities
- Hospitals and other health care facilities.

Load reduction measures are the least expensive way to avoid adding new generating capacity to a utility's service area. But if demand continues to grow beyond the capacity of existing generation in a particular locale, it can sometimes be cheaper and easier to meet that demand by adding new generators close to the load instead of adding transmission and distribution capacity. Small, modular power plants can be approved and sited close to a new load in a matter of months. Transmission line upgrades typically take several years.

Transmission and distribution networks are also inherently expensive to build and maintain. Overall, one utility company estimates that it spends $1.50 to deliver power for every $1.00 it spends producing it. Power transmission also incurs some electricity losses. The Energy Information Administration estimates that approximately 9% of the power produced at a central generating plant is lost in delivery.

Power companies can avoid or defer some of these costs by investing in distributed energy systems.

Major Potential Benefits of Distributed Energy

The use of distributed energy has the potential to produce benefits on both sides of the electric meter.

Benefits to the consumer:

- Better power reliability and quality
- Lower energy costs
- More choice in energy supply options
- Greater predictability of energy costs (lower financial risk) with renewable energy systems
- Energy and load management
- Combined heat and power capabilities
- Environmental benefits, including cleaner, quieter operation, and reduced emissions
- Faster response to new power demands because capacity additions can be made more quickly.

Benefits to the utility:

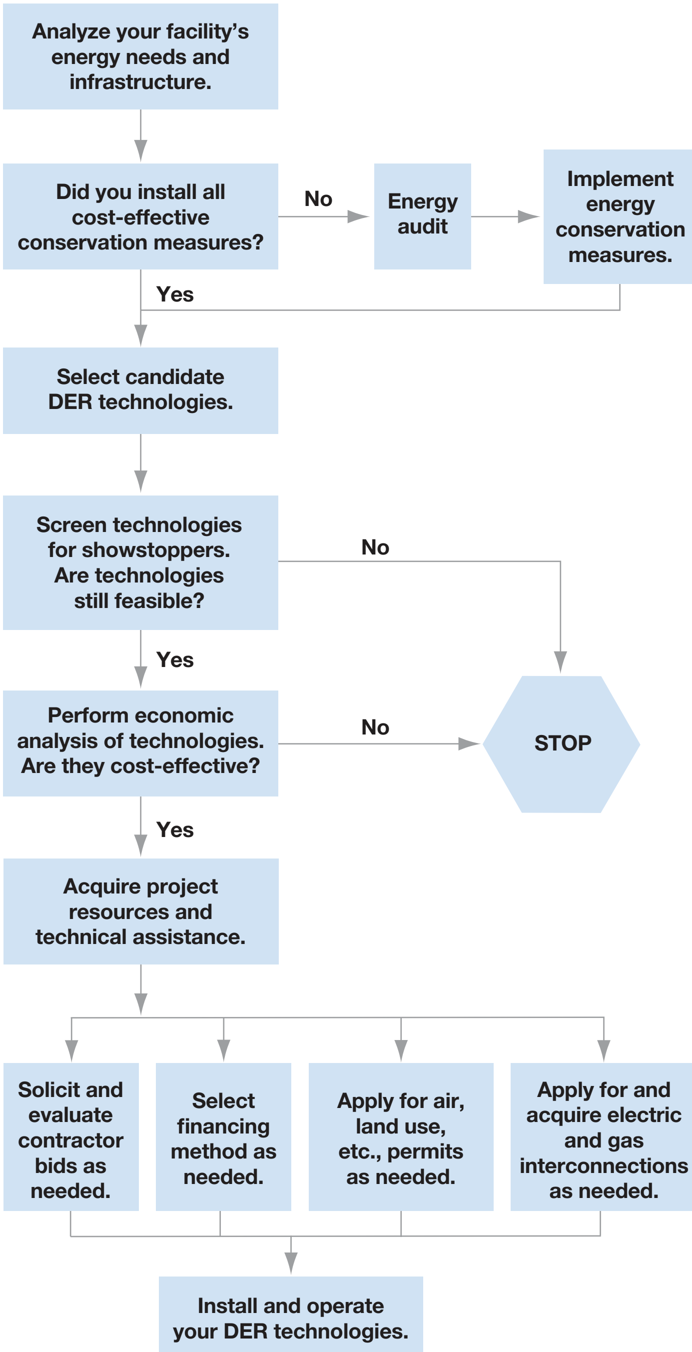
- Reduced energy losses in transmission lines
- Reduced upstream congestion on transmission lines
- Reduced or deferred infrastructure (line and substation) upgrades
- Optimal use of existing grid assets, including the potential to free up transmission assets for increased wheeling capacity
- Less capital tied up in unproductive assets because the modular nature of distributed generators means capacity additions and reductions can be made in small increments, closely matched with demand, instead of constructing central power plants sized to meet estimated future demand
- Improved grid reliability
- Higher energy conversion efficiencies than central generation
- Faster permitting than transmission line upgrades
- Ancillary benefits, including voltage support and stability, contingency reserves, and black-start capability, that is, the ability to start up the distributed power source without an external source of power (such as during a blackout).

Matching the Technology to the Application

Standby Power

To acquire the most economical distributed power-generating system to use when the utility supply is down, one should first estimate how often the system will have to start up and how many hours per year it will have to operate. For standby power applications, fuel and maintenance costs will be low because outages usually occur only a few hours per year; consequently, the emphasis should be placed on minimizing

Distributed Energy Process Flowchart



the capital costs while still meeting the requirements of the specific application. Diesel engines are likely to be the least expensive option, but they can present environmental challenges. Natural gas and dual-fuel engines may be more environmentally acceptable than diesels. Microturbines can be a good choice for small applications (less than 100 kilowatts); combustion turbines can be good for larger applications, where natural gas is available and emissions are a concern.

Uninterruptible power supply (UPS) systems are well suited to applications where outages last less than about 15 minutes. Batteries can handle applications as large as several megawatts for outages of one to two hours. Hybrid technologies, which combine generation and storage technologies for specific applications, have many benefits and may be best if one needs fuel redundancy, expects a wide range in duration of outages, or has multiple applications.

Low-Cost Energy

If low-cost fuel is available, or local electric rates are high, or both, you may be able to reduce your utility bill by generating some or all of your own power. Diesel, dual-fuel, and natural gas reciprocating engines are the least expensive to purchase, but emissions and maintenance costs should be considered when the number of operating hours is high. Combustion turbines are preferred for large applications; they have lower maintenance costs and much lower emissions than reciprocating engines. Microturbines, which are relatively lower in efficiency and have higher capital costs, are probably not as cost-effective. Photovoltaics (PV), although high in cost initially, often make sense in the long term, especially if the local utility has established net metering rules (see Systems Integration and Load Control Technologies for more information). Wind turbines are less expensive than PV arrays, but may be prohibited by zoning regulations in urban areas. However, in rural and suburban areas with high average wind speeds, turbines can provide a substantial amount of energy. Hybrid systems—such as PV or wind with batteries—are more expensive but work over a broader range of fuel costs and applications than single technologies. In addition, using the waste heat generated by some DER technologies to produce both heat and power on site can reduce overall energy costs.

Stand-Alone Systems

A distributed resource in this application will be expected to run around the clock and constantly match its output to the demand. Therefore, high efficiency is required to minimize fuel costs and emissions. Maintenance costs are also an important factor, and reliability is paramount. Reciprocating engines and combustion turbines are often the first choices in terms of capital cost. Engines and microturbines are usually preferable for smaller applications; combustion turbines are preferable for larger applications. Fuel cells are the most expensive to install but desirable from an environmental perspective. PV, wind turbines, and hybrid systems are beneficial in areas without adequate supplies of fossil fuels or where environmental permitting is difficult and in off-grid applications where grid extensions are very expensive. Particularly in remote, off-grid areas, the cost of operating and maintaining fossil-fuel-fired engine gensets is significant. The cost of transporting and storing fuel, combined with the potential for fuel spills and subsequent cleanup, can make hybrid renewable energy systems much more life-cycle cost-effective than fossil gensets alone.

Combined Heat and Power

Only the power-generation technologies that produce excess heat can be used for CHP applications; these include reciprocating engines, combustion turbines, fuel cells, and microturbines. Additional equipment must be installed to capture the heat and use it in the secondary process. Engines and turbines (including some microturbines) have been used for CHP applications. Any distributed energy technology that can produce waste heat can be used in a CHP application with greater overall system efficiencies (because of the higher fuel utilization efficiency) and often better economics.

Peak Shaving

Distributed energy systems can generate power during the times when purchasing energy from the utility would be very expensive. These include peak-demand hours, when time-of-use rates are in effect, and hours when utilities are capacity-constrained. Utilities often assess demand charges—monthly charges based on highest peak usage—for industrial, commercial, and residential customers. Using distributed resources to limit peak usage will help avoid these costs. The system may run 200 to 2,000 hours per year, so one should consider the trade-off between installation costs and efficiency to select an appropriate distributed energy technology. Engines and hybrids are likely to be preferable for small applications at lower run times, and turbines for larger applications at higher run times. PV systems can provide peak shaving in facilities where the greatest requirement for energy occurs when the solar resource is at its highest intensity, such as for air conditioning in commercial buildings. For these applications, PV systems have excellent load-matching characteristics.

Power Quality

Any distributed prime mover technology can be used to provide dedicated, high-quality power to highly sensitive or mission-critical loads and to eliminate downtime. For small applications and brief power outages, a UPS is likely to be the most economical choice. For voltage sags, spikes, noise, and other random power quality anomalies, preferred technologies include batteries, flywheels, and superconducting magnetic energy storage. They can be operated in a constantly on mode, filtering out unwanted qualities of the power signal. Adding higher quality electronics and energy storage systems can improve the power quality of any prime mover technology.

RENEWABLE POWER GENERATION

The United States still relies heavily on nonrenewable, fossil fuels such as coal, oil, and natural gas for its energy needs. But the use of renewable energy resources—those that are constantly replenished and cleaner—continues to grow for power generation. In 2010, renewable energy represented nearly 12% of total installed capacity and more than 10% of total generation in the United States. For electricity, renewable energy capacity reached 59 gigawatts (GW), and renewable energy net generation reached 171 billion kilowatt-hours (kWh).

This chapter of the guidebook provides an overview of renewable energy technologies that can be used to generate electricity, including biopower, geothermal power, hydroelectric power, solar power, and wind power.

Biopower

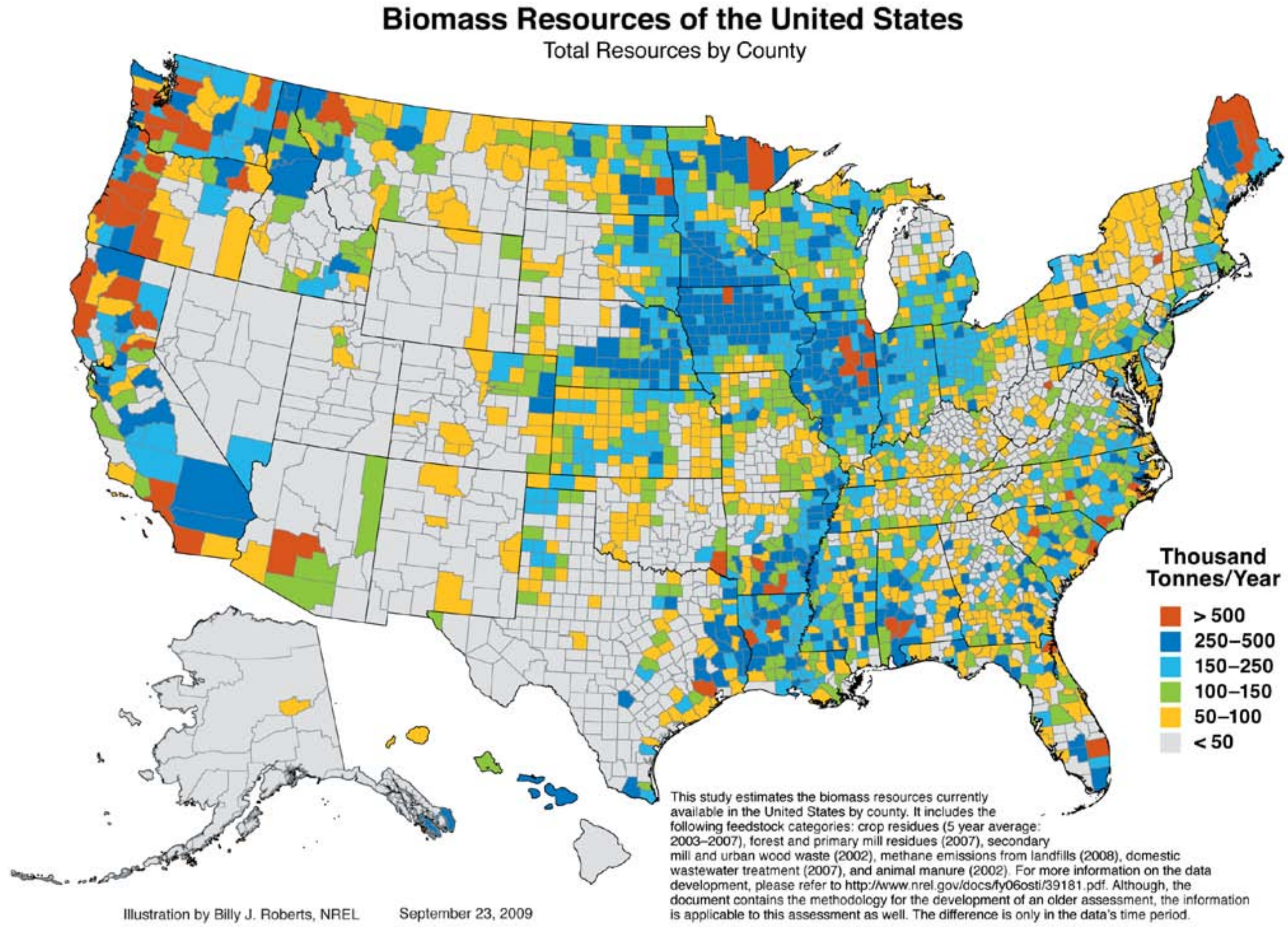
Biopower or biomass power is the use of biomass to generate electricity. In addition to generating renewable electricity, biopower plants provide an environmentally friendly option for disposing of organic waste. According to the Biomass Power Association, the biopower industry prevents over 30 million tons of organic waste from being dumped in landfills, burned, or left to decay in the open, which reduces greenhouse gas emissions by 15.2 million tons each year. And biopower is generally considered "carbon neutral"—it doesn't add any new carbon dioxide (CO_2) to the atmosphere. During the combustion process, a biopower plant releases the same amount of CO_2 that the organic matter would release naturally as it decomposes. However, land-use changes caused by biomass harvesting can throw off this balance, so biopower has the greatest carbon benefit when it doesn't involve clearing forest lands.

Biomass resources that can be used for generating electricity include:

- Wood residues – sawdust, urban wood waste, and forest thinnings
- Agricultural residues – corn stover, wheat straw, rice hulls, and sugarcane bagasse
- Energy crops – switchgrass, hybrid willow, and hybrid poplar
- Methane – animal manure and municipal solid waste.

See the map on page 10 for total biomass resources in the United States by county.

Unlike solar and wind power plants, biopower plants constantly produce electricity, so they're advantageous when a steady supply of electricity is needed. In 2010, biopower accounted for 1.4% of total U.S. electricity generation and 33% of total renewable electricity generation. The electricity generated from biomass costs on average between 6 and 7 cents per kWh, according to the Biomass Power Association.



Biopower systems range in capacity from small modular systems at 5 kilowatts (kW) to larger systems that can produce hundreds of megawatts (MW) of electricity. System technologies include direct combustion, cofiring, gasification, pyrolysis, methane-powered systems, and biofuel-powered systems.

Direct Combustion

Most biopower plants use direct-combustion or direct-fired systems. They directly burn biomass in a boiler to produce high-pressure steam. This steam drives a turbine, which turns a generator that converts the power into electricity. In some industries, the spent steam from the power plant is also used for manufacturing processes or to heat buildings. Such combined heat and power (CHP) systems greatly increase overall energy efficiency.

Biomass power boilers typically fall in the 20-50 MW range. There are two types of direct-combustion boiler systems: fixed-bed (stoker) and fluidized-bed. In a fixed-bed system, the biomass is fed onto a grate where it combusts as air passes through the fuel, releasing hot flue gases into a heat exchanger section of the boiler to generate steam. In contrast, a fluidized-bed system feeds biomass chips or pellets into a hot bed of suspended, incombustible particles such as sand, where the biomass combusts to release the hot flue gas. This technology produces more complete combustion of the feedstock, reducing sulfur dioxide (SO_2) and nitrogen oxide (NOx) emissions and improving system efficiency. Fluidized-bed boilers also can utilize a wider range of feedstocks. However, fluidized-bed systems have greater parasitic loads than stokers. But both systems can meet stringent emissions limits with proper emissions-control technology.

While steam generation technology is very dependable and proven, its efficiency can be limited. Direct-combustion biomass systems that produce electricity using a steam turbine have a conversion efficiency of 15% to 35% depending on the manufacturer; a CHP system can have an overall efficiency up to around 85%. A system's efficiency depends on the following factors:

- Moisture content of the biomass
- Combustion air distribution and amounts
- Operating temperatures and pressures
- Fuel feed handling, distribution, and mixing
- Furnace retention time.

Although most direct-combustion systems utilize steam-driven turbines to generate power, some companies are developing technologies that use hot, pressurized air or another gaseous medium to drive a gas turbine. Heat engines, such as a Stirling engine, can also be used to convert the energy from a hot flue gas directly into electricity, without the use of a boiler. Another technology involves coupling an organic Rankine cycle power generator to a biomass hot-water source. The organic Rankine cycle technology uses hot water to vaporize a working fluid that has a lower boiling point than water. In this manner, electricity can be produced from low-temperature (approximately 185°F and greater), low-pressure sources, such as biomass hot-water boilers.

Cofiring

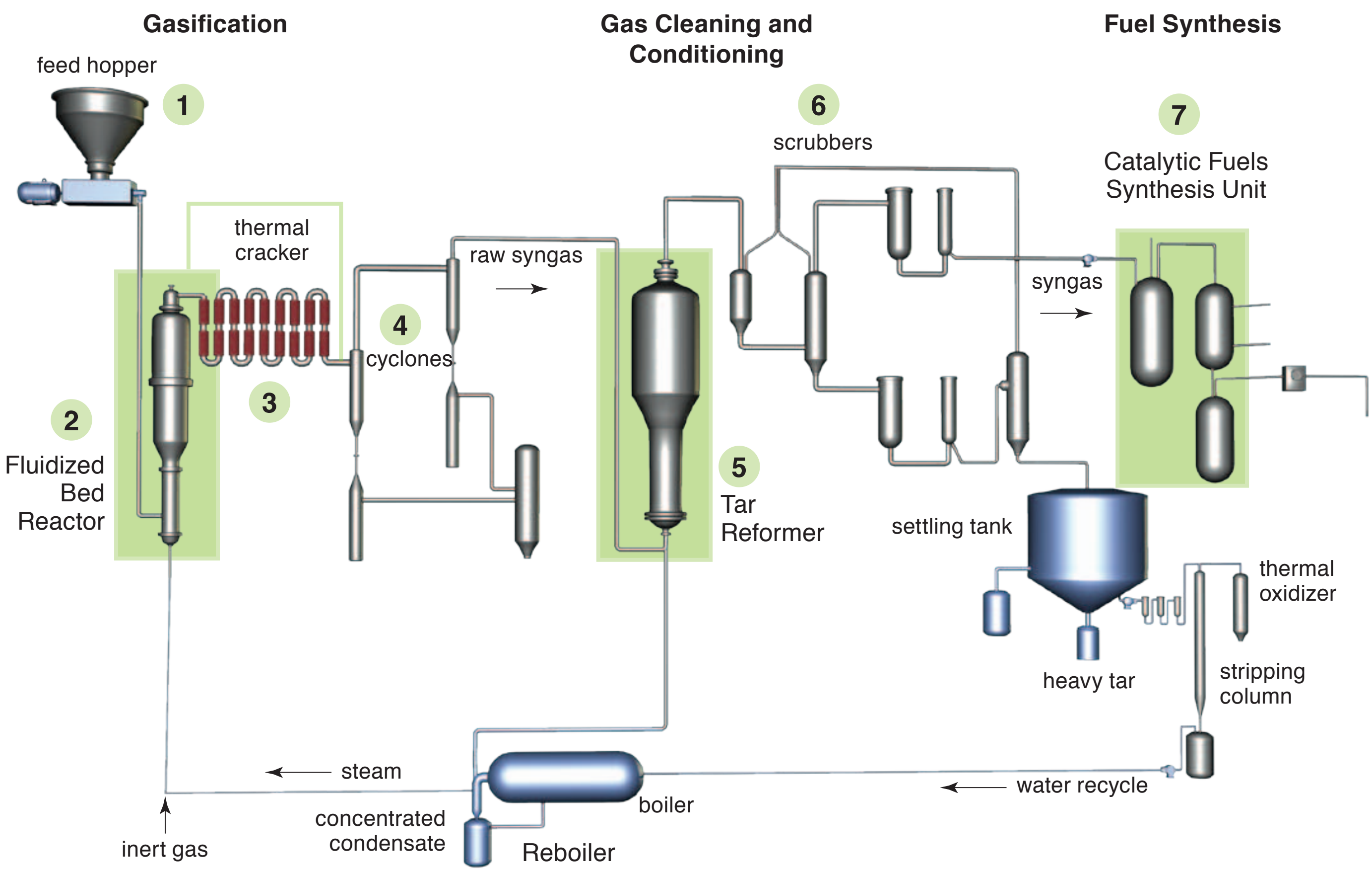
Cofiring involves using biomass to replace a portion of the coal that is fed into a high-efficiency, coal-fired boiler. Compared to the coal it replaces, the biomass reduces SO_2, NOx, and other air emissions. Additionally, there is little or no loss in total boiler efficiency after adjusting combustion output for the new fuel mixture. This allows the energy in the biomass to be converted to electricity with the high efficiency (in the 33%-37% range) of a modern coal-fired power plant.

Cofiring has been successfully demonstrated in most boiler technologies, including pulverized coal, cyclone, fluidized bed, and spreader stoker units. Because much of the existing power plant equipment can be used without major modifications, cofiring is less expensive than building a new biopower plant. A typical cofiring installation includes modifications to the fuel-handling and storage systems and possibly the burner to accommodate biomass. Costs can increase if the biomass needs to be dried, the size needs to be reduced, or the boiler requires a separate feeder. Ash deposition and disposal also need to be considered.

Gasification

Gasification systems use high temperatures and an oxygen-starved environment to convert biomass into synthesis gas, a mixture of hydrogen and carbon monoxide. In a close-coupled gasification system, the combustible gas is burned directly for space heat or drying, or burned in a boiler to produce steam.

Biomass Conversion via Gasification



Biomass gasification in a fluidized-bed reactor. *Illustration by the National Renewable Energy Laboratory (NREL)*

Alternatively, in a two-stage gasification system, tars and particulate matter are removed from the combustible gas. This synthesis gas, or "syngas," can then be chemically converted into other fuels or products, burned in a conventional boiler, or used instead of natural gas in a gas turbine. Gas turbines are very much like jet engines, only they turn electric generators instead of propelling a jet. Highly efficient to begin with, they can be made to operate in a "combined cycle," in which their exhaust gases are used to boil water for steam, a second round of power generation, and even higher efficiency.

Similar to those used for direct-combustion systems, there are two types of gasification conversion technologies: fixed-bed and fluidized-bed. The technology used in fixed-bed systems—a grate inside the gasification chamber that's piled with biomass—is simple, inexpensive, and proven, but it typically produces a gas with lower heat content. In a fluidized-bed system, combustible gas is generated by feeding biomass into a hot bed of suspended, inert material (see the figure below). This approach generally offers improved overall conversion efficiency and the ability to handle various biomass feedstocks, but with greater complexity and cost. Although a fluidized-bed design produces gas with lower tar content, it produces a greater level of particulates compared to fixed-bed systems.

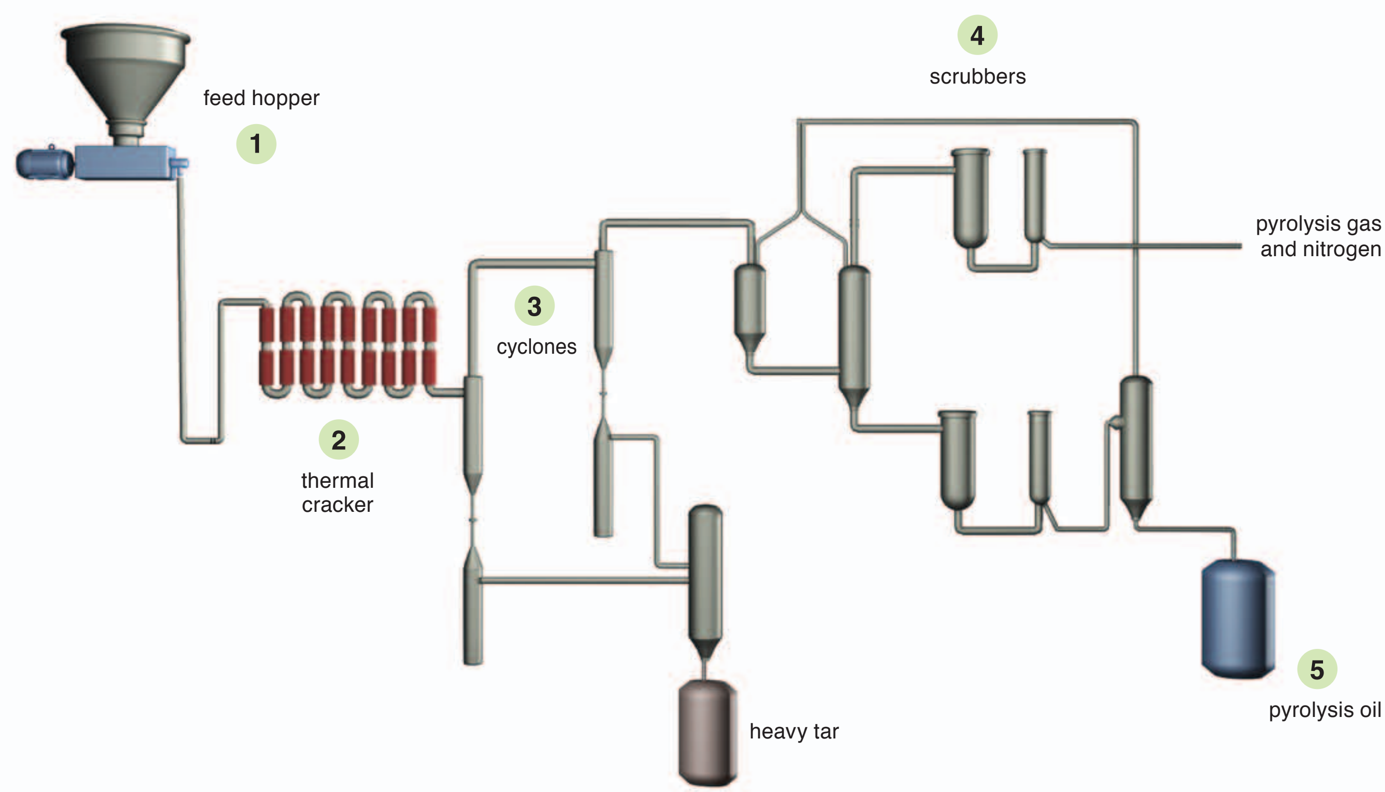
Some high-moisture biomass feedstocks might not be economical for gasification systems because of high drying costs. Also some agricultural residues generate a combustible gas, which requires special processing before it can be utilized in a boiler, turbine, or engine.

Pyrolysis

Pyrolysis is the process of heating biomass in the absence of added oxygen. It decomposes the biomass and produces a liquid called pyrolysis oil or bio-oil. The pyrolysis oil can be burned to generate electricity or further refined for making fuels, plastics, adhesives, or other bioproducts.

Fast pyrolysis requires a very high particle-heating rate and a short period of heat transfer to the biomass. In the thermochemical pyrolysis process, biomass is fed into a fluidized-bed reactor; an entrained-flow reactor, in which the fuel particles are carried through the system by the gas stream; or a bubbling-bed reactor system, in which air is bubbled through a bed that contains the fuel. See the figure below for an entrained-flow system. The biomass is heated in the absence of oxygen within a thermal cracker to a temperature between 500-700°C, creating vapor, gas, and char. Nitrogen is used in the process in place of steam to provide the inert environment necessary for pyrolysis. The cyclones clean the char from the vapor. Finally, the vapors are quenched in the scrubbers to create pyrolysis oil.

Biomass Conversion via Pyrolysis



Pyrolysis in an entrained-flow reactor. *Illustration by NREL*

Methane-Powered Systems

The natural decay of biomass in an oxygen-free environment—a process called anaerobic digestion—produces a biogas, which typically contains around 50% methane, 50% CO_2, and trace amounts of non-methane organic compounds. The methane can be captured and used to generate electricity or heat. The anaerobic bacteria that produce methane thrive where there are high concentrations of compacted, wet organic matter, such as in the solid waste at municipal landfills and in animal manure at farms.

Landfill Gas

According to the U.S. Environmental Protection Agency (EPA), municipal solid waste landfills are the third-largest source of human-related methane emissions in the United States. At these landfills, wells can be drilled to extract the methane. Through pipes from the wells, a blower/flare (or vacuum) system directs the gas to a central point, where it is filtered and cleaned before burning to produce electricity.

The electricity generated from landfill gas can be used on-site or sold to the grid. Electricity can be generated through a variety of technologies: internal combustion engines, turbines, Stirling engines, organic Rankine cycle engines, and fuel cells. The majority of landfill gas power projects use internal combustion (reciprocating) engines or turbines. Microturbines are often used at smaller landfills. Landfill gas can also be used for CHP projects.

Using landfill gas for electricity production or CHP helps reduce odors, hazardous emissions, and greenhouse gases (because methane is a powerful greenhouse gas, burning it reduces its greenhouse impact, even though it generates CO_2 in the process). As a result, it can reduce a landfill's environmental compliance costs.

Anaerobic Digesters

At farms, existing liquid/slurry manure management systems can be readily adapted to collect and transport manure to anaerobic digesters. Anaerobic digesters are designed to stabilize manure and optimize the production of methane.

The most commonly used anaerobic digesters include a covered anaerobic lagoon, a plug-flow digester, and a complete mix digester. An anaerobic lagoon is sealed with a flexible cover, and the methane is recovered and piped to a combustion device. Some lagoon systems use a single cell for combined digestion and storage. A plug-flow digester—a long, narrow concrete tank with a flexible cover—is built partially or fully below grade to limit the demand for supplemental heat. Plug-flow digesters are only used at dairy farms that collect manure by scraping. Meanwhile, a complete mix digester consists of an enclosed, heated tank with a mechanical, hydraulic, or gas mixing system. Complete mix digesters work best when excreted manure can be diluted with water, such as wastewater at a milking center.

From the digester, the captured methane is transported via a pipe either directly to a gas use device or to a gas treatment system. A gas treatment system removes excess moisture and/or hydrogen sulfide before combustion.

Biofuel-Powered Systems

Biofuels are normally used to power vehicles, but they can also replace diesel fuel or fuel oil in engine-driven generators or in oil-fired power plants. Some backup power systems or standby emergency generators can use 100% biodiesel (B100). Temporary backup generators typically operate without the need for exhaust after-treatments to reduce emissions. According to the National Biodiesel Board, using B100 in these generators instead of petroleum-based diesel eliminates most hydrocarbons and SO_2 emissions, and reduces particulate matter by a third and carbon monoxide emissions by around 50%.

On the Hawaiian Islands, a few electric utilities are using biodiesel and other biofuels on a larger scale for generating electricity. Biodiesel can replace petroleum in oil-fired power plants, which are rare in most of the United States but are more common in Hawaii. Using biodiesel processed from locally grown biomass feedstocks helps reduce the islands' need to import fossil fuels. Hawaiian Electric in 2009 completed a 110-MW generating station designed to be fueled exclusively with B100. In 2011, the company also successfully used a 100% renewable biofuel from crude palm oil to fuel an oil-fired power plant and signed a deal to buy 150,000 gallons of algae-based biofuel to burn at another generating station. Additionally, Maui Electric uses biodiesel from sugarcane bagasse to power its diesel generators, and it has explored using an algae-based biofuel as well to generate electricity.

Modular Systems

Gasification, anaerobic digestion, and other biopower technologies can be used in small, modular systems—rated between 5 kW and 5 MW—with internal combustion or other generators. These systems are most useful in remote areas where biomass is abundant and far from the electrical grid, especially if they can use the waste heat for crop drying or other local industries. They also fit well with distributed energy generation systems.

Terms and Definitions

Anaerobic digestion – Degradation of organic matter by microbes that produces a gas composed mostly of methane and CO_2, usually under wet conditions, in the absence of oxygen.

Bagasse – Residue remaining after extracting a sugar-containing juice from plants like sugarcane.

Biodiesel – A biodegradable transportation fuel for use in diesel engines that is produced through the transesterfication of organically derived oils or fats. It may be used either as a replacement for or as a component of diesel fuel.

Biofuels – Biomass converted to a liquid or gaseous fuel, such as ethanol.

Biogas – A gaseous mixture of CO_2 and methane produced by the anaerobic digestion of organic matter.

Biomass – An energy resource derived from organic matter.

Carbon dioxide (CO_2)– A colorless, odorless gas produced by respiration and combustion of carbon-containing fuels, used by plants as food in the photosynthesis process.

Cofiring – The use of a mixture of two fuels within the same combustion chamber.

Digester – A biochemical reactor in which anaerobic bacteria are used to decompose biomass or organic waste into methane and CO_2.

Fast pyrolysis – Pyrolysis in which reaction times are short, resulting in higher yields of certain fuel products.

Feedstock – Any material used directly as a fuel or converted to another form of fuel or energy product.

Fixed bed – A collection of closely spaced particles through which gases move up or down for purposes of gasification or combustion.

Fluidized bed – A gasifier or combustor design in which feedstock particles are kept in suspension by a bed of solids kept in motion by a rising column of gas. The fluidized bed produces approximately isothermal (constant temperature) conditions with high heat transfer between particles and gases.

Fly ash – Small ash particles carried in suspension in combustion products.

Gasification – Any chemical or heat process used to convert a feedstock into a gaseous fuel.

Landfill gas – Biogas produced from the natural degradation of organic matter in landfills.

Pyrolysis – The breaking apart of complex molecules by heating in the absence of oxygen, producing solid, liquid, and gaseous fuels.

For More Information

Biomass Power Association
www.usabiomass.org
An organization working to expand and advance the use of clean, renewable biomass power in the United States.

EPA AgSTAR Program
www.epa.gov/agstar
A voluntary outreach and educational program that promotes the recovery and use of methane from animal manure.

EPA Landfill Methane Outreach Program
www.epa.gov/lmop
A voluntary assistance program that helps to reduce methane emissions from landfills by encouraging the recovery and beneficial use of landfill gas as an energy resource.

Market Assessment of Biomass Gasification and Combustion Technology for Small- and Medium Scale Applications
www.nrel.gov/docs/fy09osti/46190.pdf
A publication developed by the National Renewable Energy Laboratory.

National Biodiesel Board - Biodiesel for Electrical Generation
www.biodiesel.org/markets/ele
An overview on using biodiesel to power generators.

U.S. Department of Energy Biomass Program
www.eere.energy.gov/biomass
A program working with industry, academia, and our national laboratory partners on a balanced portfolio of research in biomass feedstocks and conversion technologies.

Western Governors' Association Biomass Energy Program
www.westgov.org/index.php?option=com_content&view=article&id=218&Itemid=80
A regional initiative promoting the increased use of bioenergy and biobased products through the conversion of biomass residuals from forest health projects and commercial agriculture.

Geothermal Power

Geothermal ("Earth heat") energy comes from the residual heat left over from the Earth's formation and from the decay of radioactive atoms that occur naturally in small amounts in all rocks. The Earth's interior reaches temperatures greater than 7,000°F, and this geothermal energy flows continuously to the surface.

The energy contained in U.S. geothermal resources to a depth of 2 miles is estimated to be 3 million quads [a quadrillion British thermal units (Btu) or 1,015 Btu]. The United States currently consumes about 100 quads of energy per year for all of its energy needs, so 3 million quads is equivalent to a 30,000-year supply of energy for the United States.

While the heat from the Earth rises towards the surface everywhere on the globe, this resource can be used for power generation only when two other factors are present: fluids and permeability—the existence of subsurface fractures through which the fluid can move. The fluid is essentially rainwater and snowmelt that seeps downward from the surface and, as it flows through the fracture system, it takes on the thermal energy of the Earth's heat. The resulting hot water and steam are known as hydrothermal resources.

While hydrothermal fluids reach the surface naturally in many locations, they are usually accessed by wells drilled hundreds or thousands of feet into the ground. The hydrothermal resource is then pumped to the surface to be used as a source of energy. Because the fluids are later pumped back into the hydrothermal reservoir to be reheated and recirculated, geothermal energy is considered a fully sustainable and renewable resource.

Geothermal energy can currently be harnessed in three different ways:

- Electricity production is possible with the hottest hydrothermal resources (220°F-700°F).
- Lower-temperature hydrothermal resources can be used directly for space and water heating (70°F-300°F).
- Geothermal heat pumps can be used for space heating and cooling anywhere in the country; however, the efficiency will vary from one climatic region to another.

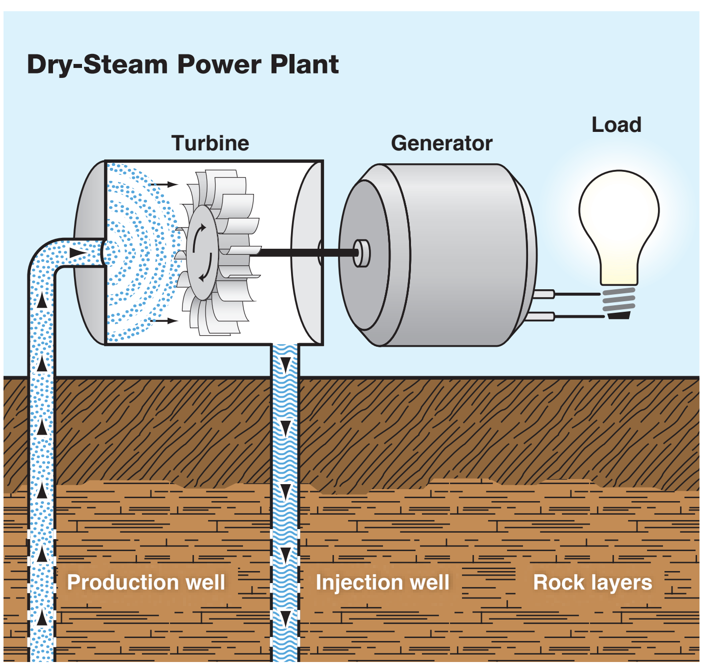
Electricity production is covered in this section of the guidebook. See the chapter on Direct Use of Renewable Resources for information about other geothermal technologies.

Hydrothermal Electricity Generation

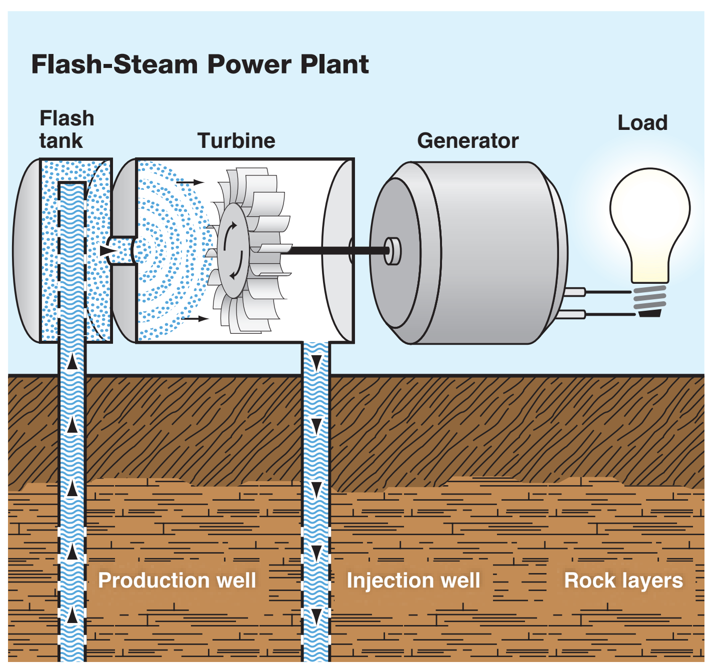
High-temperature hydrothermal resources (220°F-700°F) can be used for electricity generation in geothermal power plants. The United States is the world leader in this technology, with 30% of the world's total geothermal electricity production. In 2010, the United States had a total electricity generating capacity of around 15,000 MW.

At present, geothermal energy is producing electrical power using natural hydrothermal reservoirs that exist at relatively shallow depths. Domestic production is primarily in California and Nevada, but geothermal power plants exist or are planned in 11 additional western states. See the map on page 16 for locations of identified hydrothermal sites.

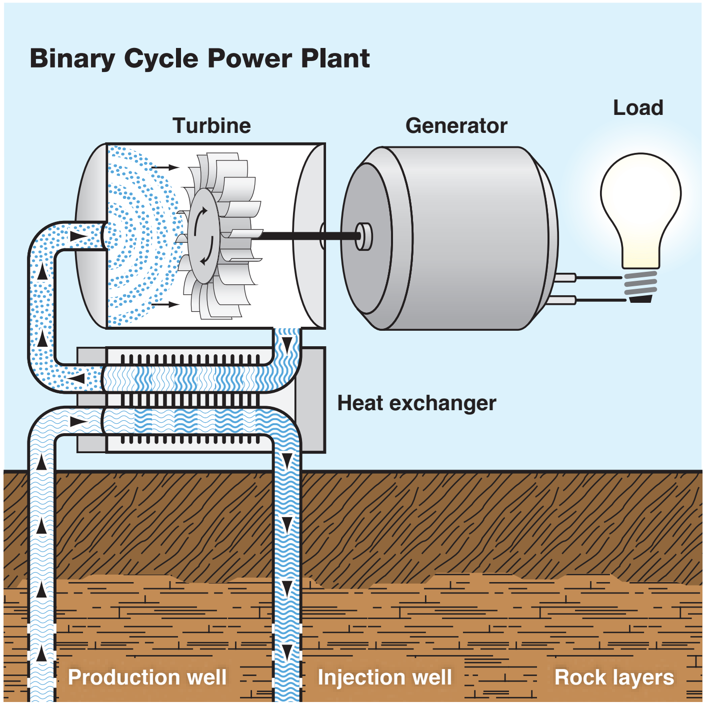
Geothermal electricity is a baseload energy resource—it is available 24 hours a day, 365 days a year, with capacity factors usually above 95%. This attribute makes geothermal a desirable part of a sustainable energy mix that includes variable sources, such as solar and wind power. Geothermal power plants have a relatively small environmental footprint and produce no or few global warming emissions.



A dry-steam geothermal power plant uses steam directly to turn a turbine. *Illustration by NREL*



A flash-steam geothermal power plant "flashes" hot water into steam driving a turbine. *Illustration by NREL*



Binary-cycle geothermal power plants vaporize a secondary working fluid to drive the turbine. *Illustration by NREL*

A hydrothermal resource is converted to electricity by using existing power conversion technology to drive a turbine attached to an electric generator. Three technologies can be used to convert hydrothermal fluids to electricity. The type of conversion used depends on the state of the fluid resource (whether steam or water) and its temperature:

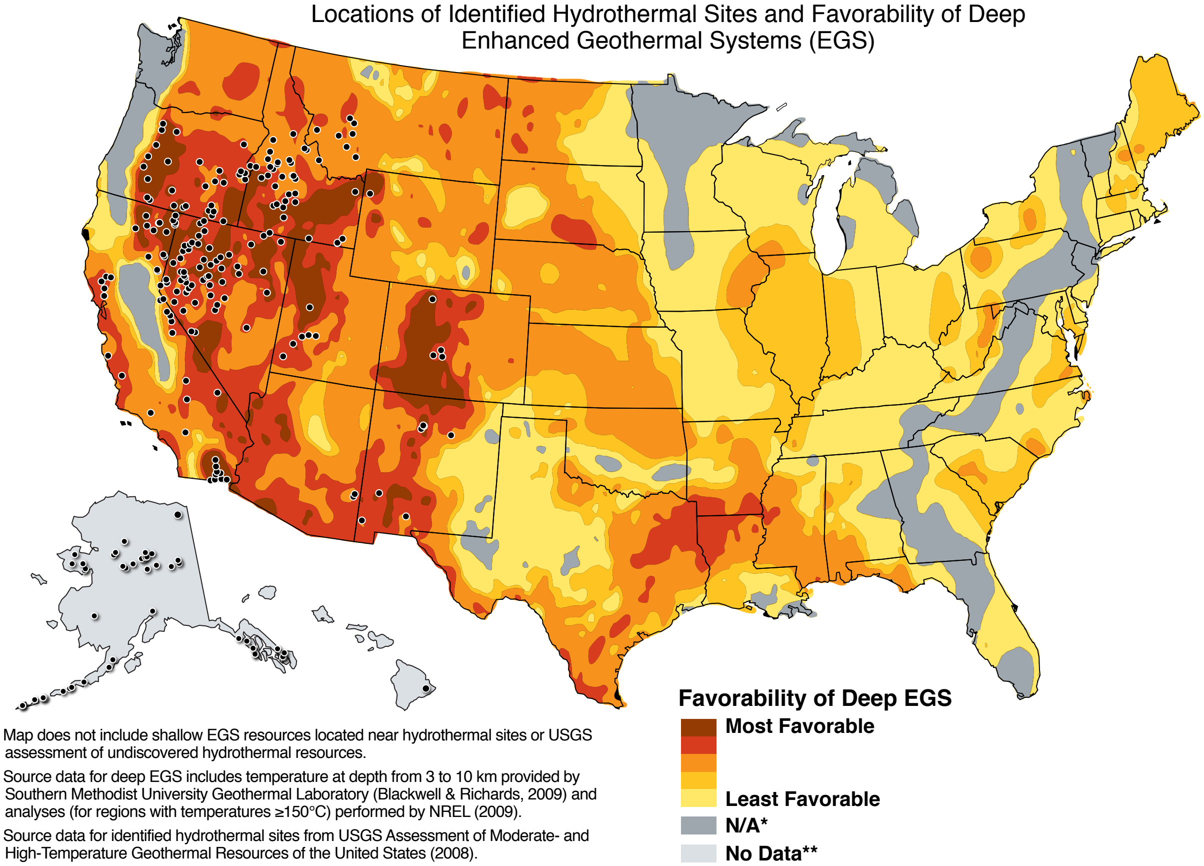
- Dry-steam plants use geothermal steam directly to turn turbines.
- Flash-steam plants pull deep, high-pressure hot water into lower-pressure tanks and use the resulting flashed steam to drive turbines.
- Binary-cycle plants pass moderately hot geothermal water by a secondary fluid with a much lower boiling point than water, causing the secondary fluid to flash to vapor and, in turn, drive the turbines.

Dry Steam

Conventional dry-steam turbines are used with hydrothermal fluids that are wholly or primarily steam. The underground steam is routed directly to a turbine, which drives an electric generator. There are only two known underground resources of steam in the United States: The Geysers in northern California and Yellowstone National Park in Wyoming. Because Yellowstone is protected from development, the only dry-steam plants in the country are at The Geysers.

Geothermal Resource of the United States

Locations of Identified Hydrothermal Sites and Favorability of Deep Enhanced Geothermal Systems (EGS)



- Map does not include shallow EGS resources located near hydrothermal sites or USGS assessment of undiscovered hydrothermal resources.
- Source data for deep EGS includes temperature at depth from 3 to 10 km provided by Southern Methodist University Geothermal Laboratory (Blackwell & Richards, 2009) and analyses (for regions with temperatures ≥150°C) performed by NREL (2009).
- Source data for identified hydrothermal sites from USGS Assessment of Moderate- and High-Temperature Geothermal Resources of the United States (2008).
- *"N/A" regions have temperatures less than 150°C at 10 km depth and were not assessed for deep EGS potential.
- **Temperature at depth data for deep EGS in Alaska and Hawaii not available.

Illustration by Billy J. Roberts, NREL October 13, 2009

Dry-steam power plants draw steam directly from geothermal wells and use it to drive a turbine, which spins a generator to produce power. The spent steam is either vented to the atmosphere or is condensed and reinjected into the geothermal reservoir.

Flash Steam

Flash-steam technology is used with hydrothermal fluids above 360°F that are primarily water. This very hot water flows up through wells in the ground under its own pressure. In these systems, the hydrothermal fluid is sprayed into a tank held at a much lower pressure than the fluid, causing some of the fluid to rapidly vaporize, or flash, to steam. The steam is then used to drive a turbine, which drives an electric generator. If any liquid remains in the tank, it can be flashed again in a second tank to extract even more energy. Any leftover water and condensed steam are injected back into the reservoir, making this a sustainable resource.

Flash-steam power plants direct high-temperature water to a flash tank, where the pressure on the fluid is released, causing the majority of the fluid to flash to steam, typically leaving the remainder as a salty brine. As in a dry steam power plant, the steam from the flash tank feeds a turbine, which drives a generator to produce power. The condensed steam and the brine are then reinjected into the geothermal reservoir.

Binary Cycle

Binary cycle technology is used to generate electricity from water with temperatures of around 225°F to 360°F. In these systems, the hot geothermal fluid vaporizes a secondary working fluid—usually an organic compound with a low boiling point—which then drives a turbine and generator. The water is then injected back into the ground to be reheated. The water and the working fluid are kept separated during the whole process, so there are little or no air emissions. Moderate-temperature water is by far the most common hydrothermal resource.

Enhanced Geothermal Systems

While geothermal energy is available at varying depths and temperatures throughout the world, resources that are readily accessible for today's energy uses are limited to areas with geologically recent volcanic activity. These alone represent a substantial energy source for the United States, but the future promise of geothermal power lies in the technology of enhanced geothermal systems (EGS). See the geothermal resources map on page 16 for areas that are favorable for EGS.

EGS employs rock-fracturing technologies in high-temperature geological formations that exist deep underground—as much as 3 miles below the surface of the Earth—and can be used to either create a geothermal reservoir of hot water or steam where none existed before or to extend and enhance an existing geothermal reservoir.

Once referred to as "hot dry rock" technology, EGS was invented to draw energy from deep underground areas where geothermal heat is abundant, but no water exists to carry the heat to the surface. To tap the energy in this hot dry rock, a well is drilled into it, and water is injected at high pressure, forming fissures to create a geothermal reservoir consisting of water-impregnated fractured rock. At least one production well is then drilled into the reservoir to draw the hot water back to the surface. A completed facility would direct the hot fluid from the production well to a power plant, which would extract the heat from it to produce power, after which the cooled fluid would be injected back into the ground.

The advanced EGS technologies currently in development could greatly extend the total usable geothermal resource, enabling geothermal electricity generation nearly anywhere in the world. The U.S. Department of Energy (DOE) estimates that EGS could supply the United States alone with 100 GW of electricity within 50 years.

Terms and Definitions

Baseload plants – Electricity generating units that are operated to meet the constant or minimum load on the system. The cost of energy from such units is usually the lowest available to the system.

Binary–cycle plant – A geothermal electricity generating plant employing a closed–loop heat exchange system in which the heat of the geothermal fluid (the "primary fluid") is transferred to a lower–boiling–point fluid (the "secondary" or "working" fluid), which is thereby vaporized and used to drive a turbine and generator set.

Direct use – Use of geothermal heat without first converting it to electricity, such as for space heating and cooling, food preparation, industrial processes, etc.

Dry steam – Very hot steam that doesn't occur with liquid.

Enhanced geothermal systems – Rock fracturing, water injection, and water circulation technologies to sweep heat from unproductive areas of existing geothermal fields or new fields either lacking sufficient production capacity or with sufficient geothermal heat, but lacking a hydrothermal resource.

Flash steam – Steam produced when the pressure on a geothermal liquid is reduced. Also called flashing.

Geologic reservoir – A natural underground container of fluids, such as water, steam, oil or natural gas.

Geothermal – Relating to the Earth's interior heat.

Geothermal heat pumps – Devices that take advantage of the relatively constant temperature below the surface of the Earth, using it as a source and sink of heat for both heating and cooling. When cooling, heat is extracted from the

(Continued on page 18)

(Continued from page 17)

building space and dissipated into the ground; when heating, heat is extracted from the ground and pumped into the building space.

Hydrothermal resource – Underground systems of hot water or steam.

Injection – The process of returning spent geothermal fluids to the subsurface. Sometimes referred to as reinjection.

Permeability – The capacity of a substance (such as rock) to transmit a fluid. The degree of permeability depends on the number, size, and shape of pores and fractures in the rock and their interconnections. It is measured by the time it takes a fluid of standard viscosity to move a given distance. The unit of permeability is the Darcy.

Turbine – A bladed, rotating engine activated by the reaction or impulse, or both, of a directed current of fluid. In electric power applications, such as geothermal plants, the turbine is attached to and spins a generator to produce electricity.

For More Information

An Assessment of Geothermal Resource Development Needs in the Western United States
www.geo-energy.org/reports/States%20Guide.pdf
A publication developed by the Geothermal Energy Association.

DOE Geothermal Technologies Program
www.eere.energy.gov/geothermal
A program sponsoring geothermal research and development, and works closely with industry to help commercialize research discoveries. Also provides information about geothermal energy and its applications.

Geothermal 101: Basics of Geothermal Energy Production and Use
www.geo-energy.org/reports/Geo101_Final_Feb_15.pdf
A publication developed by the Geothermal Energy Association.

Geothermal Energy Association
www.geo-energy.org
A trade association providing information on the costs, benefits, and current use of geothermal power generation and direct-heat applications. Includes a searchable database of geothermal energy producers, suppliers, contractors and associations.

State Geothermal Resource Maps
https://inlportal.inl.gov/portal/server.pt/community/geothermal/422/maps
Detailed geothermal resource maps from Idaho National Laboratory for 11 western states, plus Alaska and Hawaii.

Hydroelectric Power

Hydroelectric power refers to the generation of electricity from water. Most, but not all, hydroelectric systems do this by capturing the energy in flowing water. Outside of engineering circles, the terms hydroelectric power, hydropower or just "hydro" are usually reserved for terrestrial (land-based) projects. But hydroelectricity can also be generated from ocean currents, tides, and the temperature difference between the surface and deeper water in the oceans. Another type of hydroelectric system, "pumped hydro," is described in the Energy Storage and Hybrid Power chapter of this guidebook.

Terrestrial Hydropower

Historically the most successful of the renewable energy technologies, hydropower played an important role in the development of the U.S. industry. In the 1940s, 40% of the country's electricity came from hydroelectric plants. Today, the use of hydropower can conserve depletable energy resources: each 600 kWh of electricity generated with a hydropower plant is equivalent to the energy contained in one barrel of oil (assuming an efficiency of 38% for the conversion of oil into electricity).

There are several types of terrestrial hydropower plants, ranging in size from small, local projects producing a few kW to huge dams and reservoirs that generate 10,000 MW or more and supply energy to millions of people. Although output varies greatly from year to year depending on the amount of precipitation received in upstream watersheds, hydropower is the largest source of electricity from renewable resources, generating roughly 10% of the electricity used in the United States. Current hydropower generating capacity is about 80,000 MW, and DOE has identified approximately 5,680 additional sites around the country with undeveloped capacity totaling about 30,000 MW.

Traditional water wheels were first used by the Greeks over 2,000 years ago, and have been in use ever since to do mechanical work such as grinding grain into flour and driving machinery. Water wheels have also been used to generate electricity, but these have largely been replaced by turbines, which can handle higher power levels in a smaller form factor and hence at lower cost.

Modern hydropower plants are sometimes classified according to their size. Although there is little uniformity in these classifications, DOE defines large-scale hydropower as facilities that have a capacity of more than 30 MW, "small hydro" as facilities with a generating capacity of 100 kW to 30 MW, and "microhydro" as plants with capacities up to 100 kW.

Impoundment Dams

These are the best-known and most contentious type of hydropower facility. They use a large dam on a river to store water in a reservoir behind the dam. Water released from the reservoir flows through a penstock (conduit) to a turbine, causing it to spin due to the force of the water against the turbine blades. The turbine is physically connected to a generator that spins to produce electricity.

Although there are still undeveloped hydro resources, very little of this potential is currently slated for development. Significant legal and regulatory impediments, such as land acquisition and environmental protection, are obstacles to any major hydro project. In addition, reservoirs are typically built and managed as municipal water supply and flood control systems, and secondarily for power production. While many existing large-scale hydropower facilities are being relicensed, it is unlikely that new plants requiring large impoundment dams would receive the necessary permits. However, there are significant opportunities to add hydropower facilities to existing impoundment dams (many of which exist mainly for flood control) and to upgrade existing hydropower facilities. Hydropower upgrades usually offer additional environmental benefits, such as more fish-friendly turbines, better water aeration, or additional measures to aid with fish passage past the dams.

The main advantage of large-scale impoundment dams is the dispatchability of the power. Their operational flexibility (the ability to change output quickly) is highly valued by system operators; and their unique voltage control, load-following, and peaking capabilities help maintain the stability of the electricity grid. However, most dam operators must now comply with environmental restrictions that mandate minimum and maximum flows below the dam, complicating the dispatchability of the power. Some dams are also experimenting with occasional high flows to simulate natural flow cycles downstream of the dam. These high-flow water releases may not correspond to peak power demands and may hamper the operational flexibility of the dam.

Their main disadvantage is that damming a river can change the local or regional ecology. For example, the water below the dam is often colder and lower in dissolved oxygen than natural river water, and these conditions can kill fish. Fish populations can also decline because they are unable to swim past the dam to spawning grounds upstream or because they are killed by passing through the turbine on their way downstream. The water level of the river below the dam can be higher or lower than its natural state, which affects the plants that grow along the riverbanks, and downstream flow rates are also affected. All terrestrial hydropower facilities can be impacted by drought; when sufficient water isn't available, the hydropower plants can't produce electricity.

Diversion and Hydrokinetic Systems

Diversion systems are typically free of the environmental impacts associated with impoundment facilities because they use a "run-of-river" design that does not require a large dam and storage reservoir. Instead, run-of-river systems generate electricity by diverting only part of the river or stream through a canal or penstock to a turbine. This produces relatively little change in the stream channel and flow, and minimizes impacts on fish migration, water quality, and wildlife habitat. Some diversion systems use a small dam or weir to raise the head by a few feet so that the energy in the flowing water can more easily be captured.

Hydrokinetic energy conversion devices offer ways to tap the energy of moving water without requiring the impoundment dams or stream diversion necessary with conventional hydroelectric facilities. This can be as simple as a propeller-like turbine that is lowered directly into a river or stream. In other cases, the turbine may be placed on the bottom of a riverbed with an upstream funnel that channels water through the turbine at increased pressure.

Diversion and hydrokinetic systems can supply enough electricity to power a remote home, farm, or small rural community that does not have access to the national electricity grid, and their environmental impact is much lower than that of impoundment dams. These systems can be planned and built in a relatively short time with fewer materials and for much lower cost than impoundment projects. Such systems can also be considered as distributed energy resources, adding clean generating capacity within urban centers because many of the country's major cities are located on rivers.

Diversion and hydrokinetic systems require no fuel and limited maintenance, so running costs are low when compared to fossil-fueled power systems. Diversion systems are also a long-lasting and robust technology; systems can last for 50 years or more without major new investments. In contrast, hydrokinetic systems are in the early stages of commercialization, so they generally lack long-term operating experience. Because they are located directly in the water flow, hydrokinetic systems are potentially more vulnerable to extreme events, such as high river flows due to flooding.

The disadvantage of both diversion and hydrokinetic systems is that they are both site-specific technologies, requiring that the source of water power be close to a location where the power can be economically exploited. There is always a maximum useful power output available from a given hydropower site, which limits the level of expansion of activities that make use of the power. In addition, river flow rates can vary considerably with the seasons, and this can limit the reliable power output to a small fraction of the possible peak output.

Types of Hydropower Turbines

There are two main types of hydro turbines: impulse and reaction. The type of hydropower turbine selected for a project is based on the height of standing water (the head) and the flow of water at the site. Other deciding factors include limits set by efficiency and cost, as well as requirements for how deep the turbine must be set.

Impulse Turbine

In an impulse turbine, the water stream hits each bucket on the runner in turn and discharges at atmospheric pressure. There is no suction on the downside of the turbine, and the water flows out the bottom of the turbine housing after hitting the runner. An impulse turbine is generally suitable for high-head, low-flow applications.

Pelton and Turgo Wheels

A Pelton wheel has one or more free jets discharging water into an aerated space and impinging on the buckets of a runner. Draft tubes are not required for impulse turbines because the runner must be located above the maximum tailwater to permit operation at atmospheric pressure.

A Turgo wheel is a variation on the Pelton and is made exclusively by Gilkes in England. The Turgo runner is a cast wheel whose shape generally resembles a fan blade that is closed on the outer edges. The water stream is applied on one side, goes across the blades and exits on the other side.

Cross-Flow Turbine

A cross-flow turbine is drum-shaped and uses an elongated, rectangular-section nozzle directed against curved vanes on a cylindrically shaped runner. It resembles a "squirrel cage" blower. The cross-flow turbine allows the water to flow through the blades twice. The first pass is when the water flows from the outside of the blades to the inside; the second pass is from the inside back out. A guide vane at the entrance to the turbine directs the flow to a limited portion of the runner. The cross-flow was developed to accommodate larger water flows and lower heads than the Pelton.

Reaction Turbine

In a reaction turbine, the runner is placed directly in the water stream flowing over all of the blades rather than striking each blade individually. Reaction turbines are generally used for sites with lower head and higher flows than impulse turbines.

Propeller Turbine

A propeller turbine generally has a runner with three to six blades in which the water contacts all of the blades constantly. Picture a boat propeller running in a pipe. The pitch of the blades may be fixed or adjustable. The major components besides the runner are a scroll case, wicket gates, and a draft tube. There are several different types of propeller turbines:

- Bulb turbine - The turbine and generator are a sealed unit placed directly in the water stream.
- Straflo - The generator is attached directly to the perimeter of the turbine.
- Tube - The penstock bends just before or after the runner, allowing a straight line connection to the generator.
- Kaplan - Both the blades and the wicket gates are adjustable, allowing for a wider range of operation.

Francis Turbine

The Francis turbine has a runner with fixed buckets (vanes), usually nine or more. Water is introduced just above the runner and all around it and then falls through, causing it to spin. Besides the runner, the other major components are the scroll case, wicket gates, and draft tube.

Kinetic Turbine

Kinetic energy turbines, also called free-flow turbines, generate electricity from the kinetic energy present in flowing water rather than the potential energy from the head. The systems may operate in rivers, man-made channels, tidal waters, or ocean currents. Kinetic systems utilize the water stream's natural pathway. They do not require the diversion of water through manmade channels, riverbeds, or pipes; although, they might have applications in such conduits. Kinetic systems do not require large civil works; however, they can use existing structures such as bridges, tailraces, and channels.9933333

Formulae

Once a site's head and flow has been calculated, the power output can be calculated as follows:

Power (kW) = Flow (m^3/s) x Head (m) x 9.8 x η

where η is the efficiency of the turbine and 9.8 is the product of the density of water (1) and the acceleration due to gravity (9.8 m/s).

A detailed explanation of all formulae useful for hydropower installations is provided in chapter 2 of the *Layman's Guidebook on How to Develop a Small Hydro Site* (see For More Information on page 25).

Ocean Power

Oceans cover more than 70% of the Earth's surface. As the world's largest solar collectors, oceans accumulate thermal energy from the sun. They also produce mechanical energy from the tides and winds. Although the sun affects all ocean activity, it is primarily the gravitational pull of the moon that causes the tides, and the wind that drives the ocean waves.

There are four distinct types of ocean resource that can be used as sources of energy: waves, tides, temperature differentials (ocean thermal energy conversion), and differences in salinity (osmotic power). Except for osmotic power, which is still in its infancy, all of these technologies are at the point where demonstration projects are springing up all around the world.

Note that the Federal Energy Regulatory Commission applies the term "hydrokinetic" to all projects that draw power from freely flowing (unimpounded) water, including waves, tides, and ocean currents.

Wave Power

Wave power devices extract energy directly from surface waves or from pressure fluctuations just below the water's surface. The total power contained in the waves breaking around the world's coastlines is estimated at 2-3 million MW.

Wave power cannot be harnessed everywhere. Wave-power-rich areas of the world include the western coasts of Scotland, northern Canada and Alaska, southern Africa, Australia, and the northeastern and northwestern coasts of the contiguous United States. In the Pacific Northwest alone, it is feasible that wave energy could produce 40-70 kW per meter (3.3 feet) of western coastline.

Types of Wave Power Systems

Wave energy can be converted into electricity through both offshore and onshore systems.

Offshore Systems

Offshore systems are situated in deep water, typically more than 130-feet deep. Some devices (like the “Salter Duck” and “Powerbuoy”) use the bobbing motion of the waves to power a pump that drives a turbine to create electricity or use a linear generator that can produce power directly from the motion of the waves. Other offshore devices use water-filled hoses connected to floats that ride the waves. The rise and fall of the float stretches and relaxes the hose, which pressurizes the water, which, in turn, rotates a turbine. Yet another device is a tethered, floating version of the tapered channel, described below.

Specially built seagoing vessels can also capture the energy of offshore waves. These floating platforms create electricity by funneling waves through internal turbines and then back into the sea.

Onshore Systems

Built along shorelines, onshore wave-power systems extract the energy in breaking waves. Onshore system technologies include the following:

- **Oscillating water column —** The oscillating water column consists of a partially submerged concrete or steel structure that has an opening to the sea below the waterline. There is air in the upper part of the enclosed chamber and water in the lower part. As waves enter the chamber, they cause the water column to rise and fall. This alternately compresses and depressurizes the air column. The compressed air drives a turbine that is located in a narrow part of the chamber. As the wave retreats, the air is drawn back through the turbine as a result of the reduced air pressure on the ocean side of the turbine. The turbine generates power regardless of which direction it spins, so it generates power as the wave approaches and as it retreats.
- **Tapered channel —** The tapered channel system, consists of a tapered channel that feeds water into a reservoir constructed several meters above sea level. The narrowing of the channel causes the waves to increase in height as they move toward the reservoir. The waves spill over the walls of the channel into the reservoir, and the stored water is then fed through a turbine. Tapered channels are generally only suitable for sites with low-tidal ranges because high tides could otherwise flood the system (unless, of course, the system is designed to be submersible).
- **Pendulor device —** The pendulor wave-power device consists of a rectangular box, which is open to the sea at one end. A flap is hinged over the opening, and the action of the waves causes the flap to swing back and forth. This motion powers a hydraulic pump and a generator.

Environmental and Economic Challenges

In general, careful site selection is the key to keeping the environmental impacts of wave power systems to a minimum. Wave energy system planners can choose sites that preserve scenic shorefronts. They also can avoid areas where wave energy systems can significantly alter flow patterns of sediment on the ocean floor.

Economically, wave power systems have a hard time competing with traditional power sources. However, the costs to produce wave energy are coming down. Some European experts predict that wave power devices will find lucrative niche markets. Once built, they typically have low operation and maintenance costs.

One of the primary challenges for both onshore and offshore wave energy systems is survivability under harsh weather conditions. Severe weather has been known to destroy or damage both onshore and offshore wave energy devices, which tend to take the brunt of any storm. Some wave energy systems are designed to shut down during heavy waves to avoid damage from severe weather. Wave energy systems are also potentially susceptible to fouling or damage from marine debris.

Tidal and Ocean Current Power

Some of the oldest ocean energy technologies use tidal power. All coastal areas consistently experience two high and two low tides over a period of slightly more than 24 hours. The difference between the high and low tides is called the tidal range. Technologies that capture the potential energy in the height difference between high and low tides are referred to as tidal-range power systems. For those tidal differences to be harnessed to generate electricity using presently available technologies, the tidal range must be at least 16 feet. There are only about 40 sites on Earth with tidal ranges of this magnitude.

Other (underwater, hydrokinetic) technologies can make use of free-flowing ocean currents in many more locations; these systems are usually referred to as ocean-current or tidal-stream power systems. Tidal streams are fast-flowing currents caused by the motion of the tides. They usually occur in relatively shallow seas where a natural constriction exists that forces the water to speed up.

There are no tidal power plants in the United States at the present time. However, conditions are good for tidal power generation in both the Pacific Northwest and the Atlantic Northeast regions of the country. The best U.S. resource for marine current technologies is primarily in the Gulf of Mexico around the tip of Florida. Energy conversion from the Gulf Stream could potentially supply Florida with 35% of its electricity needs

Types of Tidal Power Systems

Tidal power technologies include a barrage or dam, tidal turbine, hydrofoil or hydroplane, and tidal fence.

Barrage or Dam

A barrage or dam is constructed across an estuary or bay that has a large tidal range. It generates electricity, much like a terrestrial hydroelectric dam, by building up a head of water and then releasing the water through turbines.

Sluice gates and turbines are installed along the dam. When the tides produce an adequate difference in the level of the water on opposite sides of the dam, the gates are opened. The water then flows through the turbines. The turbines turn an electric generator to produce electricity. The turbines can be designed to draw power from both incoming and outgoing tides, but such turbines suffer from efficiency losses.

A 240-MW barrage system has been operating at La Rance, France, since 1966. The only other commercial-scale barrage is a 20-MW facility that has been operating at Annapolis Royal in Canada since 1984.

Tidal Turbine

Tidal turbines look like wind turbines. They are sometimes arranged under water in rows, like wind farms. The turbines typically function best where coastal currents run at 3.6-4.9 knots [4.0-5.5 miles per hour (mph)]. In currents of that speed, a 50-foot-diameter tidal turbine can generate as much energy as a 200-foot diameter wind turbine would in winds of the same velocity. Ideal locations for tidal turbine farms are close to shore in water depths of 65-100 feet.

Some designs incorporate turbines that are attached to a fully submerged structure situated on the sea floor. The advantage of this arrangement is that the turbine and its support structure are out of the way of shipping; the disadvantage is getting access to the turbine for maintenance.

Other designs have turbines mounted on a vertical column that is driven into the seabed. The turbines themselves are bolted to an elevator-like structure, allowing them to be raised out of the sea for most maintenance.

A Scottish company has designed a system incorporating turbines that are attached to a semisubmerged, horizontal buoyancy tube; the advantage of this arrangement is that the entire power plant can be towed into a harbor for major maintenance. Variations on this design are being developed by other companies.

Hydrofoil or Hydroplane

A hydrofoil or hydroplane has a similar cross-section to an airplane wing (an aerofoil) but is designed to work under water instead of in air. The angle of the hydrofoil to the flow of the tide is varied precisely using a mechanical control system. Moving water pushes the foil either up or down according to the angle of the foil in the water, similar to the way an airplane flies up or down depending on the wing's angle of attack to the oncoming airstream. The energy from this up-and-down oscillation is captured and converted to electricity.

Oscillating hydrofoil technology is currently being developed by two British companies and is in the prototype stage. The Stingray system has a fully submerged support structure and uses the oscillating motion of the hydrofoil to extend and retract a cylinder, pressurizing oil that drives a hydraulic motor that in turn drives an electric generator. In the Pulse Tidal system, which is semisubmerged, mechanical linkages attached to the foil drive a conventional generator that is mounted on the part of the support structure that is located above the water surface.

Tidal Fence

A tidal fence is essentially a method for linking several hydrokinetic power generators together in a continuous line. Water flows through and around the submerged turbines at all times. The turbines are mounted on a support structure (the "fence"), part of which sticks up above the water's surface. The design of the fence is similar to that of a bridge. The electrical generators and transformers are permanently mounted above water, and the turbines are typically mounted in such a way that they can be raised above the water for maintenance.

Because tidal fences do not completely obstruct the flow of the water, they have a significantly lower impact on the local ecology than barrages and do not have the same problems with silting.

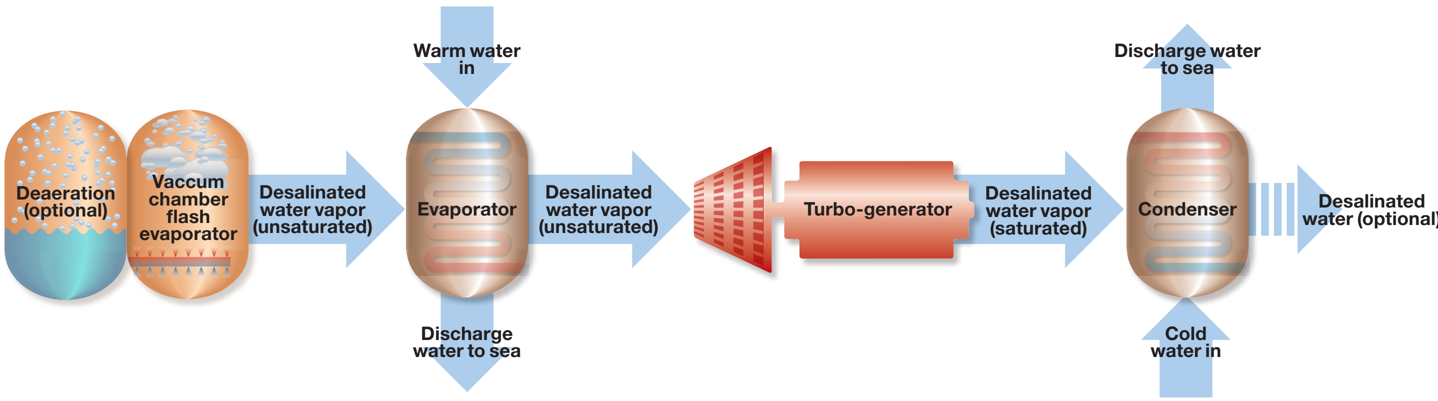
Tidal fences can be constructed across estuaries, or they can reach across channels between islands or across straits between the mainland and an island. Tidal currents in coastal waters can run at 5-8 knots (5.6-9.0 mph) and generate as much energy as winds of much higher velocity. Because seawater has a much higher density than air (832 times greater), ocean currents carry significantly more energy than air currents (wind) traveling at the same velocity.

A tidal fence is being evaluated for the Severn estuary in Great Britain as an alternative to a tidal barrage that would otherwise prevent shipping from gaining access to ports in the estuary. The total length of the tidal fence would be 9 kilometers (km) or 5.6 miles, built in three sections of 3 km (1.9 miles) each. Gaps between each section would allow shipping to pass unimpeded.

Environmental and Economic Challenges

Tidal power plants that dam estuaries can impede sea life migration, and the buildup of silt that usually occurs behind such facilities can impact local ecosystems. In addition, high-tidal ranges are generally caused by a phenomenon called tidal resonance, and barrages can potentially interfere with that resonance, causing the tides to be lower in the dammed estuary and potentially causing higher tides in other areas. Tidal fences may also disturb sea life migration, though not as much as barrages.

Tidal turbines are likely to prove the least environmentally damaging of all tidal power technologies because they don't block migratory paths. However, these systems usually have to be located in difficult coastal waters where the installation and maintenance methods are often complicated, raising costs.



A closed-cycle OTEC system uses a working fluid, such as ammonia, to run a generator. *Illustration by NREL*

It doesn't cost much to operate tidal power plants, but their construction costs are high, which lengthens payback periods. The tidal barrage proposed for the Severn estuary in Great Britain has an estimated cost of $30 billion and a capacity of 8.6 GW. The competing tidal fence proposal would cost $7 billion and have a capacity of 1.3 GW. The cost per kWh of tidal power is not competitive with conventional fossil-fuel electricity.

Ocean Thermal Energy Conversion

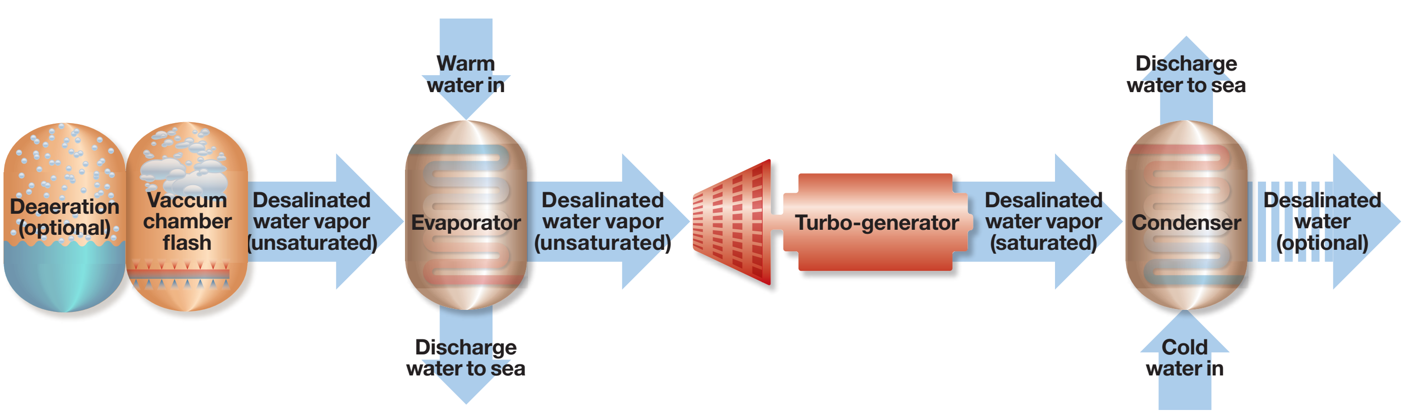
The energy from the sun heats the surface of the ocean. Ocean thermal energy conversion (OTEC) involves generating electricity by using the temperature difference between the ocean's warm surface and the cold water found at great depths—typically at least 2,000 feet down. OTEC power plants can be located on floating platforms or on shore.

In addition to generating electricity, OTEC systems can be used to desalinate water and provide refrigeration and air conditioning. The cold, deep seawater used in the OTEC process is also rich in nutrients and can be used to grow commercial marine crops near shore or conventional crops on land. OTEC can also be used to produce a variety of chemicals, including methanol, ammonia, hydrogen, and chlorine.

With today's technology, net power can be generated only if there is a difference of at least 36°F between the warm surface water and the cold deep water. This limits the use of OTEC power plants to tropical regions, where they are particularly attractive to island communities that rely heavily on imported fuel. OTEC plants in these locations could provide islanders with much-needed power and desalinated water.

OTEC technology faces many obstacles and is still in the demonstration phase. To bring the cold water to the surface, OTEC plants require an expensive, large-diameter intake pipe. Pumping large quantities of water from great depths is a significant engineering challenge that consumes a lot of energy, with the result that OTEC systems are not very energy efficient. In addition, open-ocean systems require a submarine cable to transport electricity to land.

U.S. OTEC research is focused on U.S. coastal areas, including the Gulf of Mexico, Florida, and islands such as Hawaii, Puerto Rico, and the Virgin Islands. Hawaii has been at the forefront of OTEC technology development, building the world's first OTEC plant to produce net power (the remainder after subtracting the power needed to run the system). This barge-mounted facility generated 15 kW of net electricity off the Hawaiian coast in 1979. An onshore facility generated 50 kW in 1993, and the state has announced plans to develop a commercial-scale, 10-MW plant.



An open-cycle OTEC system uses warm seawater as the working fluid. *Illustration by NREL*

Types of OTEC Systems

There are two primary types of OTEC power-generation systems: closed cycle and open cycle. Hybrid systems incorporating elements of both are also possible.

Closed Cycle

In the closed-cycle OTEC system, warm seawater vaporizes a working fluid, such as ammonia or an ammonia-water mixture, flowing through a heat exchanger (evaporator). The vapor expands at moderate pressures and turns a turbine coupled to a generator that produces electricity. The vapor is then condensed in another heat exchanger (condenser) using cold seawater pumped from the ocean's depths through a cold-water pipe. The condensed working fluid is pumped back to the evaporator to repeat the cycle. The working fluid remains in a closed system and circulates continuously.

Open Cycle

In an open-cycle OTEC system, warm seawater is the working fluid. The warm seawater is "flash"-evaporated in a vacuum chamber to produce steam. The steam expands through a low-pressure turbine that is coupled to a generator to produce electricity. The steam exiting the turbine is condensed by cold seawater pumped from the ocean's depths through a cold-water pipe. If a surface condenser is used in the system, the condensed steam remains separated from the cold seawater and provides a supply of desalinated water.

Osmotic Power

Osmosis is a natural process whereby water travels through a semipermeable membrane from an area of low salt concentration to an area of high salt concentration. This process makes it possible to generate electricity from the difference in salinity between freshwater and seawater.

When freshwater meets salty water, for instance where a river runs into the sea, enormous amounts of energy are released. In an osmotic power plant, freshwater and salt water are channeled into separate chambers, separated by an artificial membrane. The salt molecules in the seawater draw the freshwater through the membrane, causing the pressure on the seawater side to increase. This pressure is equivalent to a water column of 120 metres (390 feet) or, in other words, quite a large waterfall. This pressure can be used in a turbine to make electricity.

In 2009, the Norwegian utility Statkraft started operating the world's first osmotic power plant. According to Statkraft, the global potential of osmotic power is estimated to be 1,600-1,700 terawatt-hours per annum, equivalent to 50% of the European Union's total power production. Osmotic power plants can, in principle, be located wherever fresh water runs into the sea; they produce no noise or polluting emissions and can be integrated into existing industrial zones, for example, in the basements of industrial buildings.

Terms and Definitions

Draft tube – A conduit that carries water from the turbine outlet to the downstream water level.

Flow – The volume of water, expressed as cubic feet or cubic meters per second, passing a point in a given amount of time.

Head – The vertical change in elevation, in feet or meters, between the head-water level and the tailwater level. Net head is the equivalent vertical distance after subtracting losses from friction in the pipe or penstock.

Headwater – The water upstream of the turbine.

Hydrokinetic energy – The energy in free–flowing water that has not been dammed or diverted.

Penstock – A closed conduit or pipe that carries water from a reservoir or river to a turbine.

Ocean thermal energy conversion (OTEC) – an energy technology that converts solar radiation to electric power using the ocean's natural thermal gradient—the fact that the ocean's layers of water have different temperatures—to drive a power-producing cycle.

Osmosis – net movement of water across a semipermeable membrane driven by a difference in osmotic pressure across the membrane.

Osmotic pressure – Pressure, which if applied to a more concentrated solution, would prevent transport of water across a semipermeable membrane.

Oscillating water column (OWC) – A wave power device consisting of an air chamber in which the front wall has an opening so as to let waves enter inside; the wave action makes the water level in the air chamber to oscillate, and the air in the chamber is compressed and expanded generating airflow through an air turbine.

Runner – The rotating part of a turbine that converts the energy of falling water into mechanical energy.

Semipermeable membrane – Also called a selectively permeable membrane, a membrane that retains the salt ions but allows water through.

Tailrace – A channel that carries water away from a dam.

Tailwater – The water downstream of the turbine.

Tidal barrage – A dam used to convert tidal energy into electricity by forcing the water through turbines, activating a generator.

Tidal fence – A method for linking several hydrokinetic power generators, which look like giant turnstiles, together in a continuous line.

(Continued on page 25)

(Continued from page 24)

Tidal range – The vertical distance between the high and low tide.

Tidal stream power system – A system for extracting some of the kinetic energy from fast–flowing tidal currents and converting it into mechanical energy before being further converted to electricity.

Wave power device – Also called a wave energy converter, a technical device designed to convert wave energy to electrical energy.

Weir – A small dam in a stream or river to raise the water level or divert its flow.

Wicket gates – Adjustable elements that control the flow of water into the penstock.

For More Information

Energy Savers: Evaluating a Potential Microhydro Site
www.eere.energy.gov/consumer/your_home/electricity/index.cfm/mytopic=11070
Information for consumers from DOE on federal, state and community codes and requirements; and how to determine a site's head and flow.

Idaho National Laboratory Hydropower Website
hydropower.inel.gov
A comprehensive collection of hydropower information that includes the Virtual Hydropower Prospector, which provides a microhydro resource map that identifies the energy potential in natural streams around the country.

Layman's Guidebook on How to Develop a Small Hydro Site
www.microhydropower.net/download/layman2.pdf
Produced in Europe, this 266-page manual explains hydropower engineering principles, site evaluation methodologies, system design, environmental impacts, and economic analysis.

Marine and Hydrokinetic Technology Database
www.eere.energy.gov/windandhydro/hydrokinetic
A DOE database providing up-to-date information on marine and hydrokinetic renewable energy around the world.

Microhydro Electricity Basics
www.homepower.com/basics/hydro
Information from *Home Power Magazine* on various system configurations and required components.

National Hydropower Association
www.hydro.org
An organization working to increase the role that available, reliable, affordable, and sustainable hydropower plays in the U.S. electricity sector.

Ocean Energy Systems
www.ocean-energy-systems.org
A technology initiative of the International Energy Agency.

Ocean Power Magazine
www.oceanpowermagazine.net
An online magazine featuring news about ocean power from around the world.

Ocean Renewable Energy Coalition
www.oceanrenewable.com
A national trade association exclusively dedicated to promoting marine and hydrokinetic energy technologies.

Ocean Thermal Energy Conversion
www.nrel.gov/otec
Information from the National Renewable Energy Laboratory on OTEC technology and its applications.

Types of Hydropower Turbines
www.eere.energy.gov/water/hydro_turbine_types.html
Information from the DOE Water Power Program.

Solar Power Systems

There are two main forms of solar power: photovoltaic (PV) devices, commonly known as solar cells, convert sunlight directly into electricity, while solar thermal power systems use the sun's heat to generate electricity. Solar thermal power systems are also known as concentrating solar power (CSP) systems due to the fact that all of these systems depend on some method to concentrate the sun's heat, but the name can be confusing, because some PV systems also employ solar concentrating technologies.

Photovoltaic Devices and Systems

PV devices are generally made from semiconductors, materials such as silicon that have weakly bound electrons in the outer shell of their atoms. When sunlight of certain frequencies hits these atoms, it can excite the weakly bound electrons and free them from the atoms, causing an electron flow within the material. To build a crystalline silicon solar cell, layers of silicon with slightly different electrical properties are combined into a single device. To create the proper electrical properties, small amounts of impurities are added to the silicon to alter its electronic properties. This technique is known as "doping" the silicon.

The most basic crystalline silicon (c-Si) solar cell would consist of one layer of n-type silicon—silicon that primarily conducts negative electrons—and one layer of p-type silicon, or silicon that primarily conducts positive charge carriers. For solar cells, the positive charge carriers are actually the positive vacancies left behind when an electron is freed from the material. These positive vacancies, called "holes," can migrate through the material just like a particle. Put together, these materials form the "n" and "p" junctions of the solar cell, and they cause the device to have a built-in electrical potential across it.

Because of this electrical potential, electrons that are freed from their atoms by sunlight will tend to migrate to the "n" junction, where electrical contacts collect the current and deliver it to a wire. Another wire connected to electrical contacts on the "p" junction complete the electrical circuit.

Most of today's PV devices consist of c-Si solar cells, which are commonly 4 to 8 inches in diameter, although cells are available in sizes up to a foot in diameter (to be precise, 300 millimeters in diameter or about 11.8 inches). Solar cells were originally round, but manufacturers have developed cells that are shaped like rounded squares to allow them to be assembled closely together to form larger PV devices, called modules.

PV modules, also called solar panels, encapsulate the solar cells into a flat, rectangular plate, which generally features a transparent protective top layer (generally made of impact-resistant glass), a backing material for structural support, and an aluminum frame.

Another type of PV device, called a "thin film" solar cell, is manufactured by depositing thin films of semiconducting material onto a substrate such as glass, plastic, or flexible stainless steel. For these devices, the entire module is manufactured in one piece and is then typically scored with a laser to define the separate cells. Once electrical contacts are added, the module can be encapsulated in glass or plastic. Thin-film modules can be flexible if they use plastic or flexible stainless steel substrates encapsulated in plastic.

Solar cells generate about 0.6 volts, so within a module, they are connected in series to boost the nominal output voltage of the module, typically to either 12 or 24 volts. Modules can be connected together in series or in parallel, or a combination of both, depending on the voltage and current requirements of the application.

Benefits and Applications

PV systems are unique in their ability to generate electricity with no moving parts and no emissions. Because of those features, they are a clean energy source that is also highly reliable, requiring little or no maintenance. They also work in conditions of diffuse sunlight, so they can be employed anywhere in the United States, although systems in Alaska will not be useful during the long, dark winters. Even cloudy, rainy climates receive enough sunlight to make solar power systems practical, if not necessarily cost effective. PV systems are more expensive than most alternatives, but their benefits make them cost effective for many applications; and for many remote-power applications, they are the only practical solution.

Solar cells found their first practical applications in two areas: in power supplies for portable electronic devices, such as watches and calculators, and in space. In such applications, they are typically combined with a rechargeable battery (for small applications) or a pack of deep-cycle batteries (for larger applications) to maintain a constant supply of power. Because they can produce power nearly anywhere, they soon found a use in remote homes located off the grid, combined with a battery storage system.

Today, PV modules with battery storage systems are used as power supplies for a wide range of remote or portable power applications, including hazard warning lights on signs and along highways, emergency telephones, and remote telecommunications systems, such as relays. PV modules can also be mounted onto a trailer and brought to disaster areas to serve as a source of emergency power. While diesel generators are often used for emergency power, PV systems avoid the need to secure a supply of diesel fuel.

An increasing number of homes, schools, and businesses are now installing grid-connected PV systems on their rooftops and (for locations with ample acreage) in ground-mounted systems. A typical home installation will feature 2-4 kW of roof-mounted PV modules. School systems can run from tens to hundreds of kilowatts, while businesses can install anything up to megawatt-scale PV systems.

PV modules are typically mounted on a rack for ground or roof-mounted systems or a frame that mounts to the roof. PV modules can also be clamped directly to standing-seam metal roofs. The frame- and clamp-mounted modules are suspended slightly above the roof to let air circulate beneath them, helping them to keep cool, although it is also possible to circulate water underneath them, using the modules as a means of producing solar-heated water. The rack-mounted modules are usually tilted up to increase their energy capture. The ideal tilt angle for PV modules is typically the latitude plus or minus 15º, depending on the application (higher tilt angles perform better in the winter, while lower angles perform better in the summer). Some racks allow the tilt angle to be manually adjusted to account for the changing seasons.

Grid-connected systems include an inverter to convert the direct current (DC) output from the system into an alternating current (AC) output, as well as a controller. The controller will typically cut power from the PV system when grid power is lost, thereby avoiding an "islanding" effect of feeding power into de-energized power lines, which could cause a safety issue for utility repair crews. Sophisticated controllers can cut the power connection to the grid while continuing to supply power to one or more circuits within the building. Buildings wired to accommodate such systems will often place critical loads on one circuit that is powered by the PV system when grid power is lost. Although such controllers are commonly used, many utilities also require an emergency cutoff switch to be installed outside the building.

A small but growing number of PV systems are being integrated directly into buildings. Today's most popular building-integrated PV, or BIPV, system integrates the PV modules into the roof. United Solar Ovonic, often referred to by its Uni-Solar brand name, began offering PV shingles in the mid-1990s, and today offers a "peel and stick" PV module that can be directly bonded to the roofs of buildings (Uni-Solar's parent company, Energy Conversion Devices, entered restructuring in 2011, but Uni-Solar's products remain available). Some companies are also producing PV modules laminated with glass that can either be transparent or translucent, for use in building windows, skylights, awnings, and canopies. Future technologies, discussed below, seek to directly integrate layers of PV materials into building construction materials.

Many of today's grid-connected, customer-located PV systems do not include a battery backup, so their functionality as an emergency source of power is either limited or nonexistent. Customers that install such systems generally do it for the environmental benefits of the systems, although financial incentives sometimes lower the price enough to make the systems cost-effective as well. Many states offer direct financial incentives, and the federal government has, at times, offered tax credits. Many states and utilities also offer "net metering," which allows customers to earn credit for power fed into the grid, and some utilities offer additional financial incentives for systems that help the utilities meet their renewable portfolio standard (RPS) requirements. (See the Systems Integration and Load Control chapter for more information on grid connection, net metering, and RPS policies.)

Utilities are also either contracting to buy power from large centralized PV systems or are building, owning, and maintaining such systems themselves. These are typically megawatt-scale systems, many of which are built largely to meet RPS requirements. Such systems can also provide crucial distribution-system support in growing service areas that are placing stress on the existing transmission and distribution system. Some utilities are even building a distributed generation resource by financing, installing, and maintaining customer-located solar power systems. A key advantage of solar power for utilities is that system output is greatest when the sun is high, which is also when people and businesses crank up their air conditioning. Solar power can provide essential peak-load reductions throughout the utility grid, helping to ease the stress on power systems during heat waves.

Photovoltaic Cell Technologies

PV cell technologies include c-Si, multijunction, concentrating, thin film, and emerging technologies such as dye-sensitized solar cells, nanotechnologies, quantum dots, and organic solar cells.

Crystalline Silicon Solar Cells

As discussed above, c-Si solar cells were the first practical solar cells and remain the dominant type of solar cell in the market today. The production of c-Si solar cells is quite energy- and labor-intensive, as it starts by melting an ingot of silicon and growing a crystal from it, then sawing that crystal into individual "wafers" that are then converted into solar cells. The cells must then be assembled into PV modules. Typical c-Si modules, also called solar panels, achieve conversion efficiencies of about 15%-22%, that is, they can convert at most 22% of the solar spectrum into electricity.

Most advances in c-Si solar cells focus on making them easier and cheaper to manufacture. Some manufacturers have used micromachining to produce thinner wafers, down to about 60 microns in thickness, compared to up to 260 microns for typical c-Si solar cells. Others have found ways to grow ribbons of c-Si that are already about the right thickness, so they don't need to be sawed or micromachined. Another approach is to use silicon consisting of many small crystals rather than a single crystal. Such multicrystalline silicon is casted rather than grown, so it is simpler to manufacture.

Multijunction Solar Cells

Crystalline silicon solar cells only capture a portion of the sun's spectrum and have a theoretical upper efficiency limit of 33%. In reality, most cells achieve about half of the theoretical efficiency. An obvious approach to making more efficient solar cells is to find ways to capture more of the sun's spectrum. The solution was to produce a solar cell that combines multiple solar cells into one.

Today's "triple junction" solar cells are essentially three solar cells stacked on top of one another. Each layered cell, or junction, captures a different portion of the solar spectrum, and the remaining sunlight continues deeper into the device to the succeeding junctions. Triple-junction solar cells are generally made of various alloys of elements from the III and V columns of the periodic table, such as arsenic, gallium, germanium, indium, phosphorus, and selenium (although there are some important exceptions, which are discussed below under thin-film solar cells).

These "III-V" cells are expensive and difficult to manufacture, and are mainly used for space applications, where they are valued for producing a high amount of power with a relatively low-weight solar cell. Efficiencies of these solar cells can be as high as 30% under standard terrestrial conditions.

One of the newest methods of creating such cells is to grow the layers of the solar cell in an inverted sequence. Once the solar cell is complete, the substrate layer it is grown upon can be removed, and the layers of solar cell material can be affixed to a new "handle" material that can consist of any number of materials, such as glass, flexible foil, or plastic. This approach could greatly expand the potential applications of multijunction solar cells.

"One Sun" vs. Concentrating Solar Cells

The PV devices we see in our day-to-day lives, such as the solar modules mounted on the rooftops of homes, do not concentrate the sunlight hitting them in any way. In technical parlance, these are "one-sun" PV devices. In contrast, some solar cells are designed to convert concentrated sunlight into electricity. These concentrating solar cells are typically mounted in a structure with a Fresnel lens that concentrates the sunlight onto the cell. The idea of such concentrating PV systems is to use relatively few highly efficient, expensive solar cells to generate similar amounts of power as a non-concentrating PV panel. If their efficiency is high enough, such concentrating PV systems could produce power at a lower cost than their one-sun competitors.

The solar cells needed for such concentrating systems must operate at high efficiency and must also be tolerant of the high levels of solar radiation and heat that impinges upon them. Triple-junction solar cells are well-suited for this purpose. In fact, triple-junction cells perform at higher efficiencies under concentrated sunlight, and recent prototype cells have achieved efficiencies greater than 40% under solar concentrations of 240 suns. The new prototypes employ new methods of building the solar cells that allow for new choices of solar cell materials. This opens the door not only to new materials that better capture the solar spectrum, but also to practical solar cells that could consist of four or more junctions, potentially pushing the solar cell efficiency as high as 50%.

Currently, a major downside of concentrating PV systems is that their Fresnel lenses must be pointed toward the sun to properly concentrate the sunlight onto the cell. Because of this requirement, the modules must be mounted on two-axis tracking systems that accurately follow the sun's path across the sky. The systems also rely on direct sunlight, coming straight from the sun, rather than the diffuse sunlight scattered by clouds and nearby buildings. This means that such concentrating PV systems are generally only suited for sunny locations such as the desert Southwest. It also means that they are most likely to be employed only in utility-scale systems.

Amonix, the industry leader in the United States, began installing its fifth-generation systems in May 2000, and in the subsequent 6 years, the company installed more than 570 kW of concentrating PV technology. The company's main customer has been Arizona Public Service Company, but it has also installed a solar power system for Nevada Power Company, illustrating both the geographic boundaries of the technology and the utility-centered focus of the company.

This utility-centered focus may change with new technologies that are aiming to incorporate concentrating PV systems in simpler packages. One approach is to use lenses in the shape of a half-cylinder, with strips of concentrating solar cells running down their center. Because the curved lens can handle the movement of the sun along one axis, the systems only require a single-axis tracking device, which is relatively simple. Another approach aims to make a device similar to a solar panel. Soliant Energy, Inc. has developed a module-shaped device featuring about 35 separate miniature concentrators. All of the concentrators are pointed toward the sun through an interconnected system of pushrods that run beneath them, providing a crude method of two-axis tracking. A simpler approach with no moving parts has been developed in Japan using a module-sized array of 33 concentrators, each featuring a dome-shaped Fresnel lens.

The concept of using optics that can accept sunlight at a wide range of angles is also being put to work in a device currently under development through the Defense Advanced Research Projects Agency. Using secret military optics, this new solar device aims to include a solar concentrating capability in a device barely thicker than today's solar modules. As planned, the surface of the device will consist of a series of clear plastic or glass ridges. Each of these ridges will admit sunlight into an optical cavity that will split the light in three directions depending on its wavelength. Solar cells specifically matched to those wavelengths will be positioned in each of the three directions, and the combined efficiency of these solar cells will exceed 50%.

Each of the optical ridges on the face of the device can receive sunlight from a wide range of angles, yet still direct the sunlight efficiently into the device's optics. As a result, the device will not need to be pointed directly at the sun, and this flexibility eliminates the need for a two-axis tracking system. In fact, the U.S. military envisions incorporating such PV devices into soldier's backpacks to provide power for the sophisticated electronics required on today's battlefield. In 2007, an early prototype of the device achieved a 42.8% efficiency.

Thin-Film Solar Cells

Thin-film solar cells can be thought of as the low-efficiency, inexpensive cousins of the more sophisticated triple-junction III-V cells. Like the III-V cells, thin-film solar cells consist of thin films of PV material on a substrate, but III-V solar cells are typically grown as crystals on expensive germanium substrates, while thin-film solar cells are rapidly deposited onto relatively inexpensive substrates such as glass, flexible stainless steel, foil, or plastic. There are three main thin-film technologies: amorphous silicon (a-Si), cadmium telluride (CdTe), and alloys of copper, indium, gallium, and selenium, which is referred to as CIGS.

The earliest of these technologies to reach commercial status was a-Si, and it continues to play a major role today. Unlike c-Si, which is brittle and difficult to work with, a-Si is flexible, like plastic. It is formed by depositing a plasma of silane (SiH4) onto a substrate. The leading manufacturer of a-Si modules today is Uni-Solar, which deposits a-Si onto a flexible stainless steel substrate (Uni-Solar's parent company, Energy Conversion Devices, entered restructuring in 2011, but Uni-Solar's products remain available). Uni-Solar actually creates a triple-junction cell by depositing multiple layers of a-Si with different doping to create junctions that absorb distinctively separate portions of the solar spectrum.

The key to the Uni-Solar device is the high-output manufacturing process. Uni-Solar runs mile-and-a-half-long rolls of stainless steel through a "roll-to-roll" process, similar to how newspapers are printed. Their process deposits nine layers of thin-film materials onto six rolls of stainless steel simultaneously. A number of startup companies are now pursuing a-Si technology, as is Sharp Electronics Corporation.

Like all thin-film technologies, a-Si solar cells perform at relatively low efficiencies, around 10%-15%. Amorphous silicon also suffers uniquely from one problem, namely that its efficiency initially decreases over time as it is exposed to sunlight. Most manufacturers report "stabilized" power output for a-Si modules, which is the power output after the module has suffered this initial degradation.

CdTe is currently the leading thin-film technology in terms of global manufacturing capacity. The technology employs a vapor deposition technique to deposit thin films of the material onto glass. This is a high-throughput process that yields low production costs. Because the substrate is glass, CdTe modules are rigid and are similar to c-Si modules. The leading manufacturer in the world is U.S.-based First Solar, Inc., although a number of startup companies are also pursuing the technology.

The main advantage to CdTe is low cost; First Solar has cut its manufacturing costs to $1.14 per watt, which should yield competitive prices. The films are also stable over long periods. The drawback is that they employ cadmium, a toxic heavy metal. Although there is little or no danger of the cadmium leaching out of the solar panels during operation, there is a concern about disposal of the modules. Because of this, manufacturers are setting up recycling programs for their products.

The final contenders in the thin-film industry are CIS—made from alloys of copper, indium, and selenium—and CIGS, which adds gallium to the mix. CIS and CIGS have the advantage of being able to be deposited on a wide variety of substrates. Japan's Solar Frontier is the largest manufacturer of CIS solar modules, depositing CIS films on glass.

The current market leader for CIGS, Global Solar Energy, is depositing CIGS films on flexible stainless steel substrates that can be rolled up and easily transported, making the modules useful for applications such as recharging electronics in remote locations. Because of these advantages, the product is being used by the U.S. military, among others. Like CdTe, CIGS is a film with long-term stability, and while it currently lacks the cost advantages of CdTe, it benefits from its ability to be deposited on flexible substrates such as plastic. CIGS solar cells achieve about a 10% efficiency.

Companies are exploring new, cheaper ways to manufacture thin-film solar modules and are exploring ways to extend these technologies to other products. One example is HelioVolt, which is working with the National Renewable Energy Laboratory (NREL) on ink-based "precursors" for CIGS films. Using ink-jet technology—the same used in computer printers—the inks can be sprayed onto a material, after which the material is subjected to a process that converts the inks into a crystalline layer of CIGS. The company has demonstrated that the inks can be sprayed onto complex shapes and a wide variety of substrates and then converted into CIGS. The technology opens the door to spraying CIGS onto a variety of building materials, such as standing-seam metal roofs, and thereby manufacturing true building-integrated PV devices. A company called Nanosolar is using a similar approach, depositing CIGS films on aluminum foil.

Dye-Sensitized Solar Cells

In the pursuit of less-expensive ways to produce solar cells, one contender is the dye-sensitized solar cell, also called the Grätzel cell after one of its inventors. The cell can be thought of as a solar-powered battery, and the process is often compared to photosynthesis. These cells involve particles of titanium dioxide coated with a photosensitive dye and embedded in an electrolyte (typically an iodide) or a conductive polymer. A transparent conductive oxide layer (typically tin oxide) forms an anode at the top of the cell, while a conductive layer at the bottom (typically platinum) forms the cathode. The cell works best if the titanium dioxide is formed into a complex structure on the scale of a billionth of a meter (a nanometer), or what is known as "nanostructured" titanium dioxide. Ideally, this structure provides a direct electronic connection with the anode.

Sunlight hitting the cell frees an electron from the photosensitive dye, and the electron then passes into the titanium dioxide and is conducted through the nanostructure to the anode. Meanwhile, the electron lost from the dye is replaced with an electron from the electrolyte, and the oxidized electrolyte molecule migrates to the cathode, where it accepts an electron, completing the electrochemical process and creating a current.

A key factor in the dye-sensitized cell is that the electrolyte is rapidly oxidized, creating essentially no opportunity for the electron to recombine with the dye molecule. Such recombinations are a limiting factor in the performance of most solar cells, so this feature gives the cells an advantage. Still, efficiencies are low, at about 10%-11%, but this is balanced by the relatively inexpensive components that make up the cell.

A company in Wales, G24 Innovations, Ltd. began limited manufacturing of dye-sensitized solar cells in 2007, using a roll-to-roll manufacturing process similar to those used for manufacturing newspapers. An Australian company, Dyesol, is also commercializing the technology. Dyesol announced in 2008 that it had developed a 10% efficient solar cell using an inexpensive glass substrate, thanks to the combination of two dyes and its proprietary pastes and electrolytes used to build the cell.

One factor that limits the effectiveness of dye-sensitized solar cells is the relatively slow migration of electrons through the titanium dioxide. Researchers have been studying alternate nanostructures, such as whisker-like "nanowires," as an alternative structure to guide the electrons more effectively to the anode. Another approach is to form "popcorn ball"-shaped clusters of titanium dioxide, an approach under investigation at the University of Washington. Researchers are also trying to incorporate "quantum dots," discussed below, as another means of boosting the efficiency of the cells.

Nanotechnologies and Quantum Dots

The field of nanotechnologies—technologies that use materials on the "nanoscale" of billionths of a meter—has gained prominence in recent years, as researchers are applying nanotechnologies to a wide range of technical challenges. As the above discussion on dye-sensitized solar cells indicates, nanotechnologies are finding their way into solar cells in a number of ways. In general, researchers are investigating whether replacing traditional materials in solar cells with nanostructured materials can boost their efficiency. It's also worth noting, however, that a strong interest in nanotechnologies is causing some companies to emphasize the "nano" aspects of technologies that have long been used. For instance, colloidal structures of titanium dioxide, developed decades ago, are now referred to as nanostructured titanium dioxide.

One truly unique nanotechnology that entered the scene around the beginning of this century is "quantum dots," named after their unique properties due to effects arising from quantum physics. Quantum dots are nanoscale particles of semiconductor that, because of their submicroscopic size, behave is a strange way: the wavelengths of light that they absorb are determined by their diameter. The larger the dot, the greater the wavelength. Because of this unique property, quantum dots offer the possibility of creating solar cells that are "tuned" to certain wavelengths of sunlight. In 2010, NREL certified the first all-quantum-dot solar cell, using quantum dots made of lead sulfide.

Quantum dots are also unusual in another way: rather than generating free electrons from sunlight, they instead form a bound pair consisting of the electron and the positively charged "hole" it leaves behind in the semiconductor. These bound pairs are called "excitons," and the difficult part is to capture the electron from the exciton and produce useful current from it before the exciton pair recombines. Solar cells that employ such excitons are sometimes referred to as "excitonic" solar cells.

One potential advantage of solar cells incorporating quantum dots is that unlike standard semiconductor materials, quantum dots can actually yield more than one exciton per photon of light: in essence, the cell can produce more than one electron per photon, so it can potentially achieve much higher efficiencies than traditional solar cells. This "multiple exciton" effect was originally observed in quantum dots made of materials that would be unsuitable for solar cells, but in 2007, researchers found that silicon quantum dots could also produce multiple excitons. Theoretical studies have shown that solar cells employing this effect could reach efficiencies of 65%.

The first working example of a solar cell that employs the multiple exciton effect was announced by NREL in 2011. Although the solar cell was not optimized and had a relatively low conversion efficiency, the fact that it successfully employed the multiple exciton effect demonstrated future potential for this approach.

Organic Solar Cells

Organic or polymer (plastic) solar cells are solar cells made of electrically conductive plastics. Sunlight hitting the plastic generates excitons that migrate randomly within the material. One way to capture these excitons and convert them into useful current is to embed within the polymer many soccer-ball-shaped carbon molecules, known variously as "buckminsterfullerenes," "buckyballs," or just plain "fullerenes" (all of which are references to the geodesic domes designed by Buckminster Fuller, which resemble the molecule). These 60-carbon molecules, which kicked off the nanotechnology era, are effective at separating the excitons into electrons and holes. The holes migrate effectively through the polymer chains, while the electrons are conducted through the material.

The key to organic solar cells is to quickly separate the excitons into electrons and holes. Excitons will migrate only short distances, so organic solar cells using fullerenes must have them dispersed throughout the cell. Other approaches to the charge separation include using long, whisker-like nanofibers, embedding the polymer in a porous semiconductor film, or by using dendritic polymers, which branch out in a tree shape. Of all these approaches, the use of fullerenes appears most promising to date, with efficiencies exceeding 5%, whereas most organic solar cells are achieving at best 2%-3% efficiencies. One potential approach to reaching higher efficiencies is to embed quantum dots within the polymer.

One drawback of organic solar cells is their degradation when exposed to ultraviolet (UV) light (a component of sunlight) for long periods of time. Early cells have addressed that by covering the cell with glass, an approach that defeats many of the advantages of organic solar cells. But in 2008, researchers developed a UV-blocking plastic based on Saran, the plastic known widely for Saran wrap. The extra ingredient in the plastic was boron nitride nanotubes—yet another example of how nanotechnology is being applied to the next generation of solar cells.

The current leader in actually manufacturing organic solar cells is Konarka Technologies, which has developed a roll-to-roll manufacturing process. The company began commercial manufacturing at a factory in Massachusetts in 2008. Konarka has also demonstrated a method of applying the solar cell material using ink-jet technology. This simple manufacturing approach has led some to jump to the conclusion that we will soon be able to paint solar cells onto surfaces. However, the need for precisely controlled applications of multiple layers, including a means of collecting and delivering the current and of providing a protective covering over the material, suggests that true “paint-on” solar cells remain out of reach for the foreseeable future.

Solar Thermal Power Systems

Solar thermal power systems all work by concentrating the sun’s heat onto a receiver and then converting that concentrated solar heat into electricity. Because all solar thermal systems involve concentrated solar energy, they are also known as CSP systems. There are three main types of solar thermal power systems: parabolic troughs, dish-engine systems, and power towers.

Like most concentrating PV systems, solar thermal power systems rely on direct solar radiation, that is, the sunlight coming directly from the sun. Clouds, haze, or even humidity can interfere with such radiation, so the best U.S. locations for solar thermal power systems are in the desert Southwest. Solar thermal power plants are pollution-free power sources. Parabolic troughs and power towers are utility-scale technologies, but dish-engine systems can be installed as a single unit (appropriate for some businesses, large institutions, small towns, and remote villages) or as a utility-scale array of units.

Parabolic Troughs

Parabolic trough systems employ long lines of parabolic, or “u”-shaped mirrors, and are named for their slight resemblance to shallow watering troughs. The mirrors concentrate the sun’s heat onto a receiver tube through which a heat-transfer fluid, such as oil, is circulated. The heated oil is piped through a heat exchanger in a boiler, generally providing the heat source to boil water into steam. As in a conventional power plant, the steam then spins a turbine-generator set to produce electricity. The use of a boiler allows for hybrid systems that fuel the boiler with natural gas when the sun is not available, thereby providing a continuous, baseload power source.

A variant on the standard parabolic trough technology was launched in 2006, when Arizona Public Service Company (APS) commissioned a 1-MW solar trough plant that employs the organic Rankine cycle, that is, it vaporizes an organic liquid with a boiling point lower than water, and it uses that vapor to drive the turbine. Such systems are able to produce more power at lower temperatures. The system also allows for storing the hot oil, providing the capability to “ride through” overcast conditions or to keep producing power after sunset. The oil storage system is actually made possible by the lower operating temperature: higher temperatures require an oil with a high vapor pressure, which would be unsuitable for storage in an unpressurized tank.

The mirrors in parabolic trough systems are oriented in the north-south direction, allowing the system to track the sun by rotating the mirrors about the axis of the receiver tube, an approach that requires only a relatively simple single-axis tracking system. The receiver tubes are steel tubes with a special solar absorption coating, surrounded by an evacuated glass tube for insulation.

Parabolic trough systems were the first major source of utility-scale solar power in the United States, and for decades they were also the largest source of solar power in the country. The first U.S. systems were built in California’s Mojave Desert from 1985 to 1991. These nine units, called the Solar Energy Generating Station (SEGS) Units I through IX, have a total generating capacity of 354 MW. The facilities are now owned by FPL Energy.

After 1991, nearly 30 years went by before the next facility was built, namely, the APS system discussed above. In 2007, the 64-MW Nevada Solar One plant started producing power near Boulder City, Nevada, marking the return of large-scale solar power plants to the United States, primarily due to solar energy requirements under RPS policies. California’s Pacific Gas and Electric Company has contracted to buy power from a proposed 553-MW solar trough plant, which the California Energy Commission approved in 2010. If built, the plant will cover 9-square miles in the Mojave Desert, featuring 1.2 million mirrors and 317 miles of receiver tubing.

Because of high capital costs and significant maintenance requirements, parabolic trough systems are not yet competitive with conventional power sources, but the SEGS units have demonstrated that the facilities can operate for extended periods of time. Those units have also led to the development of automated systems for washing the mirrors, an essential maintenance item, while researchers recently developed a simplified system for mirror alignment, another critical maintenance requirement. The SEGS plants have also unveiled a safety consideration for the technology, as fires have broken out at least twice. One of the fires was attributed to operator error, for allowing the heat-transfer oil to overheat.

Although parabolic trough technology has remained essentially unchanged since the first SEGS unit was built in 1985, one company is introducing some new design elements to the technology. In 2008, Ausra, Inc. built a 5-MW plant in Southern California that replaces the parabolic mirrors with a series of narrow, flat mirrors, each of which is angled to direct the sunlight at the receiver tube, thereby mimicking the function of the parabolic mirror. The approach, called a Compact Linear Fresnel Reflector, is intended to reduce the capital cost of building the plant. In another cost-cutting move, the Ausra technology passes water through the receiver pipes, boiling the water directly into steam, which is then piped to a turbine.

Dish-Engine Systems

Dish-engine systems employ a number of mirrors mounted on a dish-shaped frame to approximate a parabolic mirror (building actual parabolic mirrors would be too expensive). The mirrored dish concentrates the sun's heat on its focus, where a heat engine is mounted. Heat engines, such as the Stirling engine, convert heat into mechanical energy. Stirling engines use the heat to drive a piston, which in turn drives a generator to produce electricity. Because Stirling engines are generally the preferred heat engine for use in dish-engine systems, they are also called dish-Stirling systems. Like parabolic troughs, dish-engine systems require periodic mirror washings, and the more complicated two-axis tracking system must also be maintained to keep the unit operating at its peak.

The market leader in dish-Stirling systems was named, appropriately enough, Stirling Energy Systems, Inc., but the company filed for Chapter 7 bankruptcy in 2011, placing the future of the technology in doubt. The company built a 25-kW system consisting of 82 slightly curved mirrors mounted on a steel frame. After building a prototype at Sandia National Laboratories in 2004, the company added five more dishes later that year. Although the pilot project was a success, the company was ultimately unable to compete with the low cost of PV solar power.

While today's solar dish systems all use heat engines, it is also possible to build a dish system that concentrates the sunlight onto an absorber, through which a heat transfer fluid is pumped. Tests on such systems have generally found them to be impractical and unreliable, but if such technologies are ever revived, they would also allow for thermal storage.

Power Towers

Solar power towers are utility-scale systems that consist of a field of flat mirrors, or heliostats, that direct the sun's heat onto a receiver mounted at the top of a tower. To achieve this feat, each of the mirrors is mounted on a two-axis tracking system, and the entire solar field is computer controlled through a central control station. DOE pioneered this technology in the 1980s, when it worked with private industry to build and operate Solar One, a 10-MW demonstration plant near Barstow, California. The facility featured 1,818 heliostats that focused the sun's heat onto the top of a 310-foot tower. Water was pumped up to the receiver at the top of the tower, where it boiled into steam, and the steam was piped to a turbine-generator to produce electricity. Steam could also be directed into a holding tank containing oil, rock, and sand.

Although the system proved the technology concept, Solar One was difficult to operate because any passing cloud that interrupted the sunlight would cause the steam pressure to drop, and the turbine and generator would trip offline. The thermal storage holding tank also proved ineffective. The facility was shut down in 1988, but in the 1990s DOE returned with a consortium of project partners to revive it as Solar Two.

The new facility started operation in 1996 and used molten salt instead of water, employing the heat of the molten salt to power a boiler, which generated steam for the turbine. The solar field was revamped and slightly expanded, to 2,000 mirrors, and it had the capability to heat the "cold" molten salt from 285°C (550°F) to a maximum temperature of 565°C (1,050°F). The facility also featured a storage tank for the "hot" salt, thereby allowing the facility to "ride through" partially cloudy days and to even keep generating power for several hours after sunset, helping to meet peak power needs. After a successful run, Solar Two was shut down in 1999.

Power tower technology was first commercialized in Spain. Abengoa Solar has built an 11-MW solar power tower facility called PS10, which began commercial operations in 2007. It uses water rather than molten salt, but it includes a steam storage system that allows continued operation for 30 minutes without sunlight. In 2009, the company's second solar power tower plant, the 20-MW PS20, went online. The facility features the world's largest solar power tower, a 541-foot tower surrounded by a 210-acre field of 1,255 heliostats.

Power tower technology is also returning to the United States, as BrightSource Energy Inc. is building a power tower installation in California, with plans to build more. Located in the Mojave Desert, the Ivanpah project will consist of three separate units, for a total generating capacity of 370 MW. BrightSource Energy is also proposing to build two 250-MW solar power tower plants in California's Inyo County, and three 250-MW solar power tower plants in California's Riverside County. BrightSource Energy is the current incarnation of the company that originally built the SEGS parabolic trough plants in Southern California.

Terms and Definitions

Amorphous silicon (a–Si) – A thin–film, silicon PV cell having no crystalline structure. Manufactured by depositing layers of doped silicon on a substrate.

Anode – The positive electrode in an electrochemical cell (battery). Also, the earth or ground in a cathodic protection system. Also, the positive terminal of a diode.

Baseload – The average amount of electric power that a utility must supply in any period.

Building–integrated photovoltaics (BIPV) – A term for the design and integration of PV technology into the building envelope, typically replacing conventional building materials. This integration may be in vertical facades, replacing view glass, spandrel glass, or other facade material; into semitransparent skylight systems; into roofing systems, replacing traditional roofing materials; into shading "eyebrows" over windows; or other building envelope systems.

Cadmium telluride (CdTe) – A polycrystalline thin–film PV material.

Concentrator – A PV module, which includes optical components such as lenses (Fresnel lens) to direct and concentrate sunlight onto a solar cell of smaller area. Most concentrator arrays must directly face or track the sun. They can increase the power flux of sunlight hundreds of times.

Crystalline silicon (c–Si) – A type of PV cell made from a slice of single–crystal silicon or polycrystalline silicon.

Diode – An electronic device that allows current to flow in one direction only.

Electrode – A conductor that is brought in conducting contact with a ground.

Electrolyte – A nonmetallic (liquid or solid) conductor that carries current by the movement of ions (instead of electrons) with the liberation of matter at the electrodes of an electrochemical cell.

Electron – An elementary particle of an atom with a negative electrical charge and a mass of 1/1837 of a proton; electrons surround the positively charged nucleus of an atom and determine the chemical properties of an atom. The movement of electrons in an electrical conductor constitutes an electric current.

Fresnel lens – An optical device that focuses light like a magnifying glass; concentric rings are faced at slightly different angles so that light falling on any ring is focused to the same point.

Inverter – A device that converts DC to AC

Junction – A region of transition between semiconductor layers, such as a p/n junction, which goes from a region that has a high concentration of acceptors (p–type) to one that has a high concentration of donors (n–type).

Multijunction device – A high–efficiency PV device containing two or more cell junctions, each of which is optimized for a particular part of the solar spectrum.

Photovoltaic(s) (PV) – Pertaining to the direct conversion of light into electricity.

PV array – An interconnected system of PV modules that function as a single electricity–producing unit. The modules are assembled as a discrete structure, with common support or mounting. In smaller systems, an array can consist of a single module.

PV cell – The smallest semiconductor element within a PV module to perform the immediate conversion of light into electrical energy (DC voltage and current). Also called a solar cell.

PV module – The smallest environmentally protected, essentially planar assembly of solar cells and ancillary parts, such as interconnections, terminals, and protective devices, such as diodes, intended to generate DC power under unconcentrated sunlight. The structural (load-carrying) member of a module can either be the top layer (superstrate) or the back layer (substrate).

PV panel – often used interchangeably with PV module (especially in one–module systems), but more accurately used to refer to a physically connected collection of modules (i.e., a laminate string of modules used to achieve a required voltage and current).

Rankine cycle – The thermodynamic cycle that is an ideal standard for comparing performance of heat–engines, steam power plants, steam turbines, and heat pump systems that use a condensable vapor as the working fluid; efficiency is measured as work done divided by sensible heat supplied.

Semiconductor – Any material that has a limited capacity for conducting an electric current. Certain semiconductors, including silicon, gallium arsenide, copper indium diselenide, and CdTe, are uniquely suited to the PV conversion process.

Stirling engine – A heat engine of the reciprocating (piston) where the working gas and a heat source are independent. The working gas is compressed in one region of the engine and transferred to another region where it is expanded. The expanded gas is then returned to the first region for recompression. The working gas thus moves back and forth in a closed cycle.

Thin film – A layer of semiconductor material, such as copper indium diselenide or gallium arsenide, a few microns or less in thickness, used to make PV cells.

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For More Information

American Solar Energy Society
www.ases.org
An association of solar professionals and advocates.

Concentrating Solar Power
www.eere.energy.gov/solar/csp_program.html
Information about CSP research and development under the DOE Solar Energy Technologies Program.

DOE SunShot Initiative
www1.eere.energy.gov/solar/sunshot
A collaborative national initiative to make solar energy cost competitive with other forms of energy.

Photovoltaics
www.eere.energy.gov/solar/photovoltaics_program.html
Information about PV research and development under the DOE Solar Energy Technologies Program.

Solar Electric Power Association
www.solarelectricpower.org
An educational nonprofit dedicated to helping utilities integrate solar power into their energy portfolios for the benefit of the utility.

Solar Energy Industries Association
www.seia.org
A national trade association of the U.S. solar energy industry.

SolarPACES
www.solarpaces.org
An international cooperative network bringing together teams of national experts from around the world to focus on the development and marketing of concentrating solar power systems.

TroughNet: Parabolic Trough Solar Power Network
www.nrel.gov/csp/troughnet
Information from NREL about parabolic trough technologies.

Wind Power

Wind is caused by the uneven heating of the atmosphere of the sun, the irregularities of the earth's surface, and the rotation of the Earth. Wind flow patterns are modified by the Earth's terrain, bodies of water, and vegetation.

The kinetic energy in the wind can be converted into mechanical power for specific tasks. For thousands of years, windmills have captured the energy for pumping water or grinding grain. Today, a wind turbine—the modern equivalent of a windmill—can be used to generate electricity. Wind turbines can be used as stand-alone applications, or they can be connected to a utility power grid. Utility-scale turbines are greater than 100 kW in generating capacity, and the newest models have capacities of multiple MW. A number of companies are developing 10-MW wind turbines. Large turbines are usually grouped together to form a wind plant or wind farms either on land or offshore.

Small turbines, with capacities of 100 kW or less, are used for homes, small businesses, telecommunication dishes, or water pumping. Small wind systems also have potential as distributed energy resources. They can sometimes be used in conjunction with diesel generators, batteries, and PV systems, in what are called hybrid power systems.

Wind power is the fastest growing energy source in the world. In the United States, wind power capacity grew to more than 40,000 MW in 2010. And that's only a small portion of the U.S. wind potential, which varies depending on the height of the wind turbine tower, because winds are generally stronger at higher elevations. According to a 2010 study conducted by NREL and AWS Truepower, the United States has the potential for almost 10,500 GW of wind power capacity at a height of 80 meters (a common tower height today) and a potential for 12,000 GW of wind power capacity at 100 meters, a likely target height for future wind turbines (although some turbines are already reaching tower heights of 120 meters). Most of the wind potential comes from the windy central regions, but many eastern and western states have significant wind potential: 35 states have more than 1,000 MW of potential wind power capacity at 80 meters, and 36 states have more than 1,000 MW of potential wind power capacity at 100 meters.

Not only is wind energy readily available in many areas, but wind power is one of the lowest-priced renewable energy technologies, costing between 4 and 6 cents per kWh, depending upon the wind resource and project financing. The cost of wind power has decreased drastically, and wind power has lower operation and maintenance costs than fossil-fueled generators, mainly because the fuel is free, but the technology requires a higher initial investment than fossil-fueled generators.

Wind turbines have relatively little impact on the environment compared to conventional power plant technologies, but there is some concern over the noise produced by the rotor blades, aesthetic impacts, and birds sometimes being killed when they fly through the rotors. Most of these problems, however, have been resolved or greatly reduced through proper siting and technological development. Still, before selecting wind power as their electricity source, individuals and communities should make informed decisions.

Types of Wind Turbines

Turbines catch the wind's energy with their blades. When the wind blows, a pocket of low-pressure air forms on the downwind side of the blade. The low-pressure air pocket then pulls the blade toward it. This is called lift. The force of the lift is actually much stronger than the wind's force against the front side of the blade, which is called drag. The combination of lift and drag causes the rotor to spin like a propeller, and the turning of the shaft spins a generator to make electricity.

There are two main types of modern wind turbines: horizontal-axis and vertical axis. Horizontal-axis wind turbines are the most common. They usually have two or three blades, which are like airplane propellers, and the blade assembly is called the "rotor." The rotor is mounted on a shaft that runs through the "nacelle," a bus-shaped housing mounted at the top of the tower. The nacelle houses the guts of the wind turbine, including the drivetrain, gearbox, generator, brake assembly, and electrical controls.

Wind turbines can operate with the rotor downwind from the tower, turning like a pinwheel in the wind, or with the rotor upwind from the tower, a more complex arrangement that keeps the tower from disturbing the wind flow into the rotor. Small upwind wind turbines use a tail vane to keep the rotor pointed into the wind, much like a weathervane. For larger upwind turbines, a wind vane measures the wind direction and communicates with the yaw drive. The yaw drive keeps the rotor facing into the wind as the wind direction changes. The rotor turns the low-speed shaft at about 30 to 60 rotations per minute (rpm). To increase the rotational speed to the 1,000 to 1,800 rpm required by most generators to produce electricity, gears connect the low-speed shaft to a high-speed shaft, which drives the generator.

Because of their low rotational speed, vertical-axis wind turbines are less efficient than their horizontal-axis counterparts. They have blades that go from top to bottom with the main rotor shaft set vertically. The vertical-axis design includes the Darrieus model, named after its French inventor, which looks like a giant, two-bladed egg beater. Unlike horizontal-axis wind turbines, they don't need to be pointed into the wind. Also the generators and gearboxes can be placed close to the ground, which makes them easier to service and repair. However, the wind resource is lower and more turbulent near the ground, so this approach results in less energy production.

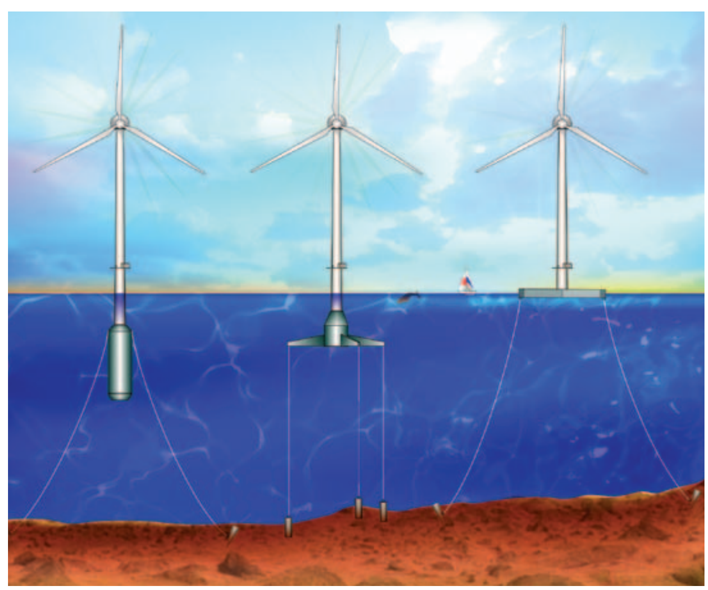
A wind turbine can be designed to rotate at a constant or variable speed. At a constant speed, the rpm is fixed, while at a variable speed, a turbine rotates at a rate proportional to the velocity of the wind. Variable-speed turbines have become more popular because when running at a constant speed, turbines can lose a great deal of wind potential, lowering the efficiency. But a variable-speed design can increase overall turbine cost because of the advanced power electronic components it requires.

To capture the most energy, wind turbines are typically mounted 100 feet or more above the ground on towers, where they can take advantage of the faster and less turbulent wind. There are two basic types of towers: self-supporting and guyed. Self-supporting towers are free standing. Most large, utility-scale wind turbines are mounted on self-supporting towers. Most small wind power systems use a guyed tower. Guyed towers, which are the least expensive, can consist of lattice sections, pipe, or tubing (depending on the design), and supporting guy wires. They are easier to install than self-supporting towers. However, because the guy radius must be one-half to three-quarters of the tower height, guyed towers require enough space to accommodate them.

Some guyed towers are "tilt-down" towers, which are mounted on a pivot near the ground so that the guy wires can be removed and the tower can be lowered to the ground without the use of a crane. Although tilt-down towers are more expensive, they offer an easy way to perform maintenance on smaller lightweight turbines, usually 5 kW or less. Tilt-down towers can also be lowered to the ground during hazardous weather such as hurricanes.

Utility-Scale Terrestrial Wind Farms

The generating capacity for terrestrial or land-based, utility-scale wind farms ranges from 5 MW to several hundred MW. They consist of a few to hundreds of individual wind turbines, and the power generated by each wind turbine is transferred to a transformer that is either located in the nacelle or in or near the base of the tower. The transformer raises the



Three concepts for floating wind turbines include the spar-buoy (left), the tension-leg platform (center), and the barge (right). *Illustration by NREL* voltage of the electricity produced by the turbine to the level of the collection system—a system of underground cables that transmit the electricity to a substation and point of interconnection switchyard, where the electricity is transferred to the power grid. To monitor and control each turbine's operation, many large wind farms have central computer systems, such as a supervisory control and data acquisition (SCADA) system. These systems are generally operated from on- or off-site operations and maintenance facilities.

Before building a wind farm, developers must first erect wind measurement systems or meteorological towers to assess the resource, and these towers are often left in place when the wind farm is operating. A meteorological tower has anemometers, which are sensors that measure wind speed and direction, a data logger, and a meteorological mast. These towers can also be equipped with sensors to measure temperature and pressure.

Unlike most electric power plants, wind farms do not consume water. Currently, thermoelectric power accounts for 48% of total water withdrawals in the United States. The water is primarily used for condensing and/or cooling steam, generating electricity in hydropower systems, purging boilers, and/or washing stacks. Therefore, using wind power in drought-prone areas can be beneficial.

Wind farm owners typically lease land from farmers and ranchers for installing wind turbines. Because a utility-scale wind turbine has a small footprint, the leased land can continue to be used for growing crops and grazing animals. A 100-MW wind farm will typically generate land lease payments of about $350,000-$500,000 per year. However, most rural areas with good wind sites are located far from where electricity is needed, which sometimes requires building new transmission lines to bring electricity from the wind farm to the city.

Large-Scale Offshore Wind Power

Off the U.S. coastlines, the energy-generating potential of wind is immense because wind speeds tend to increase with distance from land. NREL estimates that U.S. offshore winds could potentially support 4,150 GW of generating capacity, roughly four times greater than the nation's present capacity. These winds also blow more uniformly than on land, offering greater power production from each turbine and smoother and steadier operation for the wind turbines.

To date, no offshore wind turbines have been installed in the United States, but there are projects on the East Coast in the planning and permitting stages totaling more than 2,000 MW of capacity. Other projects are being considered along the Great Lakes, the Gulf of Mexico, and the Pacific Coast. Denmark led the world with the first offshore project in 1991, and Europe currently leads the world in offshore wind development. It has more than 830 grid-connected turbines providing electricity to nine countries and plans to add more than 50,000 MW in 2011 and beyond.

Although Europe now has 20 years of experience with offshore wind projects, it has primarily been in shallow waters using technology evolved from land-based wind power systems. Deeper waters, such as those off the U.S. West Coast, pose more of a technology challenge. In shallow water, a wind turbine's supporting substructure can extend to the sea floor. However, in waters deeper than 60 meters, it's no longer economically feasible to have seabed-mounted wind turbines. To make it more cost effective, new floating wind turbines are being researched and developed. Proposed concepts include the spar buoy, barge, and tension-leg platform, but to date, it's too early to determine which one is the most design- and cost-effective.

Offshore wind power in deeper waters allows for the use of larger turbine blades. Larger wind turbines are more cost-effective because they can generate more electricity per turbine. However, enabling technology to construct blades longer than 70 meters is needed. Additionally, these blades could be allowed to rotate faster because the noise is less likely to disturb communities further from the shore. Faster rotors operate at lower torque, which means lighter, less costly drivetrain components. But the greater the distance from the shore, the greater the challenges with extreme ocean conditions, long-distance electrical transmission on high-voltage submarine cables, and turbine maintenance. Other challenges unique to the offshore environment include corrosive salt waters, tropical storms and waves, and coexistence with marine life and activities.

Small Wind Energy Systems

Small wind turbines typically range in size from 400 watts to 100kW. They are suitable for homes, institutions, and small businesses. For residential use, a home needs to be situated on at least one acre of land, and many urban areas do not allow wind turbines. Despite those limitations, the potential is huge. In the United States, approximately 21 million homes are built on plots of one or more acres, and 24% of the population lives in rural areas.

There are two types of small wind electric systems: stand-alone and grid-connected. Grid-connected systems require power-conditioning units (inverters) that make the output electricity compatible with the utility grid. Because they aren't connected to the utility grid, stand-alone systems require batteries to store excess power generated for use when the wind is calm. They also need a charge controller to keep the batteries from overcharging. Deep-cycle batteries, such as those used for golf carts, can discharge and recharge 80% of their capacity hundreds of times, which makes them a good option. Additionally, small wind turbines generate DC, so to work with a conventional household's AC, an inverter will be required to convert DC electricity from the batteries to AC. Although the inverter slightly lowers the overall efficiency of the system, it allows the home to be wired for AC, which is a definite plus with lenders, electrical code officials, and future homebuyers.

DIRECT USE OF RENEWABLE RESOURCES

All of the Earth's renewable energy sources—sunlight, wind, flowing water, biomass, and geothermal energy—can be used directly without first being converted to electricity.

The sun's heat can be used directly, for example, in passive solar building design and roof-mounted solar water heating systems. The wind can be harnessed to perform mechanical work directly: roughly 6 million windmills have been installed in the United States during the past 150 years, most of them used to pump water on farms and ranches. Although no longer a significant technology in this country, water wheels have been used for over 2,000 years to do mechanical work such as grinding grain into flour and driving machinery.

Biomass can be burned to provide space and water heating, or it can be converted to a variety of liquid fuels—such as ethanol and methanol—which can be mixed with gasoline or burned by themselves in modified internal combustion engines. And geothermal energy has been used for cooking and bathing for thousands of years, and is now used to heat greenhouses, buildings, and industrial applications.

Design-Based Energy Technologies for Buildings

Passive energy technologies are practices that take advantage of a building's natural environment to reduce its energy consumption. These practices are generally divided into three categories—daylighting, passive solar heating, and passive solar cooling—although the three approaches are not mutually exclusive and often overlap with one another in the same building.

Passive energy technologies rely largely on building siting and design, although some devices also exist to help implement passive energy. For this reason, passive energy technologies are best incorporated into new buildings. Some retrofit options are available for existing buildings, although in most cases, retrofits will achieve a lower level of passive energy performance than a new building specifically designed to optimize a building's use of passive energy.

Building Siting

Effectively incorporating passive energy technologies into a building starts with the building design process, which includes the siting and landscaping of the building. So-called "whole building" design involves modeling the energy performance of a building and tweaking all aspects of the design to achieve the best balance of energy performance, utility, and cost. This is the recommended approach to achieve optimal passive energy performance.

For buildings employing natural daylighting and passive solar heating, for instance, the preferred orientation of the building is for the long side to be aligned with an east-to-west axis and for the short side to be pointed north and south. This orientation maximizes the building's exposure to the south, which is where the greatest solar resource is located for the

Terms and Definitions

Anemometer – A device to measure the wind speed.

Blades – The aerodynamic surface that catches the wind.

Downwind – On the opposite side from the direction from which the wind blows.

Nacelle – The body of a propeller–type wind turbine cont. aining the gearbox, generator, blade hub, and other parts.

Rotor – The rotating part of a wind turbine, including either the blades and blade assembly or the rotating portion of the generator.

Tower – A cylindrical support that hold the wind turbine nacelle and rotor.

Upwind – In the direction from which the wind blows.

For More Information

American Wind Energy Association
www.awea.org
A national trade association representing wind power project developers, equipment suppliers, services providers, parts manufacturers, utilities, researchers, and others involved in the wind industry—one of the world's fastest growing energy industries.

DOE Wind Program
www.eere.energy.gov/wind
A program that leads the nation's efforts to improve the performance, lower the costs, and accelerate the deployment of wind technologies.

Small Wind Electric Systems: A U.S. Consumer's Guide
www.nrel.gov/docs/fy07osti/42005.pdf
A publication developed by DOE.

Wind Energy Applications for Municipal Water Services: Opportunities, Situation Analyses, and Case Studies
www.nrel.gov/docs/fy06osti/39178.pdf
A conference paper authored by NREL and DOE.

Wind Powering America
www.windpoweringamerica.gov
A nationwide initiative of the DOE Wind Program designed to educate, engage, and enable critical stakeholders to make informed decisions about how wind energy contributes to the U.S. electricity supply.

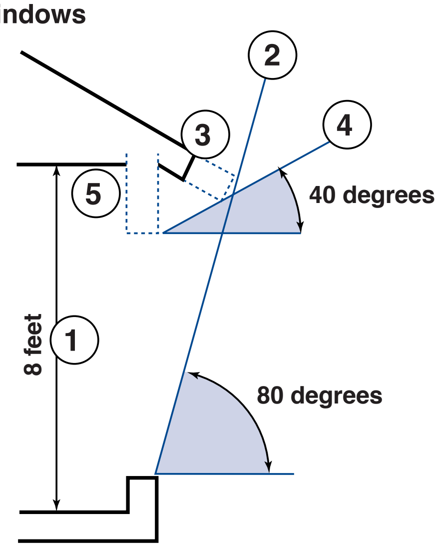
Northern Hemisphere (in the Southern Hemisphere, the solar resource is toward the north). Even buildings in hot climates are usually oriented in this direction because it offers the best opportunities to control solar heating through the use of overhangs and other design approaches.

Planners and builders can also take advantage of the natural topography of the building location. Hills and mountains can either shield a building from the wind or can interact with the wind to make it stronger, either one of which could be advantageous in certain climates and locations. Valleys collect cool air at night or when snow on the ground causes a temperature inversion, and that cool air results in lower temperatures. Water also moderates extreme temperature variations. Nearby rivers and lakes, as well as artificial ponds and fountains, can increase temperature lows and decrease temperature highs.

Landscaping is also an important consideration. Trees can decrease exposure to sunlight, reduce temperatures by as much as 15°F, and shield against winter winds. Vegetation can reduce wind speeds by as much as 90%, so vegetation, landscaping, berms, and mounds can all serve as effective wind buffers. Adjacent buildings, walls, and fences can serve as windbreaks and deflectors, and they can also cast shadows and provide reflective surfaces. The shading caused by adjacent structures can have a great cooling benefit during the warm summer months, but may provide too much shade during the winter, increasing heating loads.

Bushes or trees are often the only effective way to shade east- and west-facing walls, which often receive excessive heat from the rising and setting sun during the summer. Deciduous trees are advantageous for such locations, because they shed their leaves and allow more solar heating during the winter. Blocking the setting sun is most important to avoid the late-day heating that otherwise may need to be offset with air conditioning, contributing to peak-power demands.

Size south-facing overhangs to properly shade windows



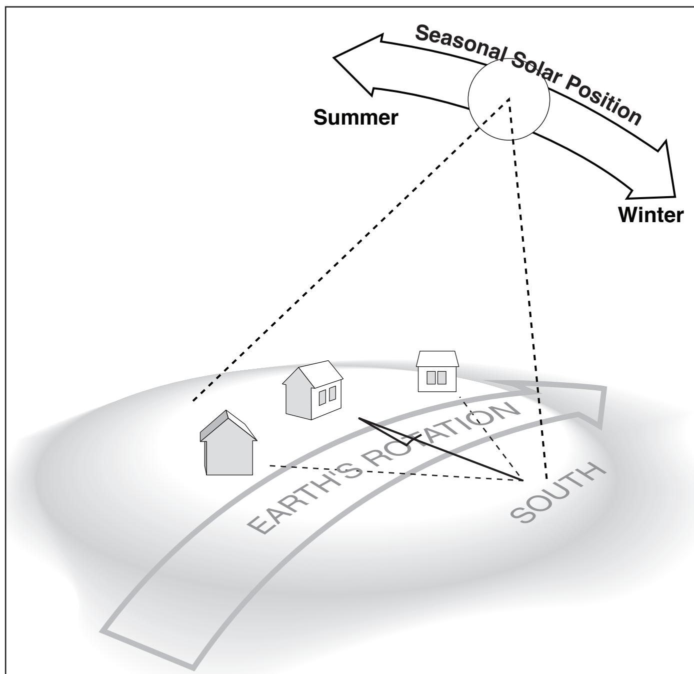
Overhang sizing rules:

1. **Draw the wall to be shaded to scale.**
2. **Draw the summer sun angle upward from the bottom of the glazing.**
3. **Draw the overhang until it intersects the summer sun angle line.**
4. **Draw the line at the winter sun angle from the bottom edge of the overhang to the wall.**
5. **Use a solid wall above the line where the winter sun hits. The portion of the wall below that line should be glazed.**

Passive Solar Design

A building that is designed with passive solar in mind is heated and lighted with materials that store or disperse the sun's energy. Such materials lower heating and lighting costs by replacing traditional mechanical systems that use natural gas or electricity. Passive solar design techniques can significantly improve energy efficiency and reduce or eliminate heating, cooling, and lighting bills. Passive solar structures can be built in any architectural style and in any part of the country. Passive solar designs are characterized by large window areas with advanced glazing materials, overhangs and other shading devices for the summer, thermal storage, and natural ventilation. The designs are generally site specific, and are based on climate, function, utility rate structure, owner preference, and cost.

High-performance windows offer excellent visible light transmittance while minimizing heat transfer through the window.



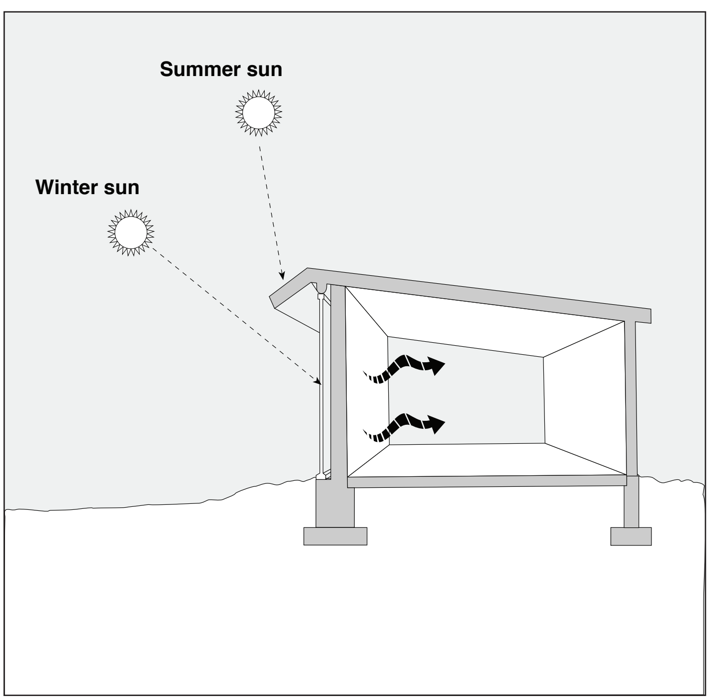
When constructing a home for passive solar features, the south side of the home must be oriented to within 30 degrees due south. *Illustration by NREL*

Windows should be chosen for their high-insulating values, high-visible light transmittance, low air leakage, and appropriate solar heat gain coefficient (SHGC), a measure of the solar thermal energy admitted by the window. The SHGC ranges from zero for a window that admits no solar heat to 1.0 for a window that admits the maximum amount of solar heat. Windows can generally be chosen to either have a high SHGC, to maximize solar heating, or a low SHGC, to minimize solar heating.

The SHGC is generally less than 0.8. In an effort to reduce the peak-cooling loads on buildings, the International Energy Conservation Code requires windows in hot climates to have an SHGC of less than 0.4, and for the hottest climates, the SHGC is restricted to less than 0.25. An SHGC of less than 0.4 can be achieved in double-paned windows with low-emissivity coatings designed for low solar gains, regardless of the window frame material. So it doesn't require window technologies different from those that are in common use today.

Wind can help to cool a building, which can be desirable in the summer and undesirable in the winter. When cooling is undesirable, there are simple ways to design a building to buffer its interior from the wind. Breezeways can provide buffers in commercial buildings, while mudrooms and garages can serve the same purpose in residential buildings. In warm climates, windows can be oriented to take advantage of prevailing winds and reduce the need for air conditioning.

Natural circulation is another feature employed in passive solar designs. Hot air rising from solar-heated parts of the building can drive a circulatory pattern within the building,



In the winter, a Trombe wall absorbs, stores, and releases solar heat into a building. An overhang blocks the sun's heat in the summer. *Illustration by NREL*

minimizing the need for ducts and fans. Open stairways and open floor plans can work together to ensure good mixing and circulation of air through the building. During the cooling season, vents or windows can be opened at high points to free rising hot air, while strategically located windows can take advantage of cool breezes.

Daylighting

Today's highly energy-efficient windows can reduce the need for artificial lighting during daylight hours without causing heating or cooling problems. The best way to incorporate daylighting depends on the climate and the building design. South-facing windows are most advantageous for daylighting and for moderating seasonal temperatures. They allow most winter sunlight into the building, but little direct sun during the summer, especially when properly shaded.

North-facing windows are also advantageous for daylighting. They admit relatively even, natural light; produce little glare; and allow almost no unwanted summer heat gain. Although east- and west-facing windows provide good daylight penetration in the morning and evening, respectively, they should be limited. They may cause glare, admit a lot of heat during the summer, and contribute little to solar heating during the winter. Skylights can also provide daylighting, but they must be well-insulated and use high-performance windows to avoid unwanted thermal penalties.

Daylighting requires careful design to deliver adequate amounts of light without causing glare. Commercial buildings can best employ daylighting if they are designed to be narrow in the north-south direction, so that daylight can easily penetrate to the interior of the building. Interior design can contribute to daylighting by providing surfaces that can both reflect and diffuse the incoming light. Offices designed for daylighting may require lowered walls and dividers to allow light to diffuse through the office.

Design Features for Daylighting

In addition to conventional windows for daylighting, two design features are commonly used: clerestories and light shelves. A clerestory, pronounced "clear story," is a band of narrow windows along the roofline, rising above its adjoining roof, while the opposing roof is extended to form an overhang above the clerestory. These types of windows were originally used for medieval Roman and Gothic cathedrals, both for beauty and utility, as they let in light without the distraction of a view. In modern architecture, clerestories are frequently used for factory buildings, but have found use in commercial and residential buildings as well. Clerestory windows are often operable to allow natural ventilation of the building.

Light shelves are horizontal light-reflecting overhangs with high-reflectance upper surfaces. They are generally made of an extruded aluminum chassis system and aluminum composite panel surfaces, which are used to reflect daylight onto the ceiling and deeper into an interior space. They are typically used in office and institutional buildings, generally on the south side, where maximum sunlight is found. Light shelves allow light to penetrate deep into the interior parts of the building, provide shade near the windows, and help reduce window glare. For maximum benefit, perimeter lighting should be controlled by photo sensors, with lighting zones appropriate to the particular installation.

Daylighting Devices

The two main devices to assist with daylighting a building include tubular daylighting devices and hybrid fiber-optic solar lighting. Tubular daylighting devices use skylight openings, lens technology, reflection, and ceiling-mounted diffusers to bring a more uniform stream of daylight to interior spaces. Such systems penetrate the ceiling plane and provide a more constant distribution pattern of daylight, as opposed to the shifting patterns of skylights and windows. A roof-mounted acrylic dome—usually 10 to 21 inches in diameter—filters out ultraviolet radiation and sends the remaining sun's rays down a narrow tube. Micro-fine layers of acrylic create a surface that sends 99.7% of spectral-reflective light down the shaft and is still transparent to infrared rays. Only visible light makes it through the device.

Hybrid fiber-optic solar lighting uses rooftop-mounted, 4-foot-wide mirrored dishes that track the sun with the help of a global positioning system receiver. The collector focuses the sunlight onto optical fibers, which can be thought of as flexible light pipes to deliver the light into the building. The fibers connect to hybrid light fixtures with special diffusion rods that spread out the light in all directions. One collector powers about eight hybrid light fixtures that can illuminate about 1,000 square feet. The system is estimated to save about 6,000 kilowatt-hours (kWh) per year in lighting and 2,000 kWh in reduced cooling needs for a total saving of 8,000 kWh per year.

Passive Solar Heating

Passive solar buildings may be heated almost entirely by the sun or may have south-facing windows that provide some fraction of the heating load. Buildings should be oriented along an east–west axis to provide northern and southern window exposures. The larger windows should be on the south side to admit indirect sunlight; the smaller windows should be on the north. This helps to avoid direct sunlight, but allows light to enter buildings to provide heating and lighting. The three main approaches to passive solar heating are direct gain, indirect gain, and isolated gain.

Direct gain is the simplest passive solar heating technique. It allows sunlight to enter a building through south-facing windows or glass doors so the floors and walls can capture the sun's heat. Floors and walls made of brick or stone absorb and store the solar heat, then release it at night. These thermal mass elements should be a dark color to help them absorb heat.

Indirect gain employs an intermediary device to store the solar heat and then radiate it into the building during the evening. For instance, a Trombe wall consists of an 8- to 16-inch thick masonry wall and a single or double layer of glass mounted about 1 inch from the front of the wall's surface. The wall is placed between the south-facing windows and the living or working spaces. It absorbs and stores solar heat while the sun shines, and then slowly distributes the heat into the building.

Isolated gain refers mainly to sunspaces, that is, a room added to a building primarily to serve as a collector of solar heat. Sunspaces are south-facing rooms with an abundance of glazing for thermal gain, as well as thermal mass incorporated into the floor and potentially in the wall that adjoins the main building. They can be open to the main building space, but often include operable doors and windows to allow the building occupants to adjust the amount of heat admitted into the building. During the summer, vents at the top of the sunspace can release the heat back to the environment. Sunspaces are primarily used as a retrofit option to increase the solar gain of a building, particularly in existing homes.

Passive Solar Cooling

Passive solar cooling depends primarily on rejecting heat from the building, while also providing an avenue to remove excess heat via an environmental heat sink such as the sky, evaporation, cool night air, or cool ground temperatures. Passive solar cooling can reduce or even eliminate the need for air conditioning. Because the sun's path and angle in the sky are different in summer than in winter, some of the same strategies that help to heat a home in the winter can also keep it cool in the summer.

Passive cooling includes overhangs for south-facing apertures, few windows on the east and west, thermal mass, and effective use of shade trees and cross ventilation. Shading on east- and west-facing walls can reduce cooling requirements, with shading on the west being most critical to reduce peak-cooling loads. Light-colored, reflective materials can be used on roofs and on shading devices, such as awnings, to minimize the heating of the building from infrared radiation.

Overhangs are an essential design element for passive cooling. In years past, many buildings were constructed with substantial eaves to shield against the summer sun and help cool interiors. Today most commercial and residential buildings have minimal (18-inch) overhangs or no overhangs at all, under the assumption that air conditioning will be used to cool the living and working spaces. Three- to four-foot overhangs over south-facing windows shield the interior from the high summer sun and allow low winter sunlight to enter for indirect heating.

Thermal mass, such as aerated concrete blocks for exterior walls, provide thermal and acoustic insulation and termite resistance. The mass cools down in the evening and retains that coolness the next day, moderating the effects of high daytime temperatures. In the Southwest, adobe buildings are an excellent example of how to use thermal mass to help maintain a cool building interior.

To help reject heat from buildings, so-called “cool roofs” have light-colored shingles that reflect heat from the surface and help to moderate indoor temperatures. Cool roofs have highly reflective and emissive materials that stay 50° to 60°F cooler in the summer sun. While reducing energy costs, cool roof technology also increases the useful lifetime of the roof and helps to reduce urban heat islands and associated smog.

An alternative approach for flat roofs is the “green roof,” in which the roof assembly is covered with a waterproof membrane that is then wholly or partially covered with soil and vegetation. Green roofs reduce runoff by retaining as much as 75% of rainwater, decrease heating by adding mass and thermal resistance, and provide amenity space for occupants. They also provide habitat for birds and insects. While green roofs are not usually justified for their energy benefits alone, the additional benefits are leading many companies and individuals to invest in this approach.

A less common cooling approach is the solar chimney, a chimney-like structure that relies on rising hot air to create an updraft, helping to draw the hot air out of a building. A variation on this is the cool tower, which is actually a very simple, active cooling technology. Water sprayed into the air or onto pads at the top of the tower evaporates, cooling the air. This causes a downdraft of cool air that can be directed into the building.

Terms and Definitions

Aperture (Collector) – A large glass area, usually a window, through which sunlight enters a building. Typically, the apertures should face within 30 degrees of true south and should not be shaded by other buildings or trees from 9:00 a.m. to 3:00 p.m. each day during the heating season.

Absorber – The dark surface of the storage element. This surface—which could be that of a masonry wall, floor, or partition—sits in the direct path of sunlight. Sunlight hits the surface and is absorbed as heat.

Daylighting – A combination of passive solar lighting and indoor mechanical lighting that provides natural light and reduces glare and solar gain.

Distribution – The method by which solar heat circulates from the collection and storage points to different areas of the house. A strictly passive design will use conduction, convection, and radiation exclusively. However, in some applications, fans, ducts, and blowers may help with the distribution of heat through the house.

Passive solar – The process of orienting a building and using fenestration to take advantage of indirect sunlight.

Thermal mass – The materials that retain or store the heat produced by sunlight. The difference between the absorber and thermal mass, although they often form the same wall or floor, is that the absorber is an exposed surface, whereas thermal mass is the material below or behind that surface.

Ultraviolet radiation – light rays that often create heat that, because they often contain too much energy, can knock electrons away from the atoms, or cause molecules to split. This can change the chemical structure of the molecule and may thus be detrimental to living organisms.

For More Information

Cool Roofs
www.consumerenergycenter.org/coolroof/index.html
Information from the California Energy Commission’s Consumer Energy Center.

Efficient Window Collaborative
www.efficientwindows.org
An organization that provides unbiased information on the benefits of energy-efficient windows, descriptions of how they work, and recommendations for their selection and use.

Energy Savers: Passive Solar Home Design
www.energysavers.gov/your_home/designing_remodeling/index.cfm/mytopic=10250
Information for consumers from the U.S. Department of Energy (DOE) on passive solar design.

Fenestration Facts
www.nfrc.org/fenestrationfacts.aspx
Information on windows, doors, and skylights from the National Fenestration Rating Council.

Green Roofs for Healthy Cities
www.greenroofs.org
A North American industry association for green roofs and walls.

Passive Solar Design
www.nrel.gov/docs/fy01osti/29236.pdf
A fact sheet from the DOE Building Technologies Program.

Lessons Learned from Case Studies of Six High-Performance Buildings
www.nrel.gov/docs/fy06osti/37542.pdf
A publication from the National Renewable Energy Laboratory.

Direct Use of Solar Energy

Solar energy—the original source of nearly all our energy—can be put to use in a variety of ways. This section describes several direct-use technologies. Passive solar design technologies are described in the preceding section, and solar electric power generating technologies are described in the chapter on Renewable Power Generation.

Solar Water Heating

Solar water heaters—including solar domestic hot water systems—can be a cost-effective way to generate hot water. They can be used in any climate, and the fuel they use—sunshine—is free.

Solar water heating systems generally include solar collectors and storage tanks, which are typically well insulated. Solar storage tanks have an additional outlet and inlet connected to and from the collector. In two-tank systems, the solar water heater preheats water before it enters the conventional water heater. In one-tank systems, the backup heater is combined with the solar energy storage in one tank.

Types of Solar Collectors

Three types of solar collectors, illustrated below, are used for residential applications:

- Flat-plate collectors
- Evacuated-tube solar collectors
- Integral collector-storage systems (see batch collector in the Passive, Batch Solar Water Heater System diagram on page 44).

Types of Systems

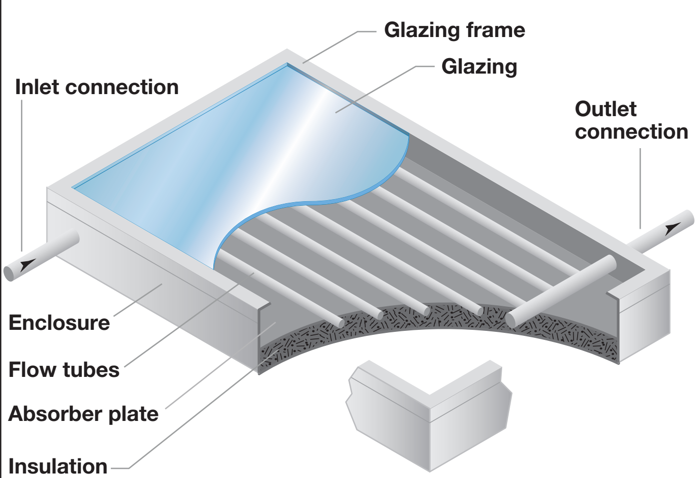
There are two types of solar water heating systems: (1) active systems, which have circulating pumps and controls, and (2) passive systems, which don't.

Active solar water heating systems include the following:

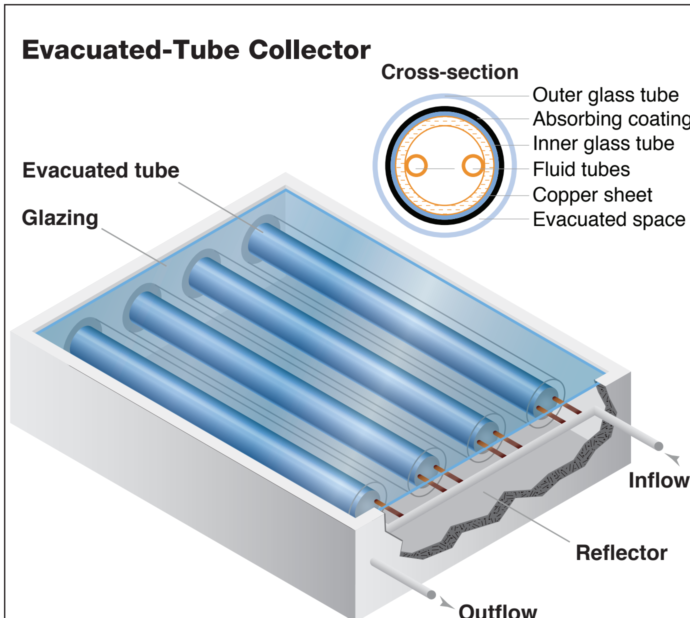
- **Direct-circulation systems** — Pumps circulate household water through the collectors and into the home. They work well in climates where the temperature rarely falls below freezing.
- **Indirect-circulation systems** — Pumps circulate a nonfreezing, heat-transfer fluid through the collectors and a heat exchanger. This heats the water that then flows into the home. They are popular in climates prone to freezing temperatures.

Passive solar water heating systems are typically less expensive than active systems, but they are usually less efficient. In addition, the pressurized potable water pipes to and from the attic can freeze and catastrophically burst, so they should be used only in mild climates. The map on page 43 shows the likelihood of a system freezing over a 20-year period. On the other hand, passive systems can be more reliable and may last longer. There are two basic types of passive systems:

- **Integral collector-storage passive systems** — These work best in areas where temperatures rarely fall below freezing. They also work well in households with significant daytime and evening hot water needs.
- **Thermosiphon systems** — Water flows through the system when warm water rises as cooler water sinks. The collector must be installed below the storage tank so that warm water will rise into the tank. These systems



Flat-plate collectors consist of flow tubes mounted against a dark absorber plate, which heats up in the sun and transfers its heat to the flow tubes. Glazing helps to hold in heat and protect the collector from the natural elements. *Illustration by NREL*



Evacuated-tube collectors use a vacuum to minimize heat loss. A double-walled glass vacuum insulation tube forms the outer wall of the collector, and a dark coating on the inside wall absorbs heat and transfers it to the tube's interior. The interior can either consist of tubes to carry fluid to the end of the collector and back (as shown here), or it can hold a heat pipe designed to transfer heat to a large header through which the fluid flows. Evacuated-tube collectors operate at higher temperatures than other collectors and are generally used for commercial or industrial processes. *Illustration by NREL* are reliable, but contractors must pay careful attention to the roof design because of the heavy storage tank. They are usually more expensive than integral collector-storage passive systems.

Solar Space Heating

Solar space-heating systems are similar to solar domestic water heating systems, but generally larger and a little more complex. Solar space heating is similar to solar water heating in that systems will usually consist of rooftop or other collectors, storage, and a distribution system to transfer the collected heat to the home or building. The collector may use liquid or air as the transfer medium. See the Solar Water Heating section for more information on the types of collectors.

Solar space-heating systems are larger and more complex than domestic-water-heating systems in that they must meet a much larger energy demand, so they need larger collector areas—generally evacuated-tube or other medium-temperature collectors—and larger tanks or other storage. Additionally, they need more complex controls. Most solar space-heating systems also include domestic-water heating. Even more so than is the case for domestic-water heating, conventional backup heating is a necessity with solar space heating.

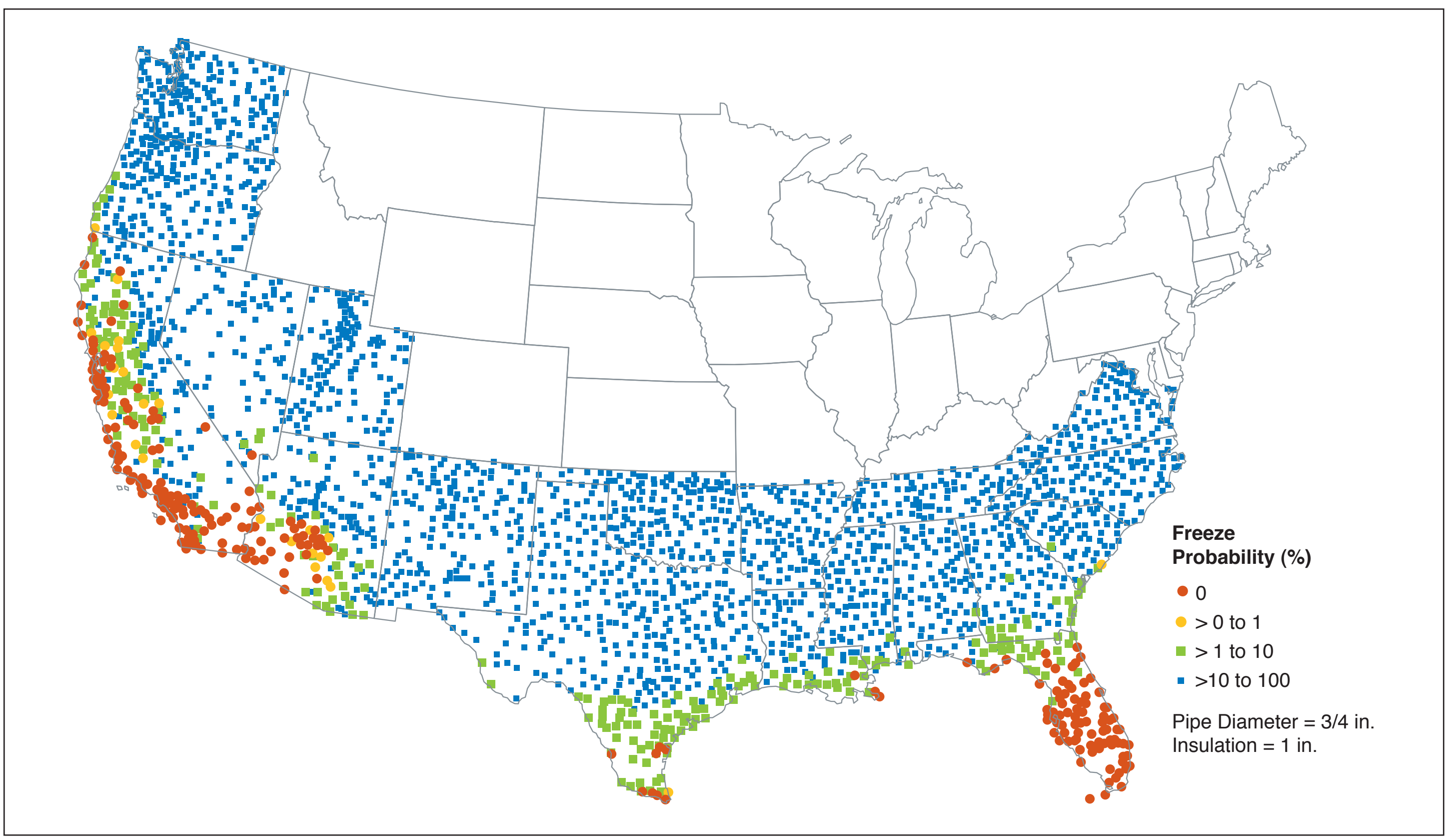
The local climate, the type and efficiency of the collector(s), and the collector area determine how much heat a solar space heating system can provide. They are typically most cost-effective when used most of the year, especially in cold climates with good solar resources, and sized to meet 40%-80% of the heating demand. Systems providing less than 40% of the heat needed for a home are rarely cost effective except when using solar air heater collectors that heat one or two rooms and require no heat storage. A well-designed and insulated home that incorporates passive solar heating techniques will require a smaller and less costly system and may need very little supplemental heat other than solar.

Solar space heating systems are most economical if they are displacing more expensive heating fuels, such as electricity, propane, and oil. The economics of a solar space heating system improves even more if it also heats domestic water because an otherwise idle collector can heat water in the summer.

Liquid Heat-Transfer Systems

Liquid collectors will generally be the same "low-temperature" flat-plate, "medium-temperature" evacuated-tube, or other collectors as used for solar water heating, though they would generally have to be active rather than passive systems.

Solar liquid collectors are most appropriate for central heating. Heat can be distributed through a radiant floor system, radiators or hot-water baseboards, or a central forced-air system. For liquid-collector systems, radiant in-floor heating works best. In a radiant floor system, the solar-heated water



For installing solar water heating systems, this map shows the freeze probability in areas with warmer climates. *Illustration by NREL* is piped through or under the floor, usually through coils embedded in a concrete slab. These systems operate well at relatively low temperature, so they can take full advantage of the solar-heated water. A carefully designed system may not need a separate storage tank, though most systems do for temperature control. A conventional boiler or even a standard domestic water heater can supply backup heat.

To be effective as a distribution system, traditional radiators or hot-water baseboards require hotter water—between 160° and 180°F—than flat-plate collectors generally provide, so you would need to use collectors that achieve hotter temperatures, such as evacuated-tube collectors; add additional conventional heat; or use oversized radiators. A liquid-to-air heat exchanger could also be used to transfer heat to the return air of a forced-air furnace. Air returning from the living space is heated as it passes over the solar-heated liquid in the heat exchanger. Although the inefficiency of using heat exchangers in this way could hurt the cost-effectiveness of such an approach.

Air Heat-Transfer Systems

Solar air-heating systems use air as the working fluid for absorbing and transferring solar energy. Solar air collectors can directly heat individual rooms or can potentially preheat the air passing into a heat recovery ventilator or through the air coil of an air-source heat pump.

Air collectors may be flat-plate boxes essentially similar to liquid collectors, but can also be integrated into a roof or wall, and are more often used for single-room rather than central systems. They are simpler than fluid collectors, with no concern about freezing and less concern about leaks. Because, however, air is a poor heat-transfer medium, air collectors are inherently less efficient than fluid collectors.

Transpired-Air Collectors

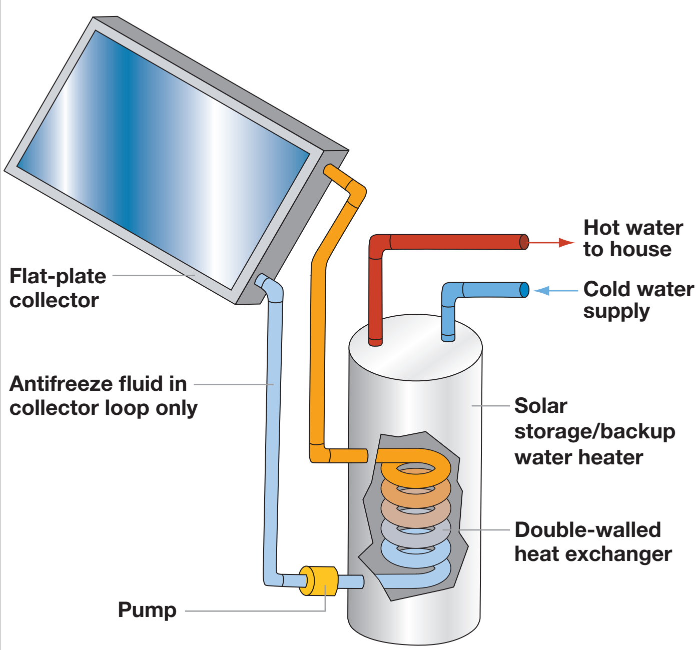
An unglazed variation on air collectors, the transpired solar collector uses solar energy to preheat commercial building ventilation air. While most multistory commercial buildings are typically faced with cooling loads, not heating loads, this technology can be useful for single-story warehouses, aircraft hangers, and other large storage facilities in cooler climates. Transpired solar collectors can also be used for crop drying or preheating industrial furnace or boiler intake air.

Commercially marketed as Solarwall® systems, transpired collectors consist of perforated cladding installed a few inches from the south-facing wall of a building (receiving much of the winter sun). The sun heats the cladding, which heats the air as it is drawn in, or transpired, through the perforations and up through the plenum between the original wall and the cladding. Transpired collectors have no moving parts, relying on the building's intake air fan to draw air through them, and because of their simplicity, they can be quite cost effective.

Room Air Heaters

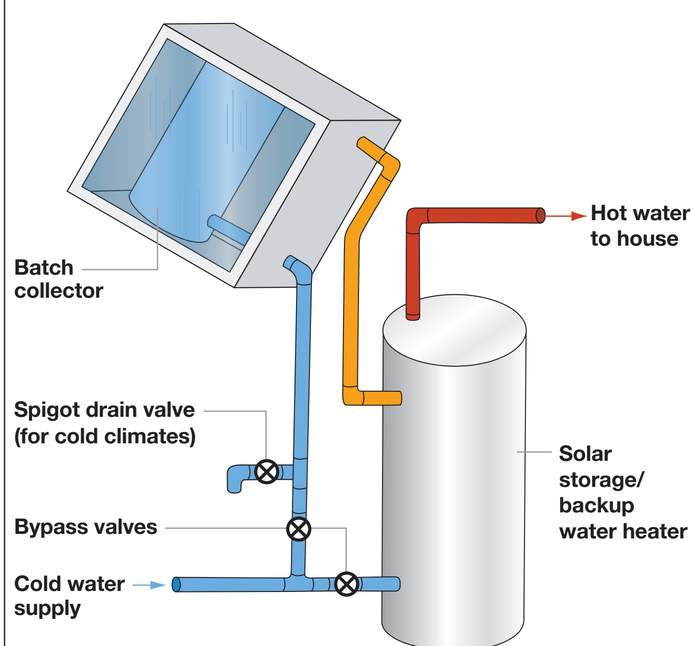
For heating one or more rooms, air collectors can be installed on a roof or an exterior wall. The collector has an airtight, insulated metal frome and a black metal plate for absorbing heat with glazing in front of it to contain the air.

Active, Closed-Loop Solar Water Heater



An active, closed-loop solar water heater uses a pump to circulate a heat-transfer fluid through the solar collector and then through a heat exchanger, where it transfers its heat to a tank of water. *Illustration by NREL*

Passive, Batch Solar Water Heater



A passive, batch solar water heater uses relatively large tubes to minimize the pressure drop across the collector. This allows the water to circulate through the system without the use of a pump, due to the tendency for hotter water to rise. *Illustration by NREL*

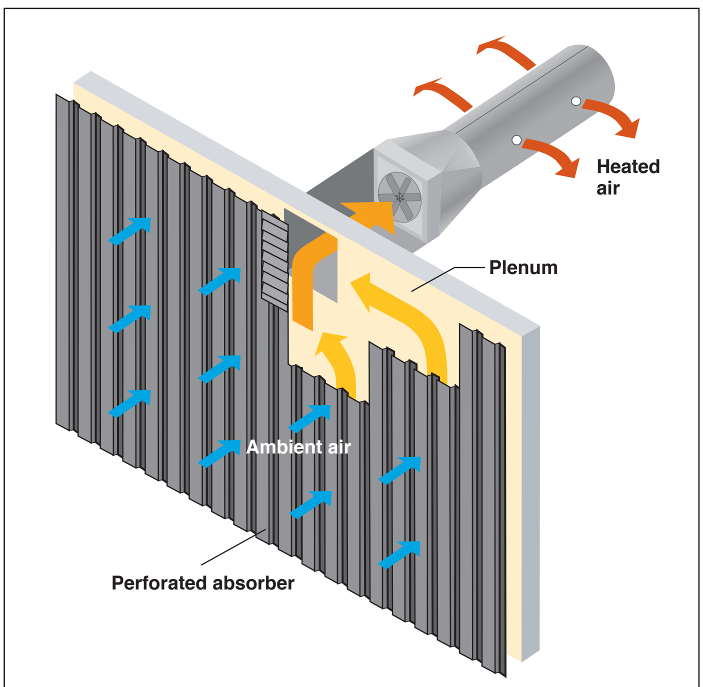
Solar radiation heats the plate that, in turn, heats the air in the collector. An electrically powered fan or blower pulls air from the room through the collector and blows it back into the room. Roof-mounted collectors require ducts to carry air between the room and the collectors. Wall-mounted collectors are placed directly on a south-facing wall; holes are cut through the wall for the collector air inlet and outlets.

Solar Space Cooling

While perhaps not intuitively obvious, solar thermal energy can be used to provide space cooling. "Thermally activated cooling systems" or TACS include absorption cooling and desiccant cooling. TACS can be driven by natural gas or propane heating, waste heat such as from boilers or fuel cells, geothermal water, or solar-heated water. The technologies are relatively expensive at this point (although new, lower-cost products are entering the market), so the main use with solar energy would be in conjunction with solar space-heating to take advantage of the system during the warm part of the year.

Absorption Cooling

As a low-boiling-point pressurized liquid escapes through a jet to a lower-pressure chamber, it vaporizes rapidly, absorbing heat in the process. This is the effective action of most refrigeration and cooling technologies. In electrically driven systems, the refrigerant is mechanically pressurized to allow the cycle to repeat. Thermally driven systems are somewhat more complex, but generally the vaporized refrigerant is absorbed into a solution, rather than being mechanically pressurized. For the cycle to repeat, that solution must then be heated to separate out the refrigerant, and the system uses thermal energy to perform that task.



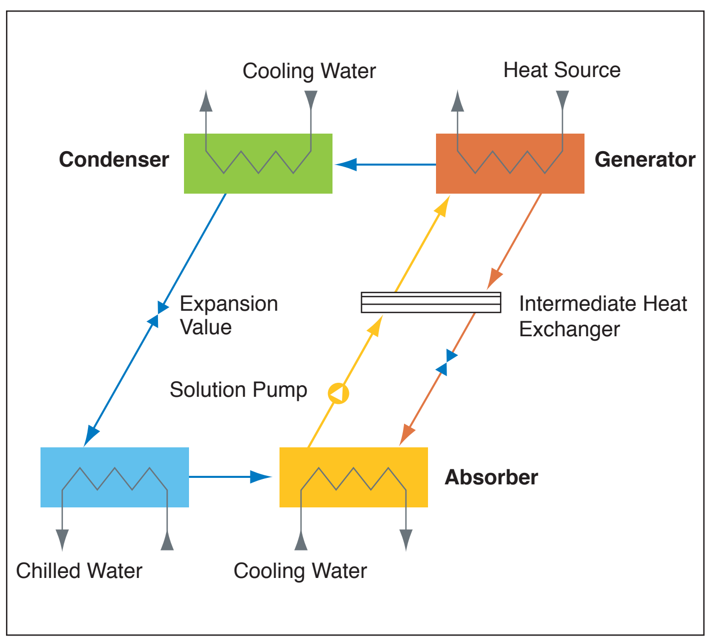
A transpired-air collector preheats air for building ventilation by using a fan to draw fresh air through the system. Outside (ambient) air is heated as it passes through holes in the collector (absorber) and is drawn up the air space (plenum) between the collector and the south wall of the building. *Illustration by NREL*

This cycle can be used for refrigeration systems, chillers that cool water for building cooling, or air-heat pumps that either both heat and cool or cool only. Absorption chillers are generally only used for large commercial buildings or industrial use. Absorption heat pumps or coolers are also more for commercial buildings but are becoming available sized for large homes. Absorption cooling is less efficient than mechanical cooling, so it most often makes sense if electricity is unavailable, highly expensive, or if a large heat source is available at little cost—which would be the case if a solar space-heating system would otherwise be sitting idle during the cooling season. Solar absorption cooling generally requires the higher heat generation of medium-temperature systems such as ones using evacuated-tube collectors.

Desiccant Cooling

Humidity control is a major element of any air-conditioning system. Desiccants are chemicals with a high affinity for water. They can be used to absorb moisture, and then subsequently be regenerated by heating them to drive off the absorbed moisture. Hence solar heating can provide the needed heat energy. Using desiccant materials to remove moisture from air can improve air-comfort systems in any of several ways. Desiccants are typically used in slow-moving "wheels" that rotate a batch of desiccant into an airstream needing dehumidification, and then rotate that batch to another point where it can be heated to remove the absorbed moisture. Liquid desiccants can also be used in these systems.

For conventional air conditioners or chillers, desiccants can remove the humidity from the incoming air, allowing the air conditioner or chiller to operate more efficiently. Chillers and



The absorption cooling process. *Illustration by NREL* air conditioners typically need to cool the air below the dew point (below comfort level) to remove moisture and then warm it back up to an appropriate temperature, wasting energy in the process. Desiccant technology can also be used in conjunction with evaporative coolers that are much more efficient than air conditioners, but cannot function with humid air.

Solar Water Purification

Solar energy can be used in several ways to purify raw or contaminated water. One set of technologies is primarily useful for developing country villages without access to central drinking water systems and emergency situations. Another is useful for desalination or industrial waste treatment. Unlike heating and cooling systems that collect heat for use elsewhere, these systems use the solar energy at the point of collection.

Small-Scale Water Supply

Both high heat and ultraviolet (UV) radiation can kill or render ineffective pathogenic microorganisms. Boiling water with a concentrating solar thermal system would be effective but impractical. Lowering temperature heating to about 80°C (176°F), though, is also effective, similar to the milk pasteurization process. While shortwave or far-UV light that is highly effective in killing pathogens (and used for sterilization and in both wastewater treatment and water treatment systems, including village applications) is largely filtered out from sunlight by the Earth's atmosphere, the UV light that does penetrate still contributes to purification, particularly in combination with high temperature. Solar water purification systems based on UV light and heat can be as simple as placing water-filled plastic bottles on a black rooftop and as sophisticated as commercial systems that transfer heat from the outgoing treated water to the incoming raw water. Most commercial systems also incorporate filter systems.

Desalination and Industrial-Wastewater Treatment

Heat and UV light are effective for disabling pathogens, but will not remove chemicals or salt. Solar distillation, however, can be used for seawater or chemically contaminated water. Again systems can range from a classic plastic-sheet-covered box to sophisticated large-scale commercial structures that reuse the energy of condensation to evaporate more water. (Reverse osmosis, the dominant desalination technology currently, could also be powered by solar cells for an indirectly solar system.)

Solar photocatalytic water detoxification is an effective technology for treatment of industrial wastewater or groundwater contaminated with low levels of various hazardous organic compounds. UV radiation in the sunlight energizes titanium oxide or other catalysts to form reactive chemicals known as "radicals," which break the contaminant compounds down to nonhazardous substances. Hazardous organic compounds in the parts-per-million range (such as benzene, toluene, trichloroethylene, and other volatile organic compounds; solvents, pesticides, dyes, and some heavy metals) can be degraded to carbon dioxide (CO_2), water, and small amounts of mineral acids. The toxic contaminants are completely destroyed rather than merely being transferred from the water to another phase as in most other toxic chemical treatment processes. Solar photocatalytic water detoxification systems may also be supplemented by a conventional detoxification system or a UV-light source to accommodate large quantities of contamination or to allow nighttime operation.

Terms and Definitions

Absorption chiller or gas chiller – Heat–driven technology that uses cooling effect of liquid evaporating to chill water for use in refrigeration or space–cooling systems.

Absorption cooler or gas cooler – Heat–driven technology that uses cooling effect of liquid evaporating for space–cooling systems.

Absorption heat pump or gas heat pump – Heat–driven technology that uses cooling effect of liquid evaporating for space heating or space cooling.

Desiccant – A chemical with a high affinity for water. Dessicants can be used to absorb moisture and subsequently release it upon heating.

Latent heat – The amount of heat absorbed by a substance as it changes state from solid to liquid or liquid to gas or conversely released in changing from gas to liquid or liquid to solid.

Organic compound – Any chemical compound based on carbon chains or rings and also containing hydrogen with or without oxygen, nitrogen, or other elements; this includes all biological material, but also includes toxic chemicals derived from fossil fuels.

Pasteurization – Application of heat for a period of time to a substance (particularly liquid, especially milk) to destroy harmful microorganisms.

Pathogen – Bacteria, virus, or other microorganism causing disease in humans.

Photocatalysis – Chemical reaction initiated by light energy acting on a chemical catalyst.

Plenum – An enclosed space between the original building wall and transpired collector cladding. Air is drawn through the cladding perforations, through the plenum and into the building's ventilation system.

Radiant floor heating – Home heating systems in which hot water or electrical heating coils are embedded in or placed under the floor.

(Continued on page 47)

(Continued from page 46)

Solar collector classification:

- *Low temperature* – Flat–plate and integral collector or other batch collectors that typically heat water to 82°C (180°F) at most.
- *Medium temperature* – Evacuated–tube and other collectors capable of heating water to between 77°C and 177°C (170°F to 350°F).
- *High–temperature* – Parabolic–trough and other collectors capable of heating water to more than 177°C (350°F), usable for power generation as well as commercial hot water and space heating.

Solar energy factor (SEF) **–** The energy delivered by the system divided by the electrical or gas energy put into the system. The higher the number, the more energy efficient the system is. SEFs are a function of the solar fraction and the system efficiency. For solar fractions of 0.5–0.75, SEFs would typically range from 1.2–2.4 for displacing gas water heating and 1.8–3.6 for displacing electric water heating. Care should be taken to match the system size to the climate and house load. The bigger the system and colder the climate, the large the system should be.

Solar fraction **–** The solar fraction is the portion of the total conventional hot-water heating load (delivered energy and tank standby losses). The higher the solar fraction, the greater the solar contribution to water heating, which reduces the energy required by the backup water heater. The solar fraction varies from 0 to 1.0. Typical solar fractions are 0.5–0.75.

Thermally activated cooling systems (TACS) **–** Technologies using heat energy for refrigeration, space cooling, or chilling water.

Transpired solar collector **–** Technology for preheating ventilation air, so called because it breathes air into the system through perforations in an unglazed metal or plastic solar collector.

Ultraviolet (UV) radiation **–** Short–wavelength, high–energy electromagnetic radiation beyond the blue end of the visible light spectrum (but not as short–wavelength or high–energy as X–rays).

- *Near UV* – roughly corresponding to terms long–wave UV, black light, or ultraviolet A (UVA) is generally defined as the 300–nanometer– to 400–nanometer–wavelength portion of the electromagnetic spectrum; most of the ultraviolet solar radiation reaching the Earth's surface is near UV.
- *Middle UV* – Roughly corresponding to terms medium–wave UV, germicidal light, or ultraviolet B (UVB) is generally defined as the 200–nanometer– to 300–nanometer–wavelength portion of the electromagnetic spectrum.
- *Far UV* – Roughly corresponding to terms short–wave UV, or ultraviolet C (UVC) is generally defined as the 122–nanometer– to 200–nanometer–wavelength (extreme UV if shorter than that) portion of the electromagnetic spectrum.

Unglazed solar collector **–** A solar collector without a glass or plastic cover; most collectors have glazing to hold in the absorbed heat.

For More Information

Energy Savers: Active Solar Heating
www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12490
Information for consumers from the U.S. Department of Energy (DOE) on solar space heating.

Energy Savers: Solar Water Heaters
www.eere.energy.gov/consumer/your_home/water_heating/index.cfm/mytopic=12850
Information for consumers from DOE on solar water heaters.

Heat Your Water with the Sun: A Consumer's Guide
www.nrel.gov/docs/fy04osti/34279.pdf
A 20-page booklet from DOE covering space as well as domestic-water heating

Solar Rating and Certification Corporation
www.solar-rating.org/default.htm
A nonprofit corporation serving the solar water heating industry and consumers by setting standards and certifying performance for solar water-heating equipment.

Solar Wall
solarwall.com/en/home.php
A website from the commercial vendor for Solarwall® transpired solar collector systems.

Thermally Activated Technologies
www.eere.energy.gov/manufacturing/distributedenergy/tat.html
Information from the DOE Advanced Manufacturing Office about absorption chillers, cycle analysis, ammonia-water absorption systems, and desiccants.

Transpired-Air Collectors: Ventilation Preheating
www.nrel.gov/docs/fy99osti/24499.pdf
A two-page fact sheet from the National Renewable Energy Laboratory (NREL).

Utility Solar Water Heating Initiative
www.eere.energy.gov/buildings/ush2o
A coalition of utilities and the solar thermal industry that works to increase the use of solar thermal technologies on a large scale. DOE and NREL provide funding and technical guidance.

Biomass Space and Water Heating

Biomass can be used for space and water heating in homes, large buildings and facilities, and for district heating. Biomass heating systems can also be combined with biopower systems to provide both electricity and heat. For information on technologies—such as gasification—that can be used for combined heat and power systems, see the Biopower section in the chapter on Renewable Power Generation.

Woody biomass is commonly used for heating, and direct combustion is the most common method for producing heat from it. With direct combustion, the biomass is burned to generate hot gas, which is used directly to provide heat or fed into a boiler to generate hot water or steam. This combustion of biomass produces emissions, including particulates and CO_2. To comply with emission regulations, most biomass heating systems have some type of system for controlling emissions. Exhaust systems are used to vent combustion byproducts—primarily CO_2, carbon monoxide, and water—into the atmosphere. But despite its emissions of CO_2, wood fuel is generally considered "carbon neutral"—it produces the same amount of CO_2 when burned as it would produce as a tree. However, land-use changes associated with harvesting biomass can result in net carbon emissions, so it's best if the biomass harvesting does not result in the clearing of forests.

Compared to other renewable energy systems, biomass heating systems require more operator interaction, which includes ordering and delivering the fuel, and maintaining moving parts. If not automated, a system may also require some fuel handling and/or ash removal. Space for storing the biomass is needed too.

Biomass heating systems range in size (output) from around 6,000 British thermal units (Btu)/hour to more than 100 MMBtu[1]/hour. Small systems are available off-the-shelf from manufacturers. They're often located in the space to be heated, which allows for space heating through radiation and natural force convection. Larger systems are usually tied into hydronic distribution systems, which provide space heating through radiant floor or baseboard systems. These large systems are commercially available from several companies, but they typically require both facility modification and system customization.

The overall design of a system—whether large or small—depends primarily on the type of biomass used. The most common types of wood include cordwood, woodchips, and pellets. Pellets can also be made from other forms of biomass, such as straw, corn stover, and switchgrass. In addition, heat can be derived from such fuels as corn, biogas, and biofuels.

1 MMBtu represents 1 million Btu.

Cordwood Systems

Cordwood is widely available and can be inexpensively stored. However, because cordwood systems require hand-firing, they're usually best suited for smaller heating loads and requirements. In homes, woodstoves are the most common appliance for burning cordwood. New catalytic stoves and inserts have advertised efficiencies of 70%-80%. Advanced combustion woodstoves provide a lot of heat but only work efficiently when the fire burns at full throttle. In addition to reaching temperatures of 1100°F, these so-called "secondary-burn" stoves have several components that help them burn combustible gases, as well as particulates, before they can exit the chimney. Components include a metal channel that heats secondary air and feeds it into the stove above the fire. This heated oxygen helps burn the volatile gases above the flames without slowing down combustion. The firebox is also insulated, which reflects heat back into it, ensuring that the turbulent gases stay hot enough to burn.

Most masonry heaters—also known as "Russian," "Siberian," and "Finnish" fireplaces—are designed primarily for burning wood with combustion efficiencies of 90%. They include a firebox, a large masonry mass (such as bricks), and long, twisting smoke channels that run through the masonry mass. A small hot fire built once or twice a day releases heated gases into the masonry tunnels. The masonry absorbs the heat and then slowly releases it into the house over a period of 12-20 hours. This is why masonry heaters cannot provide heat quickly from a cold start. In the end though, they produce more heat and less pollution than woodstoves, but they're usually more expensive.

Modern commercial and industrial cordwood boiler systems use both combustion and gasification technologies for high efficiencies, burning at temperatures of 1,800°F-2,000°F. Boiler sizes (output) range from 0.1-1MMBtu. Each system includes an induced-draft fan, controls, and stack connection. Additionally, thermal storage—such as a large-volume hot water tank—is usually built into the system.

For a boiler system, the water storage can be configured in different ways. One way has integral water storage with the combustion chamber surrounded by the water jacket tank. Another has an external hot water storage tank. To keep the water in storage heated, the fire is stoked periodically. This maintains a fire that's continually hot, fast, and clean, unlike ordinary woodstoves or cordwood boilers. A heat exchanger and circulating pump remove heat from the tank as needed for heating or hot water requirements.

Woodchip Systems

Woodchip systems commonly use a conventional grate and stoker boiler with one or more refractory-lined cells. The woodchips are augered onto the grate in the furnace cell. Heated combustion air is introduced into the cell and flows up through the grate, driving off the moisture in the biomass and releasing volatile gases. As the heated volatile gases rise up into the ignition region of the cell, additional preheated air is added for combustion. Some larger woodchip boilers use fluidized-bed technology, which consists of a heated bed of sand-like material suspended within a rising column of air to burn the fuel. Some also have fire-suppression systems. These systems prevent the spread of any fires from the combustor back up through the conveyor system where the woodchips are held.

The fuel-handling systems for woodchip boiler systems can vary greatly. Fully automated fuel-handling systems have a storage bin—typically located below grade—that can hold at least 35-50 tons of woodchips. From the storage bin, the woodchips are fed automatically to the boiler by augers and conveyors. As a result, these fully automated systems require little or no operator intervention for fuel handling. This makes them a good match for facilities that have limited staff and a need for larger boiler outputs from 2 to 10+ MMBtu/hour.

Semi-automatic fuel-handling systems are best suited to smaller facilities with lower heating requirements and boiler outputs no greater than 2 MMBtu/hour. These systems are usually installed in an on-grade slab building that includes a boiler room, woodchip storage, and a day-bin fuel hopper large enough to hold a one-to-two day supply of woodchips for feeding the boiler. An operator needs to load the day bin. From the day bin, the woodchips are delivered to the boiler with augers and conveyors. Automated controls, which are simpler than those in a fully automated system, manage fuel supply and combustion air.

Pellet and Corn Systems

Pellets—around 3/8-1 inch long—are made from compacted sawdust, woodchips, bark, agricultural crop waste, waste paper, and/or other organic materials. They usually burn a lot cleaner than wood, producing fewer harmful emissions. An alternative to pellet stoves is the corn stove, which works on similar principles but employs kernels of corn rather than pellets.

Because they're exempt from U.S. Environmental Protection Agency (EPA) smoke-emission testing requirements, pellet stoves are considered the cleanest solid fuel-burning appliance for residential use. They have heating capacities between 8,000 and 90,000 Btu/hour with combustion efficiencies of 78%-80%. They're often cheaper to install than a woodstove because many can be directly vented and do not require an expensive chimney or flue. In addition, there are pellet-burning fireplace inserts. Several companies now make pellet-fired furnaces and boilers to replace or supplement gas- or oil-fired furnaces and boilers in homes.

All pellet-fuel appliances have a fuel hopper for storing the pellets, which can hold 35 to 130 pounds, and a feeder device that drops a few pellets at a time into the combustion chamber for burning. How quickly the pellets are fed into the burner determines the heat output. The exhaust gases are vented by way of a small flue pipe directed out a side wall or upwards through the roof. More advanced models have a small computer and thermostat to govern the pellet feed rate. Note that because of the feeder and the associated controls, a pellet stove needs an external source of power to run, and cannot serve as an emergency heat source during power blackouts unless some backup power source is provided.

In larger pellet boiler systems, the pellets are usually stored in a grain silo and automatically fed into a boiler or boilers using an auger system like those used for conveying feed grain on farms. Automated controls provide the right amount of fuel to the combustion chamber based on heating demand. The boiler outputs of these systems usually range in size from 0.1 to 2 MMBtu/hour; however, multiple pellet systems can be installed for larger output requirements. Ultimately, there does not seem to be an upper limit for the size of pellet systems, as a 700-megawatt, coal-fired power plant in the United Kingdom is currently being converted to burn 100% wood pellets.

Compared to woodchip and cordwood boiler systems, pellet systems don't require as much space and are easier to use and often less expensive to install, operate, and maintain. Operation is limited to ash removal (if not automated) and maintenance, which usually takes no more than 20-30 minutes per day. Also no emission controls are anticipated for these small-scale systems.

Other Biomass Heating Systems

Any combustible form of biomass can potentially serve as a heating source. For instance, methane generated from landfills or from anaerobic digesters (described in the Biopower section in the Renewable Power Generation chapter) can be burned in place of natural gas in conventional gas-fired furnaces. Some companies are investigating the use of biogas purification and compression systems to convert biogas into pipeline-quality natural gas, which can then be sold into the natural gas market and treated like conventional natural gas. This approach may require the addition of propane to the biogas to achieve the correct energy density for commercial natural gas. A potential result of this approach is that the natural gas supplies used for heating and hot water in homes and buildings throughout the United States could gradually include increasing percentages of renewable biogas.

Biodiesel is another form of biomass, generally formed from plant oils such as soy, and it can serve as a direct replacement for diesel fuel or fuel oil. In the Northeast, some suppliers of fuel oil for heating are now blending biodiesel into their fuel to make it more sustainable and cleaner burning. Blends of up to 20% biodiesel are considered practical, although blends containing more biodiesel may also be feasible.

Terms and Definitions

Auger – A rotating, screw–type device that moves material through a cylinder.

Biodiesel – A biodegradable transportation fuel for use in diesel engines that is produced through the transesterfication of organically derived oils or fats. It may be used either as a replacement for or as a component of diesel fuel.

Biogas – A gaseous mixture of CO_2 and methane produced by the anaerobic digestion of organic matter.

Biomass – An energy resource derived from organic matter.

British thermal unit (Btu) – The amount of heat required to raise the temperature of one pound of water 1°F under one atmosphere of pressure and a temperature of 60°F–61°F.

Carbon dioxide (CO_2) – A colorless, odorless gas produced by respiration and combustion of carbon–containing fuels, used by plants as food in the photosynthesis process.

Combustion – A chemical reaction between fuel and oxygen that produces heat (and usually light).

Combustion air – The air fed to a fire to provide oxygen for combustion of fuel.

Combustion efficiency – Actual heat produced by combustion, divided by total heat potential of the fuel consumed.

Gasification – Any chemical or heat process used to convert biomass into a gaseous fuel.

MMBtu – 1 million Btu.

Particulates – A fine liquid or solid particle such as dust, smoke, mist, fumes, or smog found in air or emissions.

For More Information

Biomass Energy Resource Center
www.biomasscenter.org
An independent, national nonprofit organization that assists communities, colleges and universities, businesses, utilities, schools, and others in making the most of their local biomass energy resources.

Energy Savers: Wood and Pellet Heating
www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12570
Information for consumers from the U.S. Department of Energy about using wood and pellets for space heating.

Whole Building Design Guide: Biomass for Heat
www.wbdg.org/resources/biomassheat.php
An overview for larger facilities considering biomass heating as part of a major building construction project.

Direct Use of Geothermal Energy

Not far beneath the Earth's surface are geothermal energy resources that can be used for many applications. Geothermal reservoirs of hot water or steam—called hydrothermal resources—located within a mile of the Earth's surface can be used directly for district and space heating, and for agricultural and industrial applications. And the shallow ground of the Earth, which maintains a nearly constant temperature between 50°-60°F, can be used by geothermal heat pumps (GHPs) to heat and cool buildings.

Hydrothermal Resources

Hydrothermal resources, which range in temperature between about 70°F and 300°F, are typically accessed by drilling wells usually less than 500-feet deep. Deeper and hotter resources are used in electricity power generation. In a typical direct-use application, the well brings the heated water to the surface; a mechanical system—piping, heat exchanger and controls—delivers the heat to the space or process; and a disposal system either injects the cooled geothermal fluid underground or disposes of it on the surface.

Direct-use systems do require a larger capital investment than traditional heating technologies, but have lower operating costs and no need for ongoing fuel purchases. In addition, hydrothermal resources are clean, emitting little or no greenhouse gases, and reliable, achieving an average system availability of 95%.

The direct use of geothermal resources for heating can significantly reduce overall energy bills. For example, greenhouse growers in geothermal areas estimate that using geothermal resources instead of traditional energy sources reduces heating costs by up to 80%, which can save 5%–8% of their total operating cost.

Low-temperature geothermal resources exist throughout the western United States, and there is tremendous potential for new direct-use applications. A survey of 10 western states identified more than 9,000 thermal wells and springs, more than 900 low- to moderate-temperature geothermal resource areas, and hundreds of direct-use sites. The survey also identified 271 collocated sites—cities within 5 miles of a resource hotter than 122°F—that have excellent potential for near–term direct use. If these collocated resources were used only to heat buildings, the cities would be able to displace the energy equivalent of 18 million barrels of oil per year.

Applications

Hydrothermal resources can be used for a variety of applications including district and space heating, commercial greenhouses, and industrial and commercial uses. Additionally, spent fluids from geothermal electric plants can be subsequently used for direct-use applications in a so-called "cascaded" operation.

A 1996 survey found that these applications were using nearly 5.8 billion megajoules of geothermal energy each year—the energy equivalent of nearly 1.6 million barrels of oil.

District and Space Heating

In the United States, more than 120 operations, with hundreds of individual systems at some of those sites, are using geothermal energy for district and space heating. Space heating uses one well per structure. District systems distribute hydrothermal water from one or more geothermal wells through a series of pipes to several individual houses and buildings, or blocks of buildings, usually within a city or large complex, such as a military base or a campus. In both types, the geothermal production well and distribution piping replace the fossil–fuel–burning heat source of the traditional heating system. Geothermal district heating systems can save consumers 30% to 50% of the cost of heating with natural gas.

Greenhouse and Aquaculture Facilities

Greenhouses and aquaculture (fish farming) are the two primary uses of geothermal energy in the agribusiness industry. Thirty-eight greenhouses, many covering several acres, are raising vegetables, flowers, houseplants, and tree seedlings in eight western states. Twenty-eight aquaculture operations are active in 10 states. These operations report energy cost savings of up to 80% relative to operations heated with fossil fuels.

Industrial and Commercial Uses

Industrial applications include food dehydration, laundries, gold mining, milk pasteurizing, and spas. Dehydration, or the drying of vegetable and fruit products, is the most common industrial use of geothermal energy. The earliest commercial use of geothermal energy was for swimming pools and spas.

Geothermal Heat Pumps

GHPs can make use of the stable ground temperatures near the surface of the Earth to provide both heating and cooling to buildings. The surrounding soil, groundwater, or nearby surface water is used as a heat source in winter and a heat sink in summer.

Called by a variety of names—earth-source heat pumps, GeoExchange systems, ground-coupled heat pumps, ground-source heat pumps, and water-source heat pumps—GHPs are known for their low environmental impact, quiet operation and energy efficiency. Today, more than 500,000 GHPs have been installed nationwide, including more than 500 in schools.

GHPs consist of pipes buried in the shallow ground near the building to access the nearly constant temperatures, a heat exchanger to transfer the heat to or from the building, and a system of pipes and ductwork to deliver it. In winter, when the ground is warmer than the air, the GHP removes heat from the ground heat exchanger and pumps it into the indoor-air delivery system. In summer, when the ground is cooler than the air, the process is reversed, and the GHP moves heat from the indoor airstream into the ground heat exchanger.

GHPs reduce both heating and cooling costs compared to air-source heat pumps and air conditioners in both residential and commercial buildings. They have low operating and maintenance costs and, usually, the lowest life-cycle costs of available heating and cooling options. Consumption of electricity is reduced 25% to 50% compared to traditional heating and cooling systems, meaning that the investment in a GHP can often be recouped in just a few years. According to the EPA, GHPs can reduce energy consumption—and corresponding emissions—up to 44% compared to air-source heat pumps and up to 72% compared to electric resistance heating with standard air-conditioning equipment.

A typical GHP system includes three principal components:

- **Earth connection** – Using the Earth as a heat source/sink, a series of pipes, commonly called a "loop," is buried in the ground near the building to be conditioned. The loop can be buried either vertically in a well or horizontally in a trench. It circulates a fluid (water, or a mixture of water and antifreeze) that absorbs heat from, or relinquishes heat to, the surrounding soil, depending on whether the system is being used for heating or cooling.
- **Heat pump subsystem** – For heating, a GHP removes the heat from the fluid in the Earth connection, concentrates it and then transfers it to the building. For cooling, the process is reversed.
- **Heat distribution subsystem** – Conventional ductwork is generally used to distribute heated or cooled air from the GHP throughout the building. However, note that the ductwork for heat pumps is generally larger than the ductwork for conventional forced-air systems, making retrofits difficult.

Types of Systems

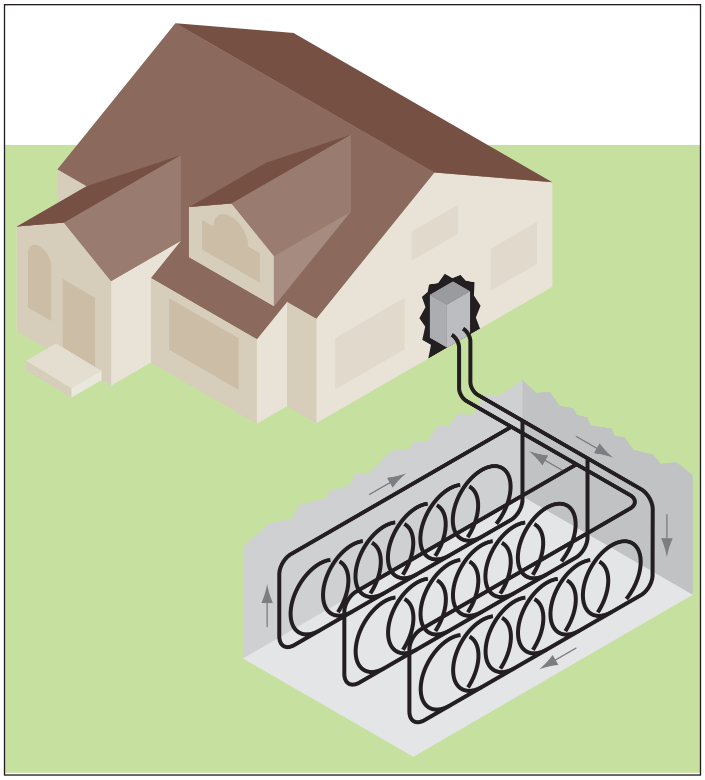
There are four basic types of ground loop systems. Three of these—horizontal, vertical, and pond/lake—are closed-loop systems. The fourth type of system is the open-loop option. Which one of these is best depends on the climate, soil conditions, available land, and local installation costs at the site. All of these approaches can be used for residential and commercial building applications.

Closed-Loop System

In closed-loop systems, the piping can be installed horizontally, vertically, or coiled in circles in ponds or lakes.

Horizontal

This type of installation is generally most cost-effective for residential installations, particularly for new construction where sufficient land is available. It requires trenches at least 4-feet deep. The most common layouts either use two pipes, one buried at 6 feet, and the other at 4 feet, or two pipes placed side-by-side at 5 feet in the ground in a two-foot-wide trench. The Slinky™ method of looping pipe allows



For horizontal closed-loop systems, the Slinky™ method of looping pipe allows more pipe in a shorter trench. *Illustration by NREL*

more pipe in a shorter trench, which cuts down on installation costs and makes horizontal installation possible in areas it would not be with conventional horizontal applications.

Vertical

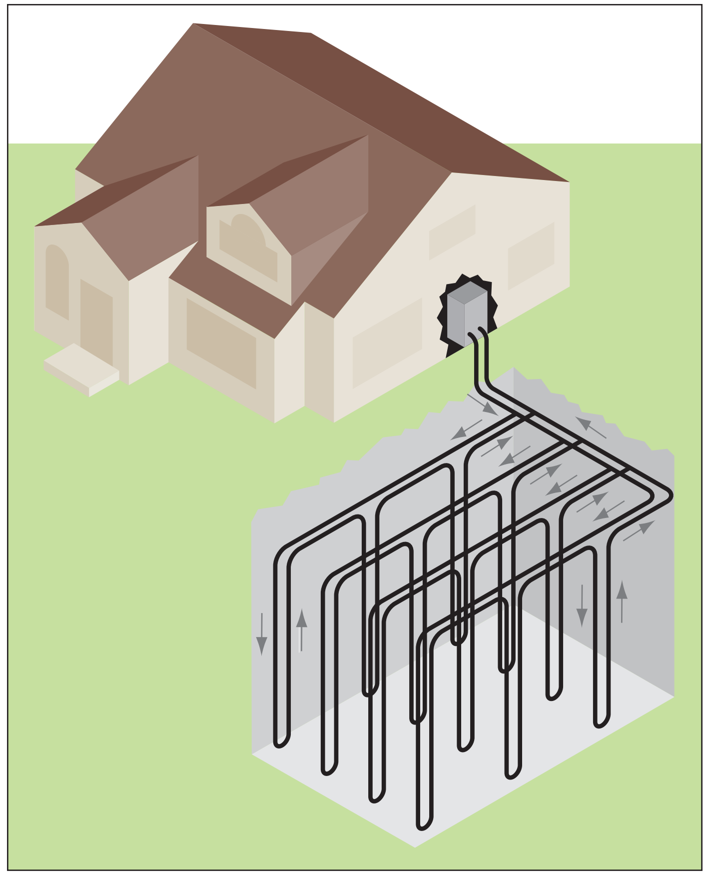
Large commercial buildings and schools often use vertical systems because the land area required for horizontal loops would be prohibitive. Vertical loops are also used where the soil is too shallow for trenching, and they minimize the disturbance to existing landscaping. For a vertical system, holes (approximately four inches in diameter) are drilled about 20-feet apart and 100–400 feet deep. Into these holes go two pipes that are connected at the bottom with a U-bend to form a loop. The vertical loops are connected with horizontal pipe (i.e., manifold), placed in trenches, and connected to the heat pump in the building.

Pond/Lake

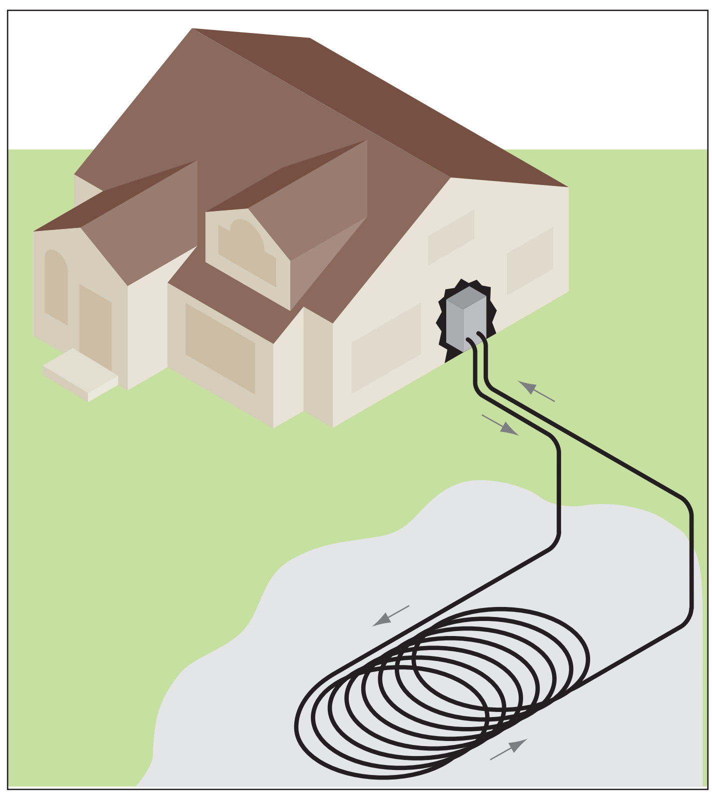
If the site has an adequate water body, this may be the lowest cost option. A supply line pipe is run underground from the building to the water and coiled into circles at least 8 feet under the surface to prevent freezing. The coils should only be placed in a water source that meets minimum volume, depth, and quality criteria.

Open-Loop System

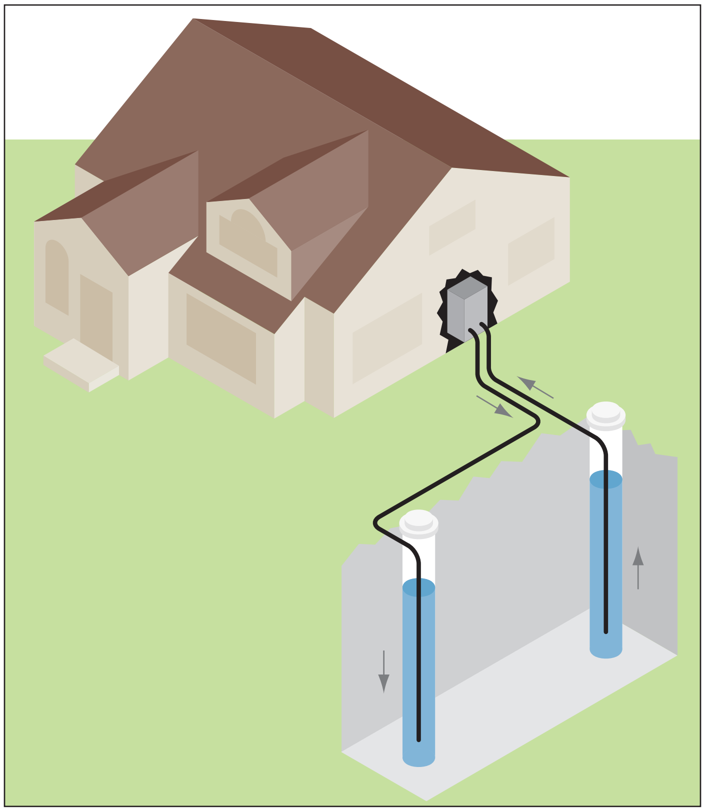
This type of system uses well or surface body water as the heat-exchange fluid that circulates directly through the GHP system. Once it has circulated through the system, the water returns to the ground through a recharge well or through



Vertical closed-loop systems employ holes (approximately 4 inches in diameter) that are drilled about 20 feet apart and 100–400 feet deep. *Illustration by NREL*



A closed-loop system can also involve a heat exchanger deployed in a pond or lake. *Illustration by NREL*



Open-loop systems draw water from a well or surface water source and return it to the source after use. *Illustration by NREL*

surface discharge. This option is practical only where there is an adequate supply of relatively clean water, and all local codes and regulations regarding groundwater discharge are met.

Residential Hot Water

In addition to space conditioning, GHPs can be used to provide domestic hot water for part of the year. Many residential systems are now equipped with desuperheaters that transfer excess heat from the GHP's compressor to the house's hot water tank. A desuperheater provides no hot water during the spring and fall when the GHP system is not operating; however, because the GHP is so much more efficient than other means of water heating, manufacturers are beginning to offer "full demand" systems that use a separate heat exchanger to meet all of a household's hot water needs. These units cost-effectively provide hot water as quickly as any competing on-demand system.

Earth Tubes

A related concept is that of shallow-earth air tubes for moderating the temperature of air before it enters the heating and cooling system of a building. This system consists of a set of pipes set in or around the foundation of a building. The incoming air travels through these tubes, taking on the ambient temperature of the earth. Earth tubes are different from a heat pump system in that they rely on passive transfer of the air and do not use any electrical or mechanical components, such as a heat exchange fluid or pump. There are various interpretations as to effective design, materials, and operational elements, such as keeping the pipes clean. However, Earth tubes have been known to suffer from condensation problems, which can lead to mold formation, potentially leading to odor problems and health hazards.

Terms and Definitions

Direct use **–** Use of geothermal heat without first converting it to electricity, such as for space heating and cooling, food preparation, industrial processes, etc.

District heating **–** A type of direct use in which a utility system supplies multiple users with hot water or steam from a central plant or well field.

Geologic reservoir **–** A natural underground container of liquids, such as water or steam (or, in the petroleum context, oil or gas).

Geothermal **–** Relating to the Earth's interior heat.

Geothermal energy **–** The Earth's interior heat made available for a variety of uses by extracting it from underground steam, hot water, or rocks.

Geothermal heat pumps **–** Devices that take advantage of the relatively constant temperature of the Earth, using it as a source and sink of heat for both heating and cooling. When cooling, heat is extracted from the conditioned space and dissipated into the Earth; when heating, heat is extracted from the Earth and pumped into the conditioned space.

Heat exchanger **–** A device for transferring thermal energy from one fluid to another.

Hydrothermal resource **–** Underground reservoirs of hot water and/or steam.

Slinky™ Ground Loop **–** In this type of closed–loop, horizontal geothermal heat pump installation, the fluid–filled plastic heat exchanger pipes are coiled like a SlinkyTM to allow more pipe in a shorter trench. This type of installation cuts down on installation costs and makes horizontal installation possible in areas it would not be with conventional horizontal applications.

For More Information

Direct Use of Geothermal Energy
www.eere.energy.gov/geothermal/directuse.html
Introduction to direct use applications from the U.S. Department of Energy (DOE) Geothermal Technologies Program.

(Continued on page 54)

(Continued from page 53)

Direct-Use Temperature Requirements: A Few Rules of Thumb
geoheat.oit.edu/bulletin/bull25-2/art1.pdf
An article from the June 2004 Geo-Heat Center Bulletin

Direct-Use Database
www.geothermal.org/library.html
A searchable database of more than 5,000 reports and articles about the direct use of geothermal energy, including GHPs, from the Geothermal Resources Council.

Energy Savers: Selecting and Installing a Geothermal Heat Pump System
www.energysavers.gov/your_home/space_heating_cooling/index.cfm/mytopic=12670
Information for consumers from DOE on GHP efficiency, economics, and site evaluation.

Geo-Heat Center
geoheat.oit.edu
The primary source of data and information about all types of direct-use applications. The center provides technical assistance to companies and individuals planning direct-use projects.

Geothermal Heat Pump Consortium's GeoExchange Industry Directory
www.geoexchange.org/index.php?option=com_content&view=article&id=200
Information about local installers, trainers, and designers for GHPs.

An Information Survival Kit for the Prospective Geothermal Heat Pump Owner
geoheat.oit.edu/ghp/survival.pdf
A publication developed by the Geo-Heat Center for DOE.

International Ground Source Heat Pump Association's Business Directory
www.igshpa.okstate.edu/directory/directory.asp
Information about local installers, trainers, and designers for GHPs.

Wind Energy for Water Pumping

The first use of wind energy was in windmills, which converted wind energy directly into mechanical energy for pumping water and grinding grain. Windmills are now most commonly used to pump water for agricultural applications, such as watering livestock and irrigating crops. Windmills typically fill a watering trough, irrigation ditch, or a storage tank, and the windmill is sized to meet the watering needs over the course of a day or week during typical weather conditions. This is an ideal direct application of wind energy because the variability of the wind resource doesn't matter, so long as the windmill is able to pump the minimum amount of water needed for its application.

A traditional windmill consists of a large, circular fan atop a tower. Windmill towers are typically constructed of steel or wood at heights of around 15 to 60 feet. The fan comprises 12-18 curved steel plates and usually a tail that orients the blades into the wind. When the wind blows, the fan rotates. The rotary motion drives a motor or set of mechanical gears that makes a long rod, called a "sucker rod," move up and down. The rod's reciprocating motion then powers a cylinder pump located deep underground in a well. From the well's aquifer to the surface, the cylinder pump creates a one-way, upward flow of water within a drop pipe. Through the continuous flow of water, the drop pipe fills and pours water into a storage tank, watering trough, or irrigation ditch.

"Third generation" windmills use a direct-drive mechanism instead of a geared transmission. They produce higher torque at low wind speeds and provide rotor speed control at high wind speed. To reduce starting torque for pumping, a counterbalance is attached to the actuating pump beam. Other design improvements include a counterbalance on the weight of the sucker rod and a variable-stroke wind pumping system. Adding a counterbalance weight on the sucker rod helps maintain a steady rotor speed for efficiency. Without a counterbalance weight, windmills tend to speed up when the sucker rod goes down and then slow down on the upstroke. Also a variable-speed wind pumping system is more efficient than an older windmill in a fixed position because its stroke varies along with the wind speed to make better use of the available wind resource.

Some modern mechanical wind pumping systems are designed to use six to eight airfoil-type blades. While these modern systems can be cheaper and twice as efficient as the more traditional, multibladed windmills, they are bulkier and are sometimes best suited for light wind regions.

Although mechanical windmills still provide a sensible, low-cost option for pumping water, wind-electric pumping systems can be more versatile and provide twice the volume for the same initial investment. For instance, mechanical windmills must be placed directly above the well, which may not take the best advantage of available wind resources. Wind-electric pumping systems can be placed where the wind resource is the best and connected to the pump motor with an electric cable. By directly coupling the wind turbine's electrical output with a motor of the same type (either direct current or alternating current), which then drives a centrifugal pump at varying speed, there's no need for batteries, inverters, and matching the wind turbine with the appropriate water pump.

Generally, modern wind-electric pumping systems use small, 1- to 10-kilowatt wind turbines. To start pumping, these wind turbines usually require higher wind speeds than mechanical windmills. They also require higher tower heights. And they can be three times more expensive per unit of rotor area than mechanical systems. For more information on small wind turbines, see the Wind Power section in the Renewable Power Generation chapter.

For More Information

Renewable Energy Water Pumping Systems Handbook
www.nrel.gov/docs/fy04osti/30481.pdf
A publication from the National Renewable Energy Laboratory.

NONRENEWABLE DISTRIBUTED ENERGY TECHNOLOGIES

Distributed energy technologies consist primarily of modular energy production and storage systems placed at or near the point of use. They also include thermally activated technologies that reduce the demand for other forms of energy, such as electricity. The use of distributed energy can lead to lower emissions and, particularly in combined heat and power (CHP or cogeneration) applications, to improved efficiency.

This chapter describes distributed electricity-generation technologies that do not typically run on renewable resources. Most are primarily fueled by natural gas and have cogeneration applications. Some, like fuel cells, run on natural gas today but are prime candidates for the future hydrogen economy. This chapter also describes some of the key thermally activated technologies that are used in CHP applications and some novel distributed power-generation technologies that could be in our future.

Since the 1980s, natural gas—which consists mostly of methane—has become increasingly popular for power generation. A combination of new technologies and regulatory changes have been responsible for this shift.

Natural gas technologies have some significant advantages over many renewable energy technologies: the fuel source is continuously available, the upfront cost of generating equipment is typically lower, and the generators themselves are much more compact than most renewable power systems.

Generating equipment that runs on natural gas can often run on other gases that happen to be available at the generation site—so-called "opportunity fuels." Sometimes it is necessary to clean up corrosive elements in the gas and/or modify the equipment to work with the alternative gas source.

Examples of opportunity fuels include:

- **Anaerobic digester gas —** A byproduct at animal farms and wastewater treatment plants, digester gas can be used in reciprocating engines, microturbines, and fuel cells.
- **Biomass fuels —** Solid fuels can be gasified and then used in a combustion turbine, potentially useful in industries that produce biomass waste, although gasifiers are currently expensive.
- **Coalbed methane —** Very similar in composition to natural gas, the gas that is released from coal seams during mining is often injected directly into local pipelines; it has also been used in on-site reciprocating engines and gas turbines to generate electricity for mining operations.
- **Landfill gas —** Similar to anaerobic digester gas (about 50% methane), landfill gas can also be used in reciprocating engines, microturbines, and fuel cells.

Combined Cooling, Heating, and Power Systems

Conventional electricity generation is inherently inefficient, converting only about a third of the fuel's potential energy into usable energy. In applications where thermal energy (i.e., heating or cooling) is needed as well, the total efficiency of separate thermal and power systems is only about 45%-50%, despite the inherently higher efficiencies of thermal conversion equipment.

Combined cooling, heating, and power (CHP) systems are significantly more efficient. Also referred to as "combined heat and power" or cogeneration, CHP involves the simultaneous or sequential generation of both electricity and thermal energy from a common energy source. As an example, these systems can recover heat that normally would be wasted in an electricity generator, then use it to produce one or more of the following: steam, hot water, space heating, humidity control, or cooling.

By recycling and using waste heat, CHP systems typically achieve efficiencies of 60% to 80%, and as high as 88%—a dramatic improvement over the average 33% efficiency of conventional power plants. These higher efficiencies have an added bonus: reducing air emissions of nitrogen oxides (NOx), sulfur dioxide (SO_2), mercury (Hg), particulate matter (PM), and carbon dioxide (CO_2). CHP systems produce much less air pollution than conventional technologies.

CHP is the simultaneous or sequential production of both electricity and useful heat from a single fuel. CHP is inherently more efficient than separate generation of electricity from central station power plants and thermal energy from boilers or other heating equipment. The diagram below compares the fuels input needed to produce 35 units of electricity and 50 units of heat using conventional separate heat and power (roughly 47% efficient) versus CHP (85% efficient). These figures will vary depending on the mix of technologies being compared.

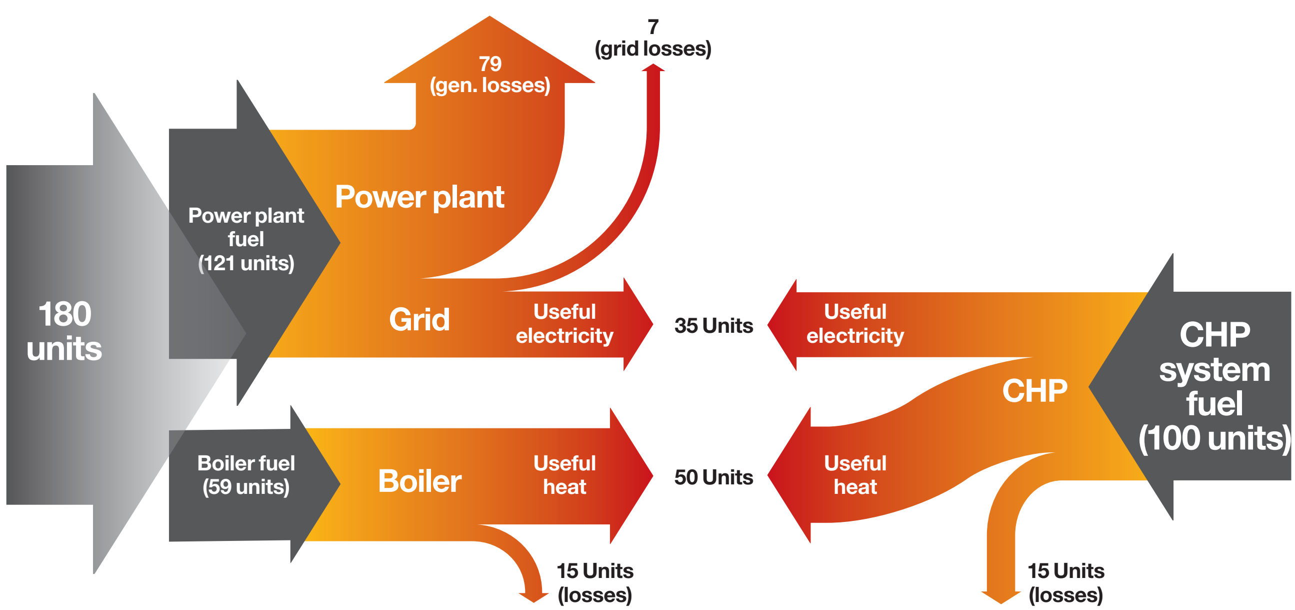
Applications and Markets

CHP isn't new. In the early 1900s, many manufacturing plants operated CHP facilities. However, as a result of improvements in the cost and reliability of electricity generated by the separate electric power industry as well as increasing regulation, the electric generation capacity at most CHP facilities was abandoned in favor of more conveniently purchased electricity. A few industries, such as pulp and paper and petroleum refining, continued to operate CHP facilities, in part driven by their need for significant amounts of steam and the ready availability of fuels as byproducts of their production processes.

In the late 1970s, interest in CHP was renewed in response to the Public Utilities Regulatory Policy Act (PURPA) of 1978, which included measures to promote CHP as an energy efficient technology. PURPA played a critical role in moving CHP into the marketplace.

Recent technological advances have resulted in the development of a range of efficient and versatile systems for a variety of key markets, including:

- **Industry —** Chemical, petroleum refining, ethanol, pulp and paper, food processing, and glass manufacturing industries
- **Institutions —** Colleges and universities, hospitals, prisons, and military bases
- **Commercial buildings —** Hotels and casinos, airports, data centers, and large office buildings
- **Municipal governments —** District energy systems, wastewater treatment facilities, and K-12 schools
- **Residential buildings —** Individual homes, multifamily housing, and planned communities.



CHP versus separate heat and power production. *Illustration by NREL*

Traditionally, distributed power generation equipment and thermally activated equipment are combined into a CHP system that is customized for each building site. This customization can translate into higher capital costs due to the need for on-site engineering.

Integrated energy systems that combine on-site power generation technologies with thermally activated technologies in a single package to provide cooling, heating, humidity control, energy storage, or other process functions using the thermal energy normally wasted in the production of electricity are in development. These systems enable the use of CHP in building applications that could not be economically served by conventional CHP systems. Some, so-called "micro-CHP" systems, are small enough to be installed in residences.

One obvious potential drawback of CHP systems is their need for a local application of thermal energy. Merchant developers of industrial-scale CHP systems have occasionally had their projects fail because a nearby industrial development, which had intended to buy the steam from the CHP system, ended up changing their plans. For this reason, most industrial-scale CHP systems are built by companies that have a need for the steam generated by the system.

Benefits

CHP systems can play an important role in reducing the environmental impact of power generation.

Efficiency benefits — CHP systems require less fuel to produce a given energy output, and avoid transmission and distribution losses that occur when electricity travels over power lines. Assuming that the combustion of fuel to produce heat (usually in a boiler) is typically 85% efficient, each British thermal unit (Btu) of heat captured from the distributed generator in a CHP process offsets the need to burn about 1.18 Btu of fuel.

Reliability benefits — CHP systems can be designed to provide high-quality electricity and thermal energy to a site regardless of what might occur on the power grid, decreasing the impact of outages and improving power quality for sensitive equipment.

Environmental benefits — Because less fuel is burned to produce each unit of energy output, CHP systems reduce air pollution and greenhouse gas emissions, including NOx, SO_2, Hg, PM, and CO_2. CHP systems have the biggest impact on curbing emissions from boilers or other processes that require heat input. This fact may be helpful in obtaining permits from local air-regulatory authorities.

Economic benefits — CHP systems can offer a variety of economic benefits for large energy users:

- **Reduced energy costs —** CHP systems can result in energy savings when compared to conventional, separately purchased power and on-site thermal energy systems. Some energy users require substantial amounts

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Formulae

Comparing system efficiencies:

Equivalent separate heat and power (SHP) efficiency

$$Eff_{SHP} = \frac{\text{SHP Output}}{\text{SHP Fuel Input}} = \frac{P+Q}{P/Eff_P + Q/Eff_Q}$$

divide numerator and denominator by (P+Q)

$$Eff_{SHP} = \frac{1}{\frac{\%P}{Eff_P} + \frac{\%Q}{Eff_Q}}$$

CHP efficiency

$$Eff_{CHP} = \frac{P+Q}{F_{CHP}} = \frac{Eff_{SHP}}{(1-S)}$$

Where P = **power output**
Q = **useful thermal output**
Eff_P = **power generation efficiency**
Eff_Q = **thermal generation efficiency**

Where $\%P = P/(P+Q)$
$\%Q = Q/(P+Q)$

Where F_{CHP} = **CHP fuel use**
F_{SHP} = **SHP fuel use**
S = **% fuel savings compared to SHP**
E_{CHP} = **CHP efficiency**
E_{SHP} = **SHP efficiency**

Calculating fuel savings with CHP:

Percent fuel savings calculated from power and thermal output, CHP fuel input, and efficiency of displaced separate heat and power.

$$S = 1 - \frac{F}{\frac{P}{Eff_P} + \frac{Q}{Eff_Q}}$$

of heat, especially industries, agricultural operations, and large buildings. In those cases, CHP can save enough on fuel costs to substantially improve the overall economics of distributed energy installations. To determine if CHP is likely to offer a compelling return on investment at a particular site, the costs of the CHP system (capital, fuel, and maintenance) should be compared to the costs of purchased power and thermal energy (hot water, steam, or chilled water) that would otherwise be needed for the site.

- **Offset capital costs —** CHP systems can be installed in place of boilers or chillers in new construction projects, or when major heating, ventilation, and air-conditioning (HVAC) equipment needs to be replaced or updated.
- **Hedge against volatile energy prices —** CHP systems can provide a hedge against unstable energy prices by enabling end users to supply their own power during times when prices for electricity are very high. In addition, a CHP system can be configured to accept a variety of feedstocks (e.g., natural gas, biogas, propane, or biomass) for fuel; therefore, a facility could build in fuel switching capabilities to hedge against high fuel prices.

Terms and Definitions

British thermal unit (Btu) **–** The amount of heat required to raise the temperature of one pound of water 1°F under one atmosphere of pressure and a temperature of 60°F–61°F.

Capital costs **–** The amount of money needed to purchase equipment, buildings, tools, and other manufactured goods that can be used in production.

Feedstock **–** Any material used directly as a fuel or converted to another form of fuel or energy product.

Public Utilities Regulatory Policy Act (PURPA) of 1978 **–** A law that requires electric utilities to purchase electricity produced from qualifying power producers that use renewable energy resources or are cogenerators. Power providers are required to purchase power at a rate equal to the avoided cost of generating the power themselves.

For More Information

Combined Heat and Power Application Tool
www.eere.energy.gov/manufacturing/tech_deployment/software_chp.html
Free online software tool from the U.S. Department of Energy (DOE) Advanced Manufacturing Office for evaluating the feasibility of using gas turbines to generate power and the turbine exhaust gases to supply heat to industrial systems.

Combined Heat and Power Basics
www.eere.energy.gov/manufacturing/distributedenergy/chp_basics.html
An overview of CHP technologies from DOE's Advanced Manufacturing Office.

Combined Heat and Power Installation Database
www.eea-inc.com/chpdata/index.html
A database of state CHP project installations from ICF International with support from DOE and Oak Ridge National Laboratory.

Combined Heat and Power Partnership
www.epa.gov/chp
Information on CHP technologies, applications, and benefits from the U.S. Environmental Protection Agency, which administers a voluntary partnership to promote CHP.

Distributed Energy Resources and Combined Heat and Power Resources
www.eere.energy.gov/femp/technologies/derchp_resources.html
CHP information resources from DOE's Federal Energy Management Program.

U.S. Clean Heat & Power Association
www.uschpa.org
A trade association promoting the merits of CHP for achieving public policy support.

Reciprocating Engines

The reciprocating, or piston-driven, engine is a widespread and well-established technology. It's the workhorse of on-site power generation. Also called the internal combustion engine, reciprocating engines require fuel, air, compression, and a combustion source to function.

Reciprocating-engine generator sets produce electricity along with waste heat that can be captured for a variety of building thermal needs. When used in CHP applications, overall system efficiencies are greatly improved.

A large majority of the smaller reciprocating engines use diesel or gasoline to provide backup power to facilities during emergency situations or power outages. Traditionally, these generators have been noisy, dirty suppliers of electricity without employing the benefits of heat recovery (exhausting heat directly into the atmosphere instead of capturing it for useful purposes).

Cleaner gas-fired reciprocating engines and packaged cogenerators have been developed to address these concerns. Current gas-fired engines offer low capital costs, easy start-up, and good reliability. Emissions have been reduced significantly in recent years, thanks to exhaust catalysts, advances in the combustion process, and operational modifications. Natural-gas-powered, high-output, and highly efficient packaged cogenerators are available for use in a variety of small- to medium-sized building applications.

When the feedstocks are properly treated, the engines can run on biofuels or on methane generated by waste treatment or anaerobic digestion.

Reciprocating engines can serve virtually any distributed energy application. Their excellent load-following ability makes them well suited to peak-shaving applications. They have good part-load efficiencies. They also offer quick start-up times for standby power applications, and diesel-fueled engines can meet emissions requirements when they operate for only a few hours a year.

Commercially available reciprocating engines for power generation range from 0.5 kilowatts (kW) to 65 megawatts (MW), although they are typically best suited to distributed generation projects requiring less than 10 MW of power. Gas-fueled reciprocating engines can be run continuously to supply baseload electricity, as can traditional diesel-fueled engines where emissions permits and noise limits are not applicable.

The various types of reciprocating engine have similar purchase costs per kW.

Types of Engines

Depending upon the ignition source, reciprocating engines generally fall into the following two categories:

- **Spark-ignited engines —** Typically fueled by natural gas in power generation and CHP applications but gasoline, propane, landfill gas, and other biogases can be used.
- **Compression-ignited engines —** Typically fueled by diesel oil, but can be modified to use a mixture of natural gas and diesel fuel.

The four-stroke, spark-ignited reciprocating engine has an intake, compression, power, and exhaust cycle. In the intake phase, as the piston moves downward in its cylinder, the intake valve opens and the upper portion of the cylinder fills with fuel and air. When the piston returns upward in the compression cycle, the spark plug emits a high-intensity spark of timed duration to ignite the compressed fuel-air mixture. This controlled reaction, or "burn," forces the piston down, thereby turning the crank shaft and producing power.

The compression-ignition engine operates in the same manner, except diesel fuel and air ignite when the piston compresses the mixture to a critical pressure. At this pressure, no spark or ignition system is needed because the mixture ignites spontaneously, providing the energy to push the piston down in the power stroke.

In the exhaust phase, the piston moves back up to its original position, and the spent mixture is expelled through the open exhaust valve.

Dual-Fuel Engine Gensets

Dual-fuel engine gensets consist of a diesel-cycle engine modified to use a mixture of natural gas and diesel fuel (typically 5% to 10% diesel by volume) connected to an electric generator.

The small amount of diesel fuel allows the use of compression ignition, and the high percentage of natural gas in the mix results in much lower air emissions (and somewhat lower power output) than those of a diesel engine. In most other cost and operational respects, dual-fuel engines are comparable to diesels.

Existing diesel-fired internal combustion engines can be converted to run in a dual-fuel mode for a relatively low cost (about $50/kW, depending on the size and type of engine).

Problems with Traditional Emergency Generators

Although diesel- and gasoline-fueled reciprocating engines are one of the most commonly distributed energy technologies, especially for standby power applications, they create significant pollution (in terms of both emissions and noise) relative to natural-gas- and renewable-fueled technologies, and their use is actively discouraged by many municipal governments.

From a reliability standpoint, there are several drawbacks to using diesel gensets as backup generators.

Backup diesel generators are rarely called upon to operate and might not start and run when needed. Unless a facility keeps up with maintenance and frequent testing, emergency generators can fail to start on the rare occasions they are needed.

Diesel fuel deliveries can be difficult or impossible to arrange during a widespread disaster. During a major hurricane or regional blackout when a prolonged outage occurs, a diesel backup system might have to shut down due to lack of fuel.

Storing large quantities of fuel imposes high costs and risks of fuel leakage or fuel degradation. Diesel fuel begins to chemically break down within 30 to 60 days of delivery and tends to absorb moisture from the air. These fuel quality issues can lead to unreliable engine operations and higher maintenance costs if fuel storage is used to hedge against potential shortages.

Diesel engines used for backup service typically have high emissions and are permitted for limited use. Having limited permitted hours for operation makes it difficult to keep the engines in the proper state of readiness and prevents generator use for meeting general facility energy needs or reducing operating costs.

Summary

The data below represent typical values for commercially available systems. Figures for spark-ignition engines assume that the engines are run on natural gas.

Advantages:

- Can deliver bulk power when utility is unavailable
- High power efficiency with part-load operational flexibility
- Fast start-up allows less-sensitive functions to be served without the need for an uninterruptible power supply
- Relatively low investment cost
- Can be used in island mode
- Good load-following capability
- Ease of maintenance (with gas-fueled gensets)
- Wide service infrastructure
- Operate on low-pressure gas

Disadvantages:

- High maintenance costs (with traditional backup gensets)
- Limited to lower-temperature cogeneration applications
- Relatively high air emissions (with traditional backup gensets)
- Must be cooled even if recovered heat is not used
- High levels of low frequency noise
- Possible on-site fuel storage requirement

Capacity:

- Spark-ignition engine – up to 5 MW
- High-speed (1200 RPM) diesel engine – up to 4 MW
- Low-speed (60-275 RPM) diesel engine – up to 65 MW

Power efficiency:

- Spark-ignition engine – 22%-40%
- Diesel engine – 27%-45%

Overall efficiency in CHP applications: 70%-80%

Typical power to heat ratio: 0.5-1

Suitability for partial loading:

- Spark-ignition engine - Okay
- Diesel engine – Good

Time between overhauls:

- Spark-ignition engine - 24,000-80,000 hours
- Diesel engine - 25,000-30,000 hours

Start-up time: 10 seconds

Noise: High

Terms and Definitions

Anaerobic digestion **–** Degradation of organic matter by microbes that produces a gas comprised mostly of methane and CO_2, usually under wet conditions, in the absence of oxygen.

Biofuels **–** Biomass converted to liquid or gaseous fuels such as ethanol, methanol, methane, and hydrogen.

Capacity **–** The load that a power generation unit or other electrical apparatus or heating unit is rated by the manufacture to be able to meet or supply.

Combustion **–** The process of burning; the oxidation of a material by applying heat, which unites oxygen with a material or fuel.

Cogeneration **–** The generation of electricity or shaft power by an energy conversion system and the concurrent use of rejected thermal energy from the conversion system as an auxiliary energy source.

Feedstock **–** Any material used directly as a fuel or converted to another form of fuel or energy product.

For More Information

Gas-Fired Distributed Energy Resource Technology Characterizations
www.nrel.gov/docs/fy04osti/34783.pdf
A publication developed for the U.S. Department of Energy.

Technology Characterization: Reciprocating Engines
www.epa.gov/chp/documents/catalog_chptech_reciprocating_engines.pdf
A publication developed for the U.S. Environmental Protection Agency's Combined Heat and Power Partnership Program.

Gas Turbines

Gas turbines (also called combustion turbines) can burn gaseous or a liquid fuels, but are usually fueled with natural gas. A gas turbine is actually a heat engine in which high-temperature, high-pressure gas is the working fluid. Part of the heat supplied by the gas is converted directly into mechanical work—high-temperature, high-pressure gas rushes out of the combustor (see the diagram below) and pushes against the turbine blades, producing a high-speed rotary motion that drives an electric generator. In most cases, the hot gas is obtained by burning a fuel in air, which is why gas turbines are often referred to as combustion turbines.

"Simple-cycle" gas turbines are used only to produce electricity, with waste heat vented to the atmosphere. But in addition to the electricity they generate, turbines produce high-quality (high-temperature) heat that can be used to generate steam or hot water, or to power thermally activated equipment such as absorption chillers. Taking advantage of the normally wasted heat means a tremendous gain in efficiency, typically in the range of 70% to 80% overall, and approaching 90% in some cases.

Recovered exhaust heat can be used to power a separate steam turbine, which may generate electricity or power a mechanical load. This is referred to as a "combined-cycle" combustion turbine because two separate processes or cycles are derived from one fuel input to the primary turbine.

Because gas turbines are compact, lightweight, quick starting, and simple to operate, they are used widely in industry, colleges, hospitals, and commercial buildings to produce electricity and heat or steam.

While they may take a few more minutes to get up to speed than reciprocating engines, mid-sized gas turbines are well suited for peaking and load-following applications, and for CHP and standby or backup power in commercial and industrial settings. Larger turbines are suitable for baseload operation. Combined-cycle power plants incorporating a gas turbine with a secondary steam turbine are the most efficient commercial technology for central station electricity-only generation.

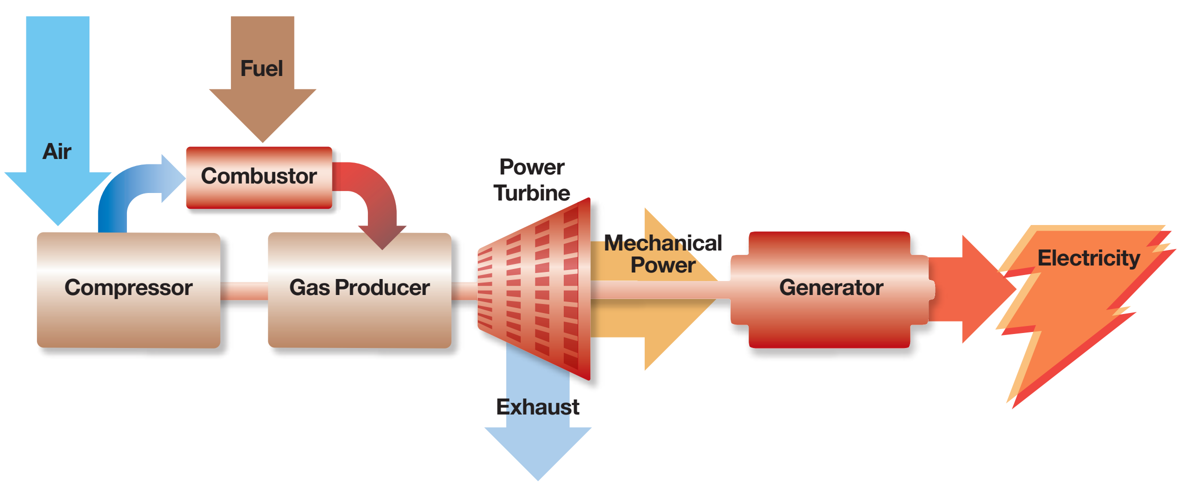
Gas turbines are one of the cleanest means of generating electricity, with emissions of NOx from some large turbines in the single-digit, parts-per-million range, either with catalytic exhaust cleanup or lean premixed combustion. Because of their relatively high efficiency and reliance on natural gas as the primary fuel, gas turbines emit substantially less CO_2 per kilowatt-hour (kWh) generated than any other fossil technology in general commercial use.

Installed costs are somewhat higher than those of reciprocating engines, and maintenance costs are slightly lower.

Gas Turbine Configurations

Gas turbines can be used in a variety of configurations. These include:

- **Simple-cycle operation –** A single gas turbine produces power only. Simple-cycle efficiencies are as high as 40% and are generally used at generation capacities less than 25 MW.
- **Power generation with heat recovery –** There are several variations:
  - **CHP operation –** A simple-cycle gas turbine with the addition of a recuperating heat exchanger that recovers the heat in the turbine exhaust and converts it to useful thermal energy, usually in the form of steam or hot water. This significantly enhances the efficiency of the system, with overall CHP efficiencies of 70% to 80%.
  - **Combined-cycle operation –** High-pressure steam is generated from recovered exhaust heat and used to create additional power using a steam turbine.
  - **Combined-cycle CHP systems –** Some combined-cycle systems also extract steam, usually at low or medium pressure, for use in industrial processes.



Components of a simple-cycle gas turbine used for power generation only. A gas turbine is a single-shaft machine (with compressor and turbine on the same shaft) that includes an air compressor, a combustor (burner), and a power turbine driving an electric generator. *Illustration by NREL*

Unfired and Fired Heat-Recovery Systems

The economics of gas turbines are greatly improved with effective use of the thermal energy contained in the exhaust gas, which generally represents 60% to 70% of the inlet fuel energy. The most common use of this energy is for steam generation in unfired or supplementary-fired, heat-recovery steam generators (HRSGs).

The turbine exhaust gases can also be used as a source of direct process energy for unfired- or fired-process fluid heaters, or as preheated combustion air for power boilers. An unfired HRSG is the simplest steam CHP configuration and can generate steam at conditions ranging from 150 psig (pounds per square inch gauge) to 1,200 psig and temperatures up to 900°F.

Because the gas turbine combustion process consumes little of the available oxygen in the turbine airflow, the oxygen content in the gas turbine exhaust permits supplementary fuel firing ahead of the HRSG to increase steam production relative to an unfired unit. Supplementary firing can raise the exhaust gas temperature entering the HRSG up to 1,800°F and increase the amount of steam produced by the unit by a factor of two. As the turbine exhaust gas is essentially preheated combustion air, the fuel consumed in supplementary firing is less than that required for a stand-alone boiler providing the same increment in steam generation.

Supplementary firing also increases system flexibility. Unfired HRSGs are typically convective heat exchangers that respond solely to exhaust conditions of the gas turbine and do not easily allow for steam-flow control. Supplementary firing provides the ability to control steam production, within the capability of the burner system, independent of the normal gas turbine operating mode.

Summary

The data below represent typical values for commercially available systems.

Advantages:

- High reliability
- Low emissions
- High-grade heat available
- No cooling required
- High efficiency in CHP applications

Disadvantages:

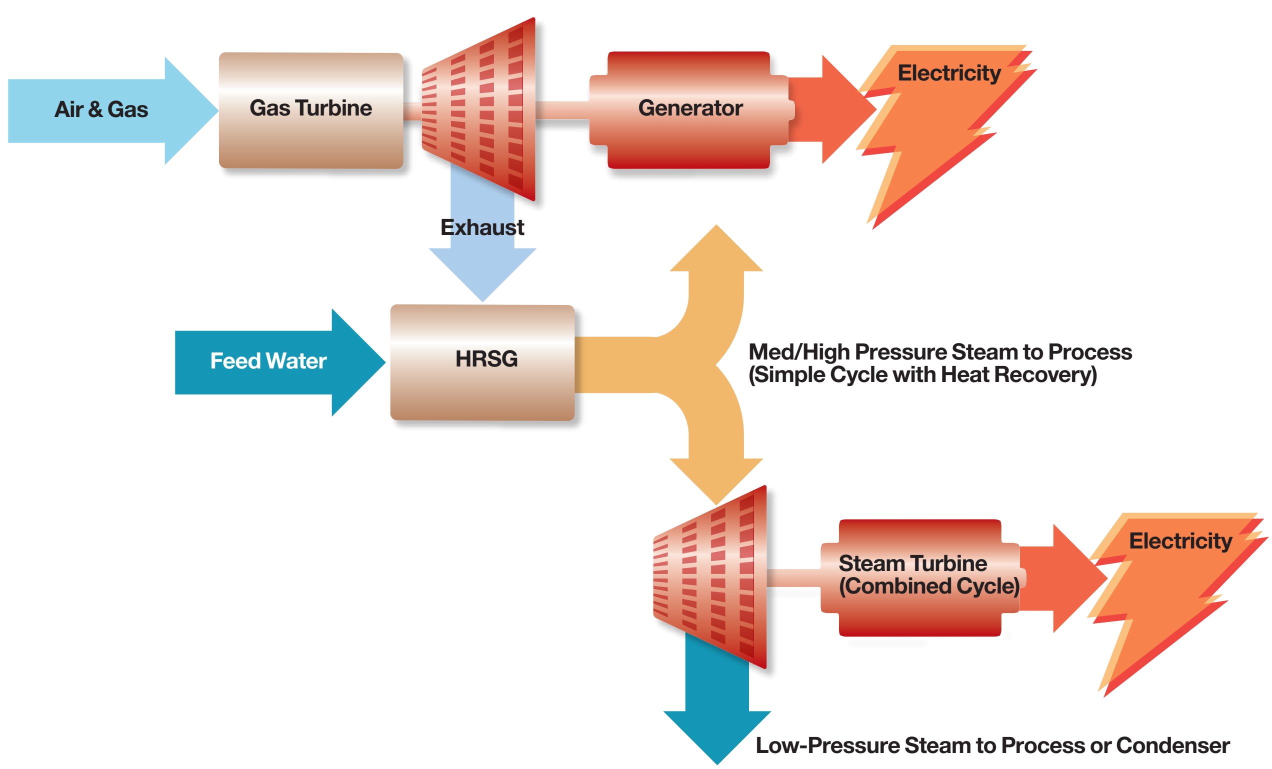
- Require high-pressure gas or in-house gas compressor
- Poor efficiency at low loading
- Output falls as ambient temperature rises

Capacity: 500 kW to 250 MW

Power efficiency:

- Simple cycle - up to 40%
- Combined cycle - up to 60%

Overall efficiency in CHP applications: 70%-80%



Options for heat recovery from a gas turbine system using an HRSG on the exhaust. *Illustration by NREL*

Typical power to heat ratio: 0.5-2

Suitability for partial loading: Poor

Time between overhauls: 30,000-50,000 hours

Start-up time: 10 minutes to 1 hour

Noise: Moderate

Terms and Definitions

Combined cycle **–** Two thermodynamic cycles to achieve higher overall system efficiency; e.g.,the heat from a gas–fired combustion turbine is used to generate steam for heating or to operate a steam turbine to generate additional electricity.

Heat engine **–** A device that produces mechanical energy directly from two heat reservoirs of different temperatures. A machine that converts thermal energy to mechanical energy, such as a steam engine or turbine.

Heat–recovery steam generator (HRSG) **–** An energy recovery heat exchanger that recovers heat from a hot gas stream. It produces steam that can be used in a process or used to drive a steam turbine.

Power boiler **–** A boiler in which steam or other vapor is generated at a pressure of more than 15 psi (pounds of pressure per square inch) for use external to itself.

Recuperator **–** A heat exchanger in which heat is recovered from the products of combustion.

Simple cycle **–** It differs from a combined cycle in that it has no provision for waste heat recovery.

Turbine **–** A device for converting the flow of a fluid (air, steam, water, or hot gases) into mechanical motion.

For More Information

Gas-Fired Distributed Energy Resource Technology Characterizations
www.nrel.gov/docs/fy04osti/34783.pdf
A publication developed for the U.S. Department of Energy.

Technology Characterization: Gas Turbines
www.epa.gov/chp/documents/catalog_chptech_gas_turbines.pdf
A publication developed for the U.S. Environmental Protection Agency Climate Protection Partnership.

Microturbines

Microturbines are smaller, somewhat less efficient versions of combustion turbines. They are about the size of a refrigerator with outputs ranging from 25 kW to 500 kW, making them well suited to small-scale power generation and cogeneration applications. Microturbines evolved from automotive turbochargers and the auxiliary-power units used in aircraft.

Microturbines are composed of a compressor, combustor, turbine, alternator, and generator. Most also incorporate a recuperator. Microturbines typically have high-rotating speeds of 90,000 to 120,000 revolutions per minute (rpm), although a few manufacturers have developed systems with lower rotation speeds.

The generator produces high-frequency alternating current (AC) power [about 1600 hertz (Hz) for a 30 kW machine], so microturbines incorporate digital power controllers (called power-conditioning units or PCUs) to convert this output into usable electricity. The high-frequency AC is rectified to direct current (DC), inverted back to 60 Hz AC, and then filtered to reduce harmonic distortion. Power conversion comes with an efficiency penalty (approximately 5%).

Electronic components also direct all of the operating and start-up functions. Microturbines are typically equipped with controls that allow the unit to be operated either in parallel with the grid or in stand-alone mode, and incorporate many of the grid- and system-protection features required for interconnection. The controls also allow for remote monitoring and operation.

Microturbines are compact in size and lightweight, have a small number of moving parts, low maintenance costs, low emissions, allow recovery of thermal heat, and offer fuel flexibility.

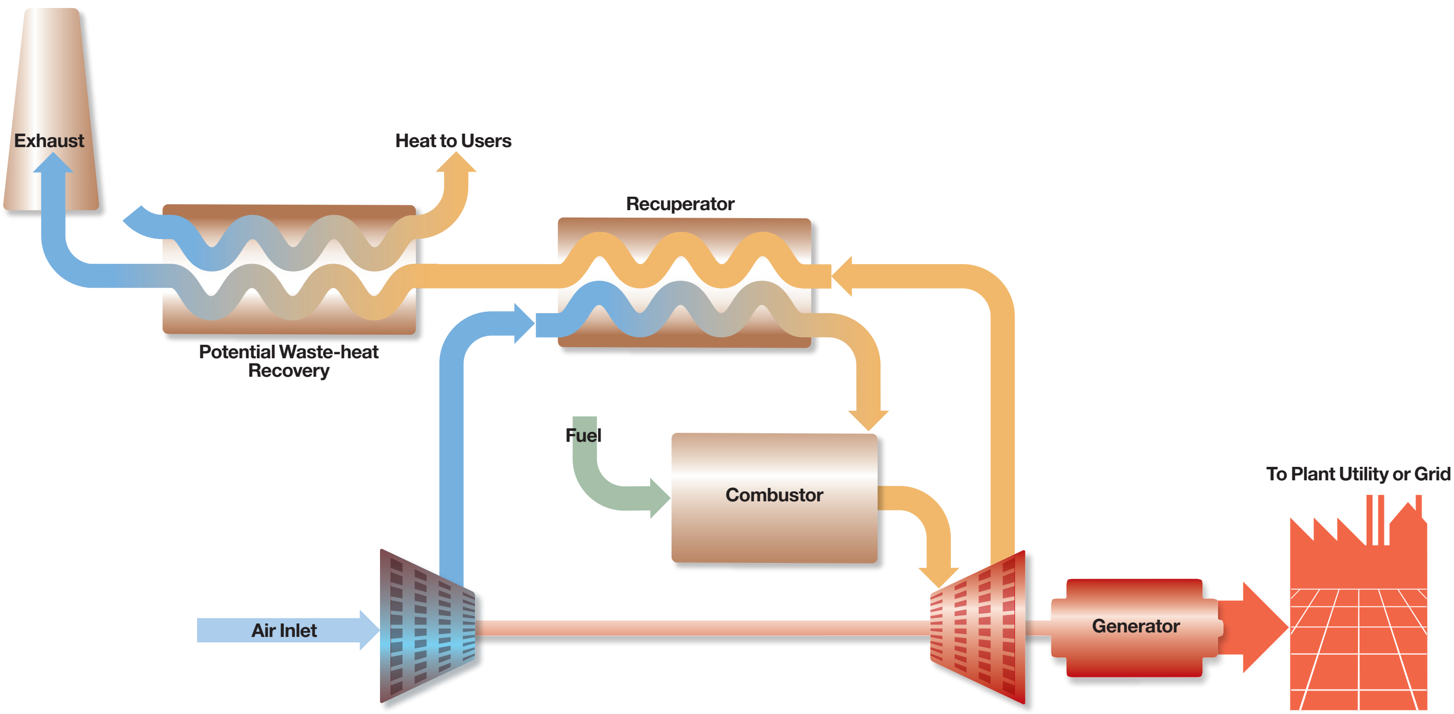
Microturbines can burn a wide variety of fuels, including natural gas, sour gases (high in sulfur and low in Btu content), and liquid fuels such as gasoline, kerosene, and diesel fuel/distillate heating oil. They also offer the opportunity to utilize waste fuels, such as landfill gas.

Microturbines have the potential to be located on sites with space limitations for the production of power. When more power is required, multiple units can be synchronized to meet changing demand.

Types of Microturbines

Like larger-scale industrial gas turbines, microturbines can be classified as simple cycle or recuperated.

In a simple-cycle (unrecuperated) configuration, compressed air is mixed with fuel and burned under constant pressure conditions. The resulting hot gas is allowed to expand through a turbine to perform work. Simple-cycle microturbines are simpler and less expensive to build, offer higher reliability, and have more waste heat available for use in cogeneration applications than recuperated units. But they also have lower efficiency.



A recuperated microturbine with supplementary exhaust-heat recovery for cogeneration applications. *Illustration by NREL*

Recuperated units use a sheet-metal heat exchanger that recovers some of the heat from the exhaust stream in order to boost the temperature of the airstream supplied to the combustor. If the air is preheated, less fuel is needed to raise its temperature to the level required at the turbine inlet. Recuperated units have a higher efficiency than unrecuperated units, using 30% to 40% less fuel as a result of preheating.

Further exhaust heat recovery can be implemented in a cogeneration configuration. In this case, the supplementary heat exchanger—referred to as the exhaust gas heat exchanger—transfers thermal energy from the microturbine exhaust to a hot water system. Exhaust heat can be used for a number of different applications, including potable water heating, thermally activated cooling, space heating, process heating, and other building uses.

Microturbines are also classified according to whether they use one or two shafts. A single shaft is the more common design as it is simpler and less expensive to build. A split shaft is used for machine-drive applications, which do not require an inverter to change the frequency of the AC power.

Summary

The data below represent typical values for commercially available systems.

Advantages:

- Small number of moving parts
- Compact size and lightweight
- Low emissions
- No cooling water required (microturbines are air-cooled)

Disadvantages:

- High costs
- Relatively low mechanical efficiency
- Limited to lower temperature cogeneration applications (insufficient thermal output for industrial applications)

Capacity: 25 kW to 500 kW

Power efficiency: 18%-27%

Overall efficiency in CHP applications: 65%-75%

Typical power to heat ratio: 0.4-0.7

Suitability for partial loading: Okay

Time between overhauls: 5,000-40,000 hours

Start-up time: 1 minute

Noise: Moderate

Terms and Definitions

Alternating current (AC) – A type of electrical current, the direction of which is reversed at regular intervals or cycles; in the United States., the standard is 120 reversals or 60 cycles per second.

Combustion turbine – A turbine that generates power from the combustion of a fuel.

Direct current (DC) – A type of electricity transmission and distribution by which electricity flows in one direction through the conductor; usually relatively low voltage and high current.

Harmonic(s) – A sinusoidal quantity having a frequency that is an integral multiple of the frequency of a periodic quantity to which it is related.

Power conditioning – The process of modifying the characteristics of electrical power (for e.g., inverting DC to AC).

Recuperator – A heat exchanger in which heat is recovered from the products of combustion.

Simple cycle – It differs from a combined cycle in that it has no provision for waste heat recovery.

For More Information

Gas-Fired Distributed Energy Resource Technology Characterizations
www.nrel.gov/docs/fy04osti/34783.pdf
A publication developed for the U.S. Department of Energy.

Technology Characterization: Microturbines
www.epa.gov/chp/documents/catalog_chptech_microturbines.pdf
A publication developed for the U.S. Environmental Protection Agency.

Fuel Cells

A fuel cell is an electrochemical device that converts the chemical energy in a fuel such as hydrogen into electricity and heat, without combustion. It can be thought of as a continuously operating battery that can be recharged while power is drawn from it. Whereas a battery stores and eventually runs out of electrical power, a fuel cell can generate electricity indefinitely, as long as it is provided with a fuel and oxygen.

The core of any fuel cell consists of three main parts: an anode and a cathode separated by an electrolyte (a substance capable of conducting electricity). The electrodes (the anode and cathode) are usually coated with a catalyst to speed up chemical reactions in the cell. Other layers of materials and hardware are designed to help draw fuel and air into the cell and to conduct electrical current through the cell. A fuel cell actually consists of several small cells stacked in layers (sometimes referred to as a “fuel cell stack”) rather than a single large cell.

Their cell chemistry varies but all commercially available fuel cells use air or pure oxygen and hydrogen or a hydrogen-rich fuel to generate electricity. Fuel cells can run on a variety of hydrogen-rich fuels, including domestic natural gas, petroleum fuels, gasified coal, and anaerobic digester gas. Power is produced electrochemically when positive ions (charged particles) formed at one of the electrodes pass through the electrolyte, forcing the negatively charged electrons to flow through the electrical circuit. Fuel cells produce DC electricity.

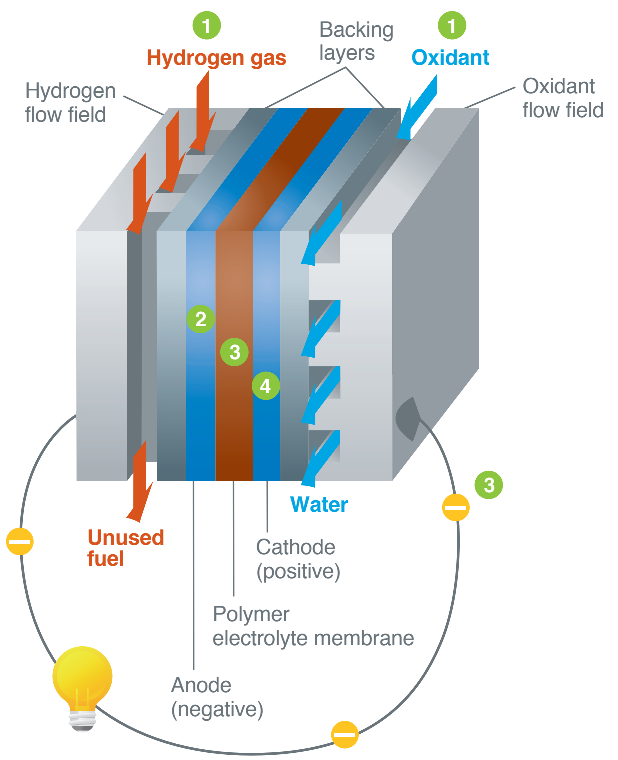
The diagram on page 66 illustrates this process using a polymer electrolyte membrane fuel cell (PEMFC), one of the most common types of fuel cell.

Fuel cells are efficient, particularly when the waste heat they create as a byproduct is used in cogeneration applications. Fuel cells that operate at higher temperatures can be fitted with heat-recovery systems to capture the waste heat and use it for water or space heating. The water produced by the cell can be used to provide humidity. Some types of fuel cells are also good at load-following.

Fuel cells produce almost zero pollutant emissions and are extremely quiet, which means they can be sited to produce and deliver electrical power in sensitive locations such as buildings. Their emissions are so low that several air quality management districts in the United States have exempted fuel cells from requiring a permit to operate.

Fuel cells are typically located outdoors where installation and maintenance are easiest. Indoor installations require a good exhaust ventilation system due to the potential risk of ozone leakage from the system, and easy access so that the fuel cell stack can be replaced at the end of its useful like. Nitrogen can “poison” a fuel cell, so fuel cells running on natural gas may require the addition of in-line nitrogen scrubbers if there is too much nitrogen in the local gas supply.

Proton Exchange Membrane Fuel Cell



1. Hydrogen fuel is channeled through field flow plates to the anode on one side of the fuel cell, while oxidant (oxygen or air) is channeled to the cathode on the other side of the cell.
2. At the anode, a platinum catalyst causes the hydrogen to split into positive hydrogen ions (protons) and negatively charged electrons.
3. The polymer electrolyte membrane (PEM) allows only the positively charged ions to pass through it to the cathode. The negatively charged electrons must travel along an external circuit to the cathode, creating an electrical current.
4. At the cathode, the electrons and positively charged hydrogen ions combine with oxygen to form water, which flows out of the cell.

Diagram showing how a fuel cell works, using a PEMFC as an example. Hydrogen is fed to the anode where a catalyst encourages the hydrogen atoms to release electrons and become hydrogen ions (protons). The electrons travel through an electric circuit as current that can be utilized before it returns to the cathode side of the fuel cell. At the same time, the protons diffuse through the membrane to the cathode, where the hydrogen atom is recombined and reacted with oxygen to produce water and heat. *Illustration by NREL*

Although it will take another 5-10 years before fuel cell cars are available for consumer purchase, stationary fuel cells are commercially available today.

Current Fuel Cell Types

Fuel cells are typically classified according to the type of electrolyte they use. There are five primary types of stationary fuel cells on the market or under development today. The table below shows some of the key operating characteristics of these systems. Efficiencies noted in the table are typical values reflecting the current state of the technology, not future projections.

Most fuel cell technologies are best suited to continuous operation because of their long start-up times. Start-up of a 100-kW or larger fuel cell system can take several days depending on the technology: phosphoric-acid fuel cell (PAFC) technology has a one-day start-up while molten-carbonate fuel cells (MCFCs) can take up to three days. Large solid-oxide fuel cells (SOFCs) can take even longer than three days to get to their efficient operating temperature.

With a lower operating temperature and faster start-up times, PEMFCs are suitable for use in vehicles and for backup power in stationary applications.

Alkaline

Since the 1960s, alkaline fuel cells (AFCs) have been the primary source of power and drinking water for space missions, including Gemini, Apollo, and the space shuttle.

Operating Characteristics of Fuel Cell Types

Fuel Cell Technology	Electrolyte	Operating Temperature	Electrical Efficiency	Total Efficiency
Alkaline	Potassium hydroxide	23°-250°C	40%-60%	60%-70%
Solid oxide	Solid metal oxide	700°-1,000°C	45%-50%	65%-80%
Phosphoric acid	Phosphoric acid	~200°C	35%-40%	70%-80%
Polymer electrolyte membrane	Ion exchange membrane	50°-100°C	30%-40%	50%-65%
Molten carbonate	Molten alkali carbonates	600°-700°C	45%-55%	70%-80%

These fuel cells typically use a solution of potassium hydroxide in water as the electrolyte and can use a variety of nonprecious metals as a catalyst at the anode and cathode. Traditional, high-temperature AFCs operate at 100°C to 250°C, and newer AFC designs operate at roughly 23°C to 70°C.

The most efficient fuel cell technology in electric-only applications, widespread adoption of AFCs has been hindered by the fact that this type of fuel cell is easily poisoned by CO_2. Even the small amount of CO_2 in the air can affect this cell's operation, making it necessary to purify both the hydrogen and oxygen used in the cell. This purification process is costly. Susceptibility to poisoning also affects the cell's longevity (the amount of time before it must be replaced), further adding to cost.

Another limiting factor is that today's AFCs maintain sufficiently stable operation for only about 8,000 operating hours. To be economically viable in utility applications, AFCs need to reach operating times of 40,000 hours or more, something that has not yet been achieved due to material durability issues. This is possibly the most significant obstacle in commercializing this fuel cell technology.

A U.S. company has patented an AFC that runs on hydrogen made from readily available liquid ammonia. The ammonia is stored in tanks and fed through an ammonia cracker, similar to the catalytic converters used in automobiles, to produce hydrogen. This technology could jump-start the hydrogen economy as ammonia is the second most common chemical produced in the world, and can be made from natural gas or with renewable energy.

Solid Oxide

SOFCs use a hard, nonporous ceramic compound as the electrolyte. Because the electrolyte is a solid, the cells do not have to be constructed in the plate-like configuration typical of other fuel cell types. The solid-state ceramic construction enables high temperatures, allows more flexibility in fuel choice, and contributes to stability and reliability.

Most SOFCs operate at very high temperatures—around 1,000°C, making them particularly suitable for CHP applications. High-temperature operation removes the need for a precious-metal catalyst, thereby reducing cost. It also allows SOFCs to reform fuels internally, which enables the use of a variety of fuels and reduces the cost associated with adding a reformer to the system.

SOFCs are the most sulfur-resistant type of fuel cell; they can tolerate several orders of magnitude more sulfur than other cell types. Nor are they poisoned by carbon monoxide, which allows SOFCs to use gases derived from coal.

High-temperature operation has some disadvantages. It results in a very slow start-up and requires significant thermal shielding to retain heat and protect personnel, which may be acceptable for utility applications but not for small portable applications. The high operating temperatures also place stringent durability requirements on materials. The development of low-cost materials with high durability at cell operating temperatures is the key technical challenge facing this technology.

Phosphoric Acid

PAFCs use liquid phosphoric acid as an electrolyte, contained in a Teflon-bonded silicon carbide matrix. They use porous carbon electrodes with a platinum catalyst.

A PAFC is considered a "first generation" technology. It is the most common type of fuel cell because PAFCs were the first to be used commercially. This type of fuel cell is typically used for stationary power generation, but a few PAFCs have been used to power large vehicles such as city buses.

PAFCs are more tolerant of impurities in fossil fuels that have been reformed into hydrogen than PEMFCs.

PAFCs are less powerful than other fuel cells, given the same weight and volume. As a result, they are typically large and heavy. PAFCs are also very expensive due to the cost of the platinum catalyst.

Polymer Electrolyte Membrane

PEMFCs—also called proton exchange membrane fuel cells—use a solid polymer as an electrolyte and porous carbon electrodes containing a platinum catalyst. The proton exchange membrane is essentially a thin plastic sheet that allows hydrogen ions to pass through it.

PEMFCs deliver high power density and have a lower weight and volume than other fuel cells. They operate at relatively low temperatures, typically around 80°-90°C. Low-temperature operation allows them to start quickly (less warm-up time) and causes less wear on system components, resulting in better durability.

PEMFCs need only hydrogen, oxygen from the air, and water to operate and do not require corrosive fluids like some fuel cells. They can vary their output quickly to meet shifts in power demand, and are well-suited for applications where quick start-up is an asset (e.g., transportation and backup power generation).

The platinum catalyst is extremely sensitive to carbon monoxide poisoning. Carbon monoxide binds to the catalyst at the anode, decreasing the fuel cell's efficiency. This makes it necessary to use an additional in-line reactor to reduce carbon monoxide in the fuel gas if the hydrogen is derived from an alcohol or hydrocarbon fuel. This adds to the cost of the system, and developers are currently exploring platinum/ruthenium catalysts that are more resistant to carbon monoxide.

Molten Carbonate

MCFCs use an electrolyte composed of a molten carbonate salt mixture suspended in a porous, chemically inert ceramic lithium aluminum oxide matrix. They operate at extremely high temperatures (650°C and above), so nonprecious metals can be used as catalysts at the anode and cathode, reducing costs.

MCFCs are currently being developed for natural gas and coal-based power plants for electric utility, industrial, and military applications. MCFCs have been operated on hydrogen, carbon monoxide, natural gas, propane, landfill gas, diesel fuel, and simulated coal gasification products.

Molten carbonate technology is significantly more efficient than phosphoric acid technology, which is part of its appeal. And unlike AFCs, PAFCs, and PEMFCs, MCFCs don't require an external reformer to convert more energy-dense fuels to hydrogen. Due to the high temperatures at which MCFCs operate, these fuels are converted to hydrogen within the fuel cell itself by a process called internal reforming, which also reduces cost.

MCFCs are not prone to carbon monoxide or CO_2 poisoning; they can even use carbon oxides as fuel. This makes them attractive for use with gases made from coal. Because they are more resistant to impurities than other fuel cell types, they could one day be capable of internal reforming of coal.

The primary disadvantage of current MCFC technology is durability. The high temperatures at which these cells operate and the corrosive electrolyte used accelerate component breakdown and corrosion, decreasing cell life. Scientists are currently exploring corrosion-resistant materials for components as well as fuel cell designs that increase cell life without decreasing performance.

Emerging Fuel Cell Technologies

Emerging fuel cell technologies include direct-methanol and direct-carbon fuel cells.

Direct Methanol

Most fuel cells are powered by hydrogen, which is sometimes obtained by reforming hydrogen-rich fuels such as methanol, ethanol, and other hydrocarbon fuels. Direct-methanol fuel cells (DMFCs), however, are powered directly by pure methanol, which is mixed with steam and fed to the fuel cell anode without going through a reforming process.

Methanol is easier to store than hydrogen because it has a higher energy density. It is also easier to transport and supply to end users with our current infrastructure because it is a liquid, like gasoline.

DMFC technology is relatively new compared to that of fuel cells powered by pure hydrogen, and DMFC research and development are roughly 3-4 years behind other types of fuel cells.

Initial development is focused on small portable-power applications at capacities ranging from less than a watt (W) to about 100 W. DMFCs operate at 60°-90°C.

Direct Carbon

A direct-carbon fuel cell (DCFC) converts carbon to electricity at very high efficiencies. Although they still haven't entered the marketplace, DCFCs are one of the most promising of all fuel cell technologies because they can make use of one of the most abundant energy resources in the United States: coal.

DCFCs generate electricity from the reaction of carbon particles (immersed in a molten salt electrolyte at 650°-800°C) and atmospheric oxygen. Instead of burning coal to produce heat for steam turbines, DCFCs convert the energy in the coal directly to electrical power. In the lab, DCFCs do this with 80% efficiency—twice that of today's coal-fired electric utility plants and approaching the theoretical limit of energy conversion from coal.

Feedstock fuels are made by thermally decomposing fossil fuels (coal, natural gas, and petroleum) or biomass residues at low temperatures. This yields a very reactive form of carbon called "turbostratic" and a useful offgas that is rich in hydrogen and simple hydrocarbons. The feed rate for charred coal is expected to be practical for utility applications.

In baseload utilities, DCFC technology would double the electric output per ton of coal, eliminate most atmospheric pollutants, and produce very pure CO_2 that can either be sequestered or used for industrial processes.

DCFCs produce no NOx because there is no combustion. Sulfur within the coal or petroleum coke is fully exhausted as gaseous carbonyl sulfide, which is readily decomposed or sequestered. No sulfurous oxides or hydrogen sulfide are emitted. The ash in coal may be chemically extracted and reduced to levels below 0.5% at minimal cost and energy penalty. This truly is a "clean coal" technology.

Summary

The data below represent typical values for commercially available systems.

Advantages:

- Low emissions and low noise (zero emissions when using hydrogen fuel)
- High efficiency converting hydrogen to electricity
- No moving parts
- Modular design

Disadvantages:

- High costs
- Low durability and power density
- Fuels require processing unless pure hydrogen is used

Capacity: < 1 W to 3 MW

Power efficiency: 30%-605%

Overall efficiency in CHP applications: 50%-80%

Typical power to heat ratio: 1-2

Suitability for partial loading: Good

Time between overhauls: 8,000-40,000 hours

Start-up time: Varies from 2 minutes to several days

Noise: Low

Terms and Definitions

Anode – The electrode at which oxidation (a loss of electrons) takes place. For fuel cells and other galvanic cells, the anode is the negative terminal; for electrolytic cells (where electrolysis occurs), the anode is the positive terminal.

Alkaline fuel cell (AFC) – A type of hydrogen/oxygen fuel cell in which the electrolyte is concentrated potassium hydroxide and the hydroxide ions are transported from the cathode to the anode.

Catalyst – A chemical substance that increases the rate of a reaction without being consumed; after the reaction, it can potentially be recovered from the reaction mixture and is chemically unchanged. The catalyst lowers the activation energy required, allowing the reaction to proceed more quickly or at a lower temperature. In a fuel cell, the catalyst facilitates the reaction of oxygen and hydrogen. It is usually made of platinum powder very thinly coated onto carbon paper or cloth. The catalyst is rough and porous so the maximum surface area of the platinum can be exposed to the hydrogen or oxygen. The platinum–coated side of the catalyst faces the membrane in the fuel cell.

Cathode – The electrode at which reduction (a gain of electrons) occurs. For fuel cells and other galvanic cells, the cathode is the positive terminal; for electrolytic cells (where electrolysis occurs), the cathode is the negative terminal.

Cogeneration – The generation of electricity or shaft power by an energy conversion system and the concurrent use of rejected thermal energy from the conversion system as an auxiliary energy source.

Direct-methanol fuel cell (DMFC) – A type of fuel cell in which the fuel is methanol in gaseous or liquid form. The methanol is oxidized directly at the anode instead of first being reformed to produce hydrogen. The electrolyte is typically a polyelectrolyte membrane.

Electrode – A conductor through which electrons enter or leave an electrolyte. Batteries and fuel cells have a negative electrode (the anode) and a positive electrode (the cathode).

Electrolyte – A substance that conducts charged ions from one electrode to the other in a fuel cell, battery, or electrolyzer.

Feedstock – any material used directly as a fuel or converted to another form of fuel or energy product.

Ion – Atom or molecule that carries a positive or negative charge because of the loss or gain of electrons.

Molten carbonate fuel cell (MCFC) – A type of fuel cell that contains a molten carbonate electrolyte. Carbonate ions are transported from the cathode to the anode. Operating temperatures are typically near 650°C.

Polymer electrolyte membrane fuel cell (PEMFC) – A fuel cell incorporating a solid polymer membrane used as its electrolyte. Protons (H+) are transported from the anode to the cathode. The operating temperature range is generally 60°C–100°C.

Solid-oxide fuel cell (SOFC)– A type of fuel cell in which the electrolyte is a solid, nonporous metal oxide, typically zirconium oxide treated with yttrium oxide, and oxygen is transported from the cathode to the anode. Any carbon monoxide in the reformate gas is oxidized to CO_2 at the anode. Temperatures of operation are typically 800°C–1,000°C.

For More Information

California Stationary Fuel Cell Collaborative
www.casfcc.org
A public-private partnership working to advance the deployment of stationary fuel cells for distributed generation and other applications throughout the state of California.

Fuel Cell and Hydrogen Energy Association
www.fchea.org
An advocacy organization dedicated to the commercialization of fuel cells and hydrogen energy technologies.

Fuel Cell Power Analysis
www.hydrogen.energy.gov/fc_power_analysis.html
Spreadsheets from the U.S. Department of Energy (DOE) to help determine the cost of delivered energy from fuel-cell based trigeneration systems that produce electricity, thermal energy and hydrogen.

DOE Fuel Cell Technologies Program
www.eere.energy.gov/hydrogenandfuelcells/fuelcells
A program working closely with its national laboratories, universities, and industry partners to overcome critical technical barriers to fuel cell commercialization.

Gas-Fired Distributed Energy Resource Technology Characterizations
www.nrel.gov/docs/fy04osti/34783.pdf
A publication developed for DOE.

Technology Characterization: Fuel Cells
www.epa.gov/chp/documents/catalog_chptech_fuel_cells.pdf
A publication developed for the U.S. Environmental Protection Agency Combined Heat and Power Partnership Program.

Thermally Activated Technologies

As the inefficiency in electrical generation and other processes manifests itself as waste heat, cogeneration or CHP is one of the best ways to increase the efficiency of energy use. Direct use of this waste heat for water or space heating is not the only way to use excess heat to improve energy efficiency.

This section describes one technology for using heat for refrigeration or space cooling, one technology for dehumidifying air, and three technologies for generating electricity or mechanical energy from low-temperature heat sources. It also describes ways to store cooling energy to shift cooling loads to off-peak periods. Heat storage is covered in the chapter on Direct Use of Renewable Resources in this guidebook.

Thermally Activated Cooling

While perhaps not intuitively obvious, thermal energy can be used to provide space cooling. "Thermally activated cooling systems" (TACS) include absorption cooling and desiccant dehumidification. Also known as "gas cooling" or "gas chilling" because they are commonly driven by natural gas or propane heat, TACS technologies are relatively expensive at this point (although new, lower-cost products are entering the market). They are generally most cost effective when they can be driven by waste heat such as from boilers or fuel cells, or by nonfuel energy such as geothermal or solar-heated water.

Absorption Cooling

When a low-boiling-point pressurized liquid escapes through a jet to a lower-pressure chamber, it vaporizes rapidly, absorbing heat in the process. This is the effective action of most refrigeration and cooling technologies. In electrically driven systems, the refrigerant is mechanically pressurized in a vapor compressor to allow the cycle to repeat.

Large commercial buildings are usually air conditioned by circulating chilled water through air handlers and fan coil units. The chilled water is produced by electrically powered equipment (called water chillers) that removes heat from the returning water and rejects that heat to the atmosphere. Absorption cooling is a way to produce the chilled water by using much less prime energy (electricity) to compress the refrigerant, instead of relying on waste or low-cost heat to do most of the work.

All absorption chillers use a working pair of fluids with a high affinity for each other: one is a refrigerant (absorbate), and the other an absorber. These fluids are separated and recombined in the absorption cycle.

Instead of pressurizing the vaporized refrigerant with an electric compressor, it is absorbed into the absorber. The mixed working fluid is then pumped up to a higher pressure in a liquid pump. Because the liquid working fluid is largely incompressible, this pumping process does not require much energy compared with the vapor compression process. If electricity is available, an electric pump can be used at this stage; if not, a heat engine (e.g., a Stirling engine) can be used instead.

The problem then is removing the refrigerant from the absorber, and that's where the heat source comes in. The heat essentially boils the refrigerant out of the absorber, starting the cycle again.

Two fluid combinations are in use today:

- Water (refrigerant) and lithium bromide (absorber)
- Ammonia (refrigerant) and water (absorber) — Ammonia is an excellent refrigerant with a high latent heat and excellent heat transfer characteristics. However, because of its toxicity, it is often restricted to applications in which the equipment is outdoors to allow natural dilution of any leaks.

Absorption chillers can be direct fired or indirect fired. In direct-fired units, the heat source can be gas or some other fuel that is burned in the unit. Indirect-fired units use steam or another transfer fluid that brings in heat from a separate source, such as a boiler or heat recovered from an industrial process.

The first absorption chillers were single-stage systems, which use a cycle consisting primarily of an evaporator, an absorber, a generator, and a condenser (see the diagram on page 71). Adding stages increases the efficiency of the overall system. Double-stage chillers, incorporating a second generator and condenser, were introduced in the 1950s. Triple-stage chillers are just now emerging into the marketplace.

These are the individual steps in a simple absorption-cooling cycle:

- The refrigerant evaporates in the evaporator, absorbing heat from system water that is run through heat-transfer coils inside the evaporator, thereby chilling the water.
- The low-pressure refrigerant vapor is piped to the absorber, where it is absorbed by the liquid absorbent.
- The fluid mixture is then pumped up to a higher pressure and piped to the generator.
- In the generator, heat is applied to boil the refrigerant out of the absorber at the higher pressure. This higher pressure refrigerant vapor is piped to the condenser.
- In the condenser, the refrigerant vapor is converted back to a liquid by piping in cooling water (through heat transfer coils) and rejecting heat to the surroundings.
- The liquid refrigerant is expanded to a low-pressure mixture of liquid and vapor (in the expander valve), which boils in the evaporator section. The cycle is then repeated.

The combination of the absorber-pump-generator is often referred to as a thermal compressor. The net effect of the thermal compressor is to raise the pressure of the working fluid and drive it through the condenser and evaporator.

Absorption cooling is less efficient than mechanical cooling, so typically makes the most sense economically if electricity is unavailable or highly expensive, or if a cogeneration or other substantial heat source is available at little cost. Although mainly used in industrial or commercial settings, absorption chillers are now commercially available in sizes suitable for larger residential homes (4,000 square feet or more).

Cooling is generally the primary cause of sharp spikes in a building's electric-load profile. Absorption cooling can flatten the peaks in a building's electric load. Absorption chillers are a good solution in situations where there are:

- High electric peak-demand charges or extended ratchet electricity rates
- Coincident needs for air conditioning and heating.

Hybrid systems, which are relatively common, combine gas systems and electric systems for load optimization and flexibility. Many hybrid systems use an electric chiller for baseload needs and an absorption chiller for peak loads.

Desiccant Dehumidification

Humidity control is a major element of any air-conditioning system, and is especially important in office buildings or in commercial buildings that include refrigeration, such as supermarkets.

A desiccant is a drying agent, or sorbent, that has a high affinity for water. Examples include silica gel, activated alumina, and lithium chloride salt. A desiccant can remove moisture from the air used to condition a building space, and then subsequently be regenerated (reactivated) by being heated to drive off the absorbed moisture.

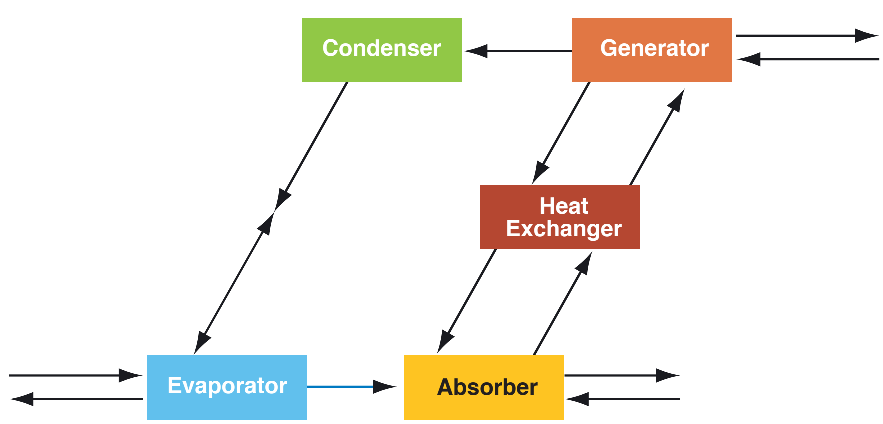
Desiccant dehumidification is considered a cooling technology because it can reduce the need for electrically driven cooling, allowing air conditioners of smaller capacity to be installed. Desiccant systems can work in tandem with chillers or conventional air-conditioning systems to significantly increase overall system energy efficiency. They do this by avoiding the overcooling (and subsequent reheating) of air that would otherwise be required simply to dehumidify the air. Desiccants can run off natural gas, solar energy, or the waste heat from distributed generation technologies, with system efficiency approaching 80% in CHP mode.

Desiccants can be solid or liquid. Solid desiccants are typically used in slow-moving "wheels" that rotate a batch of desiccant into an airstream needing dehumidification, and then rotate that batch to another point where it is heated by a warm regeneration airstream to remove the absorbed moisture. The warmer, humid exhaust air is then vented to the outside.

The sorption process creates some heat that is released into the exiting process air. This heat is removed by a heat exchanger before the air is circulated through the building's interior.

Instead of using a wheel, liquid desiccant systems spray the process air with a desiccant (lithium chloride or glycol solutions) to remove moisture. This happens in a "conditioner," a large box in which process air enters from the bottom and desiccant is sprayed into the box at the top. As the desiccant spray falls through the rising process air, it absorbs moisture and then collects at the bottom of the conditioner. The diluted desiccant solution is then pumped to a separate regenerator, where heat is applied to the solution to release its sorbed water into an exhaust airstream.

Using desiccant materials to remove moisture from air can improve air-comfort systems in several ways. For conventional air conditioners, desiccants can remove the latent heat of the water vapor in the incoming air (reducing the cooling energy it would take to condense the water). They can reduce or eliminate the inefficiency of needing to cool air below the dew point (below comfort level) to remove moisture and then warm it back up to an appropriate temperature. Desiccant technology can also be used in conjunction with evaporative coolers that are much more efficient than air conditioners, but cannot function with humid air.



Single-stage absorption cooling cycle (indirect-fired lithium bromide system).
Illustration by NREL

Thermal Recovery for Shaft or Electrical Power

Using excess heat from an electrical generator for water or space heating is the most common way to implement cogeneration, but there are other possibilities. Low-temperature waste heat, which may not be hot enough for effective heating or cooling, can be used to produce mechanical or electrical power. Potential sources of energy include excess heat from building heating, ventilation, and air-conditioning equipment.

Thermoelectric Power Generation

Heating (or cooling) one end of a junction of two dissimilar metals (or of p-type and n-type semiconductor materials) can generate electrical flow between them. Thermocouples use this phenomenon to measure temperature, but it can also generate usable power.

While not widely available commercially—the reverse operation, applying current to create a cooling effect, is more common—thermoelectric generators would be a simple way to generate electricity from the excess heat available from a boiler or other building systems. The higher (or colder) the temperature, the more efficient the electrical generation, but even relatively moderate temperatures can be used.

Organic Rankine Cycles

The Rankine cycle is the steam turbine technology used for most electric power generation. Water is boiled (by burning fuel or otherwise); the steam drives a turbine, which turns an electrical generator shaft; and the steam is condensed backed to water by cooling to repeat the cycle.

Organic Rankine generators use organic chemicals such as petroleum derivatives as working fluids. If they have significantly lower boiling points than water, this allows them to work with lower temperature heat sources such as the waste heat that might be generated by building mechanical systems. If a mechanical use for the power is available, the turbine can be used directly to turn a shaft without driving an electrical generator.

A noteworthy company in this field is Ormat Technologies Inc., which developed an organic Rankine cycle generator for geothermal power applications and then applied it to waste-heat applications. The company has found applications for its technology at gas compressor stations, gas processing plants, cement plants, and other industrial facilities.

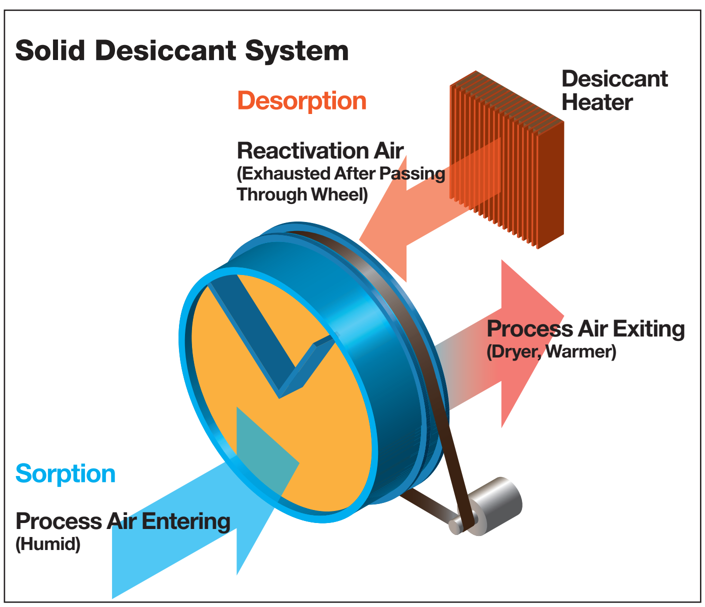
Stirling Engines

While Rankine cycle turbines use the power of a liquid expanding to a gas or vapor, Stirling engines use only a single-phase gaseous medium. The gas is maintained close to a constant temperature, so it expands as it is externally heated, driving a piston; the piston then retracts as external cooling contracts the gas.

As with thermoelectric generation and Rankine turbines, and particularly for low-temperature heat sources, the ambient or cooling side of the device is also very important. It is really the temperature difference more than the heat-source temperature itself that makes power generation possible.

As with Rankine turbines, Stirling engines are good for mechanical energy if they can directly drive a piston or turn a shaft. They are also commonly coupled with a generator to produce electricity.

While none of these thermal recovery technologies are widely used, all are good possibilities for using low-temperature heat sources such as might be available from building mechanical systems.



A solid desiccant system. Process air passes through the bottom of the wheel. Heated reactivation air passes through the top of the wheel. *Illustration by NREL*

Cool Storage

Commercial space cooling currently accounts for 20%-40% of most utilities' summer peak demand. Cool storage is a technique for shifting all or part of a building's air-conditioning requirements from peak to off-peak hours. Refrigeration equipment is typically operated at night to make ice or chilled water, which is stored in insulated tanks and used the next day to meet all or part of a building's cooling requirements.

The use of thermal storage in commercial buildings has grown steadily over the past decade. Today, there are more than 1,000 cool-storage systems in the United States. Cool-storage systems can use ice, chilled water, or phase-change materials. Water and ice are by far the most common. Systems can be designed for full storage, in which 100% of the cooling load is moved off peak, or partial storage, in which only part of the load is moved off peak, and the rest is met by the chiller.

Most cool-storage systems are installed in buildings during construction. Cool-storage systems can also be retrofitted into existing buildings, although the cost is higher and the installation may be difficult. Additionally, chilled water systems, in particular, take up substantial amounts of floor space. Packaged cool-storage systems, which are now being marketed by a number of manufacturers, facilitate the retrofitting of cool-storage systems in medium-sized buildings.

Operating savings are greatest when demand or energy charges vary by time of day. For new buildings, first-cost savings from downsizing the chiller capacity and operating-cost savings due to lower demand, pay for some—and in some cases all—of the costs of storage. Also, lower operating temperatures allow fans, pumps, and ducts to be downsized, further reducing first costs.

Cool storage is most effective in buildings that have a high, narrow cooling-load profile. During a utility's on-peak period, office, retail, and health facilities are prime candidates for this technology, followed by schools, colleges, restaurants, and lodging facilities. Because existing chillers can be used with chilled water systems, these systems may suit retrofit applications better than ice storage systems.

Terms and Definitions

Absorption chiller/cooler or gas chiller/cooler – Heat–driven technology that uses the cooling effect of liquid evaporating to chill water for use in refrigeration or space–cooling systems.

Absorption heat pump or gas heat pump – Heat–driven technology that can use the cooling effect of liquid evaporating for either space heating or space cooling.

Compressor – A device used to compress air for mechanical or electrical power production, and in air conditioners, heat pumps, and refrigerators to pressurize the refrigerant and enabling it to flow through the system.

Condenser – The device in an air conditioner or heat pump in which the refrigerant condenses from a gas to a liquid when it is depressurized or cooled.

Desiccant – Soluble, insoluble, or liquid chemical with high affinity for water that can be used to absorb moisture and subsequently release it upon heating.

Desorption – A phenomenon whereby a substance is released from or through a surface; the opposite of sorption.

Generator – A device for converting mechanical energy to electrical energy.

Kalina cycle – A thermodynamic cycle that converts heat into work by boiling a working fluid mixture, such as water and ammonia, to drive a turbine.

Latent heat – The amount of heat absorbed by a substance as it changes state from solid to liquid or liquid to gas or conversely released in changing from gas to liquid or liquid to solid.

Organic chemicals – Chemical compounds based on carbon chains or rings, including volatile petroleum derivatives.

Rankine cycle – A thermodynamic cycle that converts heat into work by boiling water or another pure fluid to drive a turbine.

Semiconductors – Silicon and other crystalline materials, with electrical conductivity somewhere between conductors and insulators, that can be manipulated to perform various microelectronic functions:

- *n–type* – Semiconductor materials having more negative electrons than positive electron vacancies, or "holes."
- *p–type* – Semiconductor materials having more positive electron holes than electrons.

Sorption – A physical and chemical process by which one substance becomes attached to another; the opposite of desorption.

Stirling engine – A closed–cycle heat engine with a gaseous working fluid. Unlike similar simpler hot air engines, Stirling engines include regeneration, increasing efficiency with an internal heat exchanger.

Thermally activated cooling systems (TACS) – Technologies using heat energy for chilling water, refrigeration, or space cooling.

Thermoelectric effect – Direct conversion of temperature differences to electric voltage and vice versa.

For More Information

Modern Industrial Assessments: A Training Manual — Chapter 7 "Thermal Applications"
iac.rutgers.edu/redirect.php?rf=industr_ch7
A U.S. Department of Energy (DOE)-sponsored training manual from Rutgers University.

Review of Thermally Activated Technologies
www.eere.energy.gov/manufacturing/distributedenergy/pdfs/thermally_activated_techreview04.pdf
A report developed for the DOE Distributed Energy Program.

Thermally Activated Technologies
www.eere.energy.gov/manufacturing/distributedenergy/tat.html
An overview from the DOE Advanced Manufacturing Office about absorption chillers, cycle analysis, ammonia-water absorption systems, and desiccants.

Novel Technologies

This section looks at a handful of unusual distributed power-generation technologies that could be in our future. Some of these technologies are already in use sporadically; others are still on the horizon.

Biofuels from Algae

The first generation of biofuel technology involves producing ethanol from the carbohydrate-rich parts of plants (such as corn kernels) and producing biodiesel from oil-seed crops (such as soybeans). The second generation of ethanol technology will use the inedible, fibrous parts of plants such as cornstalks and alfalfa stems to produce "cellulosic ethanol."

In the relatively near future, ethanol and biodiesel will both be produced from microorganisms, particularly algae. Some species of algae naturally contain oil that can be extracted and used to produce fuels for transportation, power generation, and heating. The algae are grown either in open-air ponds or in closed bioreactors. Today, open-air ponds are significantly cheaper, producing oil for $9/gallon to $18/gallon. Oil from a bioreactor would cost twice that.

Current algal biofuels technology is expected to be commercially viable sometime between 2013 and 2018.

The production of biofuels from algae has several advantages over earlier approaches:

- With current technology, algae produce about 20 times more biofuels per acre than the most productive standing crop—around 1,000 gallons per acre per year, compared to 48 gallons from soybeans—in part due to their very rapid growth rate. Researchers expect further development to push yields as high as 5,000 gallons per acre per year.
- Algae can be grown on marginal lands that cannot be used for row crops.
- Algae can be harvested every day of the year, unlike row crops.

DOE conducted research into algal biofuels during the 1980s and 1990s but ended the program at a time when fossil oil cost only $20 a barrel. High oil prices revived the technology, and researchers are currently working on further increasing oil yields through genetic engineering and other approaches.

One of the most intriguing methods to increase algal oil production also solves another problem—pollution from power plants. Since 2005, Arizona Public Service Company has been conducting a demonstration project that involves trapping the CO_2 emissions from a power plant and transferring them to a greenhouse filled with containers of algae. The algae are periodically harvested, and their starches turned into ethanol and their lipids into biodiesel, fuels which are used to run a passenger vehicle on site.

This approach does not permanently remove carbon from the atmosphere, as the CO_2 that is captured during the growth of any biofuel crop is released when the fuel is burned in a vehicle engine or diesel generator. This is why biofuels from dedicated energy crops are referred to as "carbon neutral." But it doesn't add new CO_2 to the atmosphere—unlike traditional coal, oil, or natural gas power plants—so is likely to play an increasing role as greenhouse-gas reduction becomes a stronger priority.

This development also represents a convergence of technologies and a fading of the distinction between power generation and the production of vehicle fuels.

Microbial Fuel Cells

Researchers at U.S. and Canadian universities have produced a "microbial fuel cell" that generates 350 W of electricity per square meter. The device uses a proton exchange membrane, just like a conventional hydrogen fuel cell, but with microbe-rich wastewater flowing on one side of the cell and air on the other. The fuel cell captures electrons that are naturally released by bacteria as they digest organic matter, and the system generates electricity while simultaneously removing organic waste from the water, purifying it.

Unlike conventional fuel cells, microbial fuel cells are unlikely to be used in vehicles or houses but in locations where there is a high concentration of organic matter such as at sewage treatment plants, hog farms, and food processing plants.

Vehicle-to-Grid Technology

Hybrid electric vehicles (HEVs), incorporating both an electric motor and an internal combustion engine (ICE), are substantially more fuel efficient than conventional ICE-powered vehicles and hence are growing in popularity. Because they require an onboard energy storage device (i.e., a battery), HEVs have the potential to provide support to the grid—if only the battery pack were bigger.

"Plug-in" hybrid electric vehicles (PHEVs) are currently in production, and they have extra batteries that can be recharged from either the power grid or the vehicle ICE's alternator. The intention behind this development is to allow the vehicle to be driven 20-50 miles (longer than the typical daily mileage for the average car) solely on cheap, clean, grid electricity, but still have an easily refillable fuel tank for longer trips. PHEV batteries will be big enough that, in the aggregate, they could be a substantial energy resource. Purely electric vehicles are also in production, and they have even larger battery packs.

This technological development essentially involves making the plug-in "reversible" so that electricity can flow both ways. Called "vehicle-to-grid" or "V2G" technology, a two-way plug allows the home and vehicle owner and local utility to take advantage of the extra electrical storage capacity in the vehicle batteries to meet peak demand, provide grid support services, or respond to power outages. Utilities pay premium rates for peak and backup power and could pay commuters to plug their vehicles in while at work to ensure their employer has high-quality power throughout the day.

V2G technology works with any vehicle that incorporates electric drive and a battery or other electricity storage system, including fuel cell vehicles and all-electric cars. The vehicles will be equipped with sophisticated power electronics that will allow the utility, with the owner's permission, to decide when to charge the vehicle batteries and when to draw power from them for the grid, making sure that the battery pack doesn't get too depleted. The idea is to use abundant off-peak electricity to charge the batteries and to draw on the spare vehicle battery capacity during peak periods, essentially helping to level the utility's load profile. This would reduce the need for excess generating capacity and spinning reserves, improving the overall efficiency of the power grid.

V2G also makes it easier to buffer the varying output of intermittent renewable power generators, which could allow for greater use of solar and wind power. Estimates indicate that if one-third of the vehicles in the United States were V2G-capable, it would allow half of the generating capacity on the power grid to come from wind power.

Distributed Nuclear Power

Small nuclear power plants are currently available for distributed generation applications, although none have been installed in the United States, and future permitting is far from certain.

These modular nuclear plants are sometimes called "nuclear batteries" because they do not require refueling for decades and use a sealed design similar to a dry-cell alkaline battery. This allows them to be sunk deep into the ground and encased in so much concrete that they are hard to breach using explosives. This removes most of the security and safety concerns except for large-scale terrorist attacks.

There is a native community in Galena, Alaska, that wants to host a modular nuclear plant made by the Japanese firm, Toshiba. Called the "Toshiba 4S" (Super Safe, Small and Simple), the 10-MW Toshiba reactor has no moving parts and is roughly 60 feet tall and 8 feet in diameter. The reactor would be encased in several tons of concrete and would be sealed during its operating life, estimated at 30 years.

While the Galena application is undergoing a lengthy review by the Nuclear Regulatory Commission, the community reaffirms its desire for the plant through a council vote and resolution every two years. There are, however, some significant stumbling blocks to the Galena plant:

- Reaching agreement on ownership of the plant (and hence accountability for it should something go wrong)
- Reaching agreement on the number of security guards required; Toshiba and the Galena residents feel the security standard set for conventional nuclear plants is excessive and unnecessary for nuclear batteries.
- The fact that Alaska state law prohibits the use of state funds for nuclear power projects; either federal funds would have to be obtained or state legislators would have to amend Alaska law.

In addition, although it used a completely different design than the proposed Galena facility, the March 2011 nuclear power plant accident at Fukushima, Japan, has caused many nuclear nations, including the United States, to more closely evaluate whether nuclear power should be a part of their energy supply mix. Public concern is likely to have a dampening effect on the future expansion of nuclear power systems, especially new, unproven designs such as nuclear batteries.

Terms and Definitions

Algae – Simple photosynthetic plants containing chlorophyll, often fast growing and able to live in freshwater, seawater, or damp oils. May be unicellular and microscopic or very large, as in the giant kelps.

Biofuels – Biomass converted to liquid or gaseous fuels such as ethanol, methanol, methane, and hydrogen.

Cellulose – A carbohydrate that is the principal component of wood. It is made of linked glucose molecules (a six–carbon sugar) that strengthen the cell walls of most plants. Cellulosic/woody biomass contains cellulose components.

Ethanol – A colorless, flammable liquid produced by fermentation of sugars. Ethanol is used as a fuel oxygenate; the alcohol found in alcoholic beverages.

Fuel Cell – An electrochemical device that converts chemical energy directly into electricity.

Hybrid electric vehicle (HEV) – A vehicle powered by two or more energy sources, one of which is electricity. HEVs may combine the engine and fuel of a conventional vehicle with the batteries and electric motor of an electric vehicle in a single drivetrain.

Nuclear power – Energy that comes from splitting atoms of radioactive materials, such as uranium, and which produces radioactive wastes.

Polymer electrolyte membrane (PEM) – A fuel cell incorporating a solid polymer membrane used as its electrolyte. Protons (H+) are transported from the anode to the cathode. The operating temperature range is generally 60°C–100°C.

For More Information

Algal Biofuels
www.eere.energy.gov/biomass/algae.html
Information on the U.S. Department of Energy's (DOE's) algae R&D portfolio and the Algal Biofuels Consortia Initiative.

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Small Modular Reactor Program
smr.inl.gov
Information from Idaho National Laboratory and the DOE Office of Nuclear Energy on small modular reactor technologies.

The Grid-Integrated Vehicle with Vehicle-to-Grid Technology
www.udel.edu/V2G
A website from the University of Delaware on grid-integrated vehicle and V2G technologies.

Microbial Fuel Cells
www.microbialfuelcell.org
A website devoted to microbial fuel cells or more generally bio-electrochemical systems.

ENERGY STORAGE AND HYBRID POWER

The demand for electricity is seldom constant over time. Excess generating capacity available during periods of low demand can be used to charge an energy storage device. The stored energy can then be used to provide electricity during periods of high demand, helping to reduce power system loads and electricity bills during these times.

Storing electrical energy can improve the efficiency and reliability of the electric utility system by reducing the requirements for spinning reserves to meet peak-power demands, making better use of efficient baseload generation, and allowing greater use of renewable energy technologies. A "spinning reserve" is a generator that is spinning and synchronized with the grid, ready for immediate power generation—like a car engine running with the gearbox in neutral.

The independent system operator (ISO) is required to maintain a certain amount of reserve-generating capacity that is ready for immediate power production. The term "spinning" derives from the definition that spinning reserves must have generators spinning and synchronized with the grid, ready for immediate power generation when it is needed.

Many renewable resources—wind and solar power, for example—are variable, i.e., they are not available all of the time. Storing energy from the renewable source allows supply to more closely match demand. For example, a storage system attached to a wind turbine could store energy captured around the clock—whenever the wind blows—and then dispatch that energy into the higher-priced, midday market. And energy storage allows solar electricity to be used both day and night.

By reducing peak demands for power generation and offering greater flexibility among power supply options (including renewables), energy storage systems not only help utilities by improving their cost-effectiveness, reliability, power quality and efficiency, they also reduce the environmental impact of electricity generation, transmission, and distribution.

In addition to saving money by using energy storage to shift loads away from periods when electricity is expensive, businesses, industry, and homeowners can use energy storage to provide an alternative source of power when grid electricity fluctuates or fails. Uninterruptible power supply (UPS) systems consist of a storage technology mated to control electronics that convert stored energy to alternating current (AC) electricity and dispatch it as needed (e.g., to provide full power during an outage or to smooth out power quality problems).

UPS systems provide high-quality power to equipment and facilities that cannot tolerate even brief outages, such as for computers, medical equipment, and sensitive industrial processes. Batteries are the most common storage devices used in UPS systems, but not the only ones. Flywheels, supercapacitors, and supercooled electromagnets can also be used.

This chapter describes electrical energy storage technologies that are suitable for either distributed installations or central grid support, and which are currently in use or under consideration by electric utilities and other users. It also covers hybrid power systems, which typically incorporate an energy storage technology along with a power generation technology. (Thermal energy storage is covered under Thermally Activated Technologies in the chapter on Nonrenewable Distributed Energy Technologies.)

Batteries

Batteries are the most common device used for storing electrical energy. A battery is a device that stores chemical energy in its active materials and converts it, on demand, into electrical energy by means of an electrochemical reaction. An electrochemical reaction is a chemical reaction involving the transfer of electrons, and it is that reaction that creates electricity.

There are three main parts of a battery: the anode, cathode, and electrolyte. The anode is the negative “fuel” electrode, which gives up electrons to the external circuit to create the flow of electrons or electricity. The cathode is the positive oxidizing electrode which accepts electrons from the external circuit. The electrolyte carries the electric current, as ions, inside the cell between the anode and cathode.

Batteries consist of one or more basic electrochemical units called cells. Cells are usually connected in series to increase the voltage. For example, two 1.5-volt (V) cells connected in series make a 3-V battery. Batteries or cells are traditionally made from select chemistries that have high energy content.

Utility battery storage systems allow utilities or utility customers to chemically store electrical energy for dispatch at a time when its use is more economical, strategic, or efficient. The suitability of a battery system to utility applications is affected by factors such as its response time, power density (the amount of power available from a battery in relation to its mass or volume), discharge rate, and life-cycle costs.

The three main applications for utility-scale battery energy-storage systems include spinning reserve at generating stations, load leveling at substations, and peak shaving on the customer side of the meter. Battery storage has also been suggested for holding down air emissions at power plants by shifting the time of day of the emission or shifting the location of emissions.

Careful integration with power electronics is the key to successful use of batteries for energy storage.

Lead-Acid Batteries

Lead-acid batteries are the most common type of battery in both utility and nonutility applications. The traditional lead-acid battery is made up of plates (a lead anode and lead dioxide cathode) immersed in a solution consisting of approximately 35% sulfuric acid and 65% water. This solution is the electrolyte, which causes a chemical reaction that produces electrons. Various other elements can be used to change the density, hardness, and porosity of the plates.

When you test a battery, you are measuring the amount of sulfuric acid in the electrolyte. If the reading is low, the chemistry that makes electrons is lacking. The sulfur has become stuck to the battery plates and will return to the electrolyte when the battery is recharged.

A couple of variations on the traditional design have emerged:

- **Gel-type lead-acid batteries** — Filled with a gel instead of liquid, which makes them much less likely to spill, they are very robust and can take more heat and charge abuse than traditional lead-acid batteries. These are becoming popular in Europe although they are somewhat more expensive than traditional lead-acid batteries.
- **Valve-regulated lead-acid (VRLA) batteries** — Sealed and need no topping off with water, so they require less maintenance than regular lead-acid batteries. VRLA batteries are popular in distributed power applications.

Lead-acid batteries are widely used, inexpensive, and have fairly well-known operating characteristics. This is the most prevalent battery type used for vehicle starting and ancillary power functions. Lead-acid batteries also provide backup power for utility companies, telecommunications systems, and hospitals; and are used as power sources for golf carts, forklifts, and other small motorized vehicles.

New developments in VRLA technology might revolutionize this well-established technology. A number of manufacturers are producing prototype batteries that promise to overcome the main disadvantages of VRLA batteries by using special carbon formulations in the negative electrode. The added carbon inhibits hard sulfating, which minimizes or eliminates many common sources of battery failure, e.g., premature capacity loss and water loss. In cycling applications, this new VRLA technology could dramatically lower battery energy costs by increasing cycle life, efficiency, and reliability.

Flow Batteries

Flow batteries work in a similar fashion to lead-acid batteries, but the electrolyte is stored in external containers and circulated through the battery cell stack as required. This external reservoir of rechargeable electrolyte can be as large as needed, and situated where convenient. Some flow batteries use two different kinds of electrolyte that are separated by a membrane in the battery itself and stored separately.

Types of flow battery currently undergoing development include:

- **Vanadium redox batteries** — Use plastic bags to store the electrolyte. The bags can be stuffed into available crawl space and other residual areas.
- **Zinc bromine batteries** — Use a zinc-bromide electrolyte. Metallic zinc is deposited on the negative electrode and the bromine produced at the positive electrode is stored in external tanks. The zinc deposited during the charging process must be completely removed

periodically. These batteries are available off the shelf and have been widely deployed.

The great advantage to flow batteries is that their electrical storage capacity is limited only by the capacity of the electrolyte storage reservoirs. They provide very high power and very high capacity batteries for load-leveling applications on the electricity grid.

Flow batteries offer potentially higher efficiencies and longer life than conventional lead-acid batteries. Their key advantage is that they can be a truly closed system with an electrolyte that is regenerated, rather than having to be replaced.

Another advantage is that flow batteries can cycle quickly and deeply at either high or low power output with minimal degradation. They are scalable from a few kilowatt-hours (kWh) to hundreds of megawatt-hours (MWh).

Advanced High-Temperature Batteries

High-temperature batteries are so-called because they have a liquid (molten) sodium anode that requires the battery be kept at a high operating temperature, typically above 270°C (518°F).

There has been interest in sodium since the mid-1960s because it promises batteries with very high power and energy densities. Sodium has a high reduction potential and low weight; and is nontoxic, relatively abundant, and inexpensive. Unfortunately, the construction of practical batteries requires that the sodium be molten, creating safety concerns and issues of thermal management. Sodium also has a highly exothermic reaction with water, so leaks or component failures can present significant safety issues.

The most common types:

- **Sodium sulfur —** The electrolyte consists of a hollow tube of beta alumina filled with molten sodium (the anode). This tube is partially immersed in a bath of molten sulfur (the cathode). Sodium sulfur batteries are used most extensively in Japan, which has the world's largest installation, a 34-megawatt (MW), 245-MWh unit used to stabilize local wind power. Smaller installations exist in the United States.
- **Sodium nickel chloride —** Also called "Zebra" batteries, originally developed for motive power and now being used for peak shaving and other utility applications. This is a more recent technological development that uses a molten-sodium anode and a solid-metal cathode of nickel chloride. This technology is safer than sodium-sulfur batteries and allows larger cells to be constructed.

The safety concerns with these batteries, together with the advent of lithium battery chemistries, have led to declining interest in high-temperature batteries.

Other Advanced Batteries

The latest developments in battery chemistry have produced a variety of batteries that have much smaller footprints (i.e., they take up less space) than lead-acid batteries and are much easier to maintain.

Advanced batteries can be used by utilities to supply active and reactive power to mitigate voltage sags and frequency fluctuations, although most are typically still too expensive for extensive use in large-scale utility applications. They are used for power quality and backup purposes at manufacturing plants, especially in those industries that are particularly vulnerable to power fluctuations, such as semiconductor and pharmaceutical plants. Their long lifetimes and low maintenance requirements make them more suitable for remote locations than lead-acid batteries. They are also used to power consumer goods and automobiles. In fact, some automotive companies are examining whether there might be a utility storage market for automobile batteries once their useful lifetime for powering the vehicle is reached.

For information on the use of energy stored in vehicle batteries to provide grid support, see the Vehicle-to-Grid section in the Nonrenewable Distributed Energy Technologies chapter.

Advanced battery technologies include the following:

- **Nickel cadmium (nicad) —** These sealed batteries are particularly tolerant of deep discharges, with a typical life of around 500 cycles and a high-rate discharge capacity. They have been in volume production since the early 1960s but are gradually being phased out in favor of nickel metal hydride and lithium technologies, which have superior energy density and performance characteristics. One Alaskan utility has a 3,680-amp-hour battery energy storage system comprising roughly 14,000 nicad cells that can deliver 46 MW for 5 minutes.
- **Nickel metal hydride —** Like nicads, nickel-metal hydride batteries suffer from a charge memory effect, although to a lesser extent. They are much more tolerant of partial discharge cycles than nicads but cannot discharge as quickly. They are used in a variety of applications from cell phones and power tools to hybrid vehicles. They have more than twice the energy density of lead-acid batteries and 40% higher energy density than nicads.
- **Lithium-ion —** Lithium-ion batteries are relatively lightweight, do not suffer from charge memory, and have a high-energy content. They also have a longer cycle life (3,000 cycles at 80% depth of discharge) than nickel-based batteries. Currently used in consumer goods such as cell phones and laptops, they are replacing nickel metal hydride batteries in hybrid vehicles because of their better performance in cold weather, abuse tolerance, and ability to recharge at higher rates. However, safety concerns are driving the development of other lithium-based chemistries because lithium-ion batteries are susceptible to runaway exothermic reactions that can easily lead to fires.
- **Lithium-iron phosphate —** Much safer than the previous generation of lithium-ion batteries, lithium-iron phosphate batteries are also capable of higher power levels, which makes them well-suited to hybrid electric vehicle applications. Grid applications are still on the horizon.

Comparison of Representative Battery Technologies

Technology	Advantages	Disadvantages	Current Applications
Conventional Lead-Acid	• Cost effective • Relatively efficient • Mature technology	• Low energy density • Cycle life when deeply discharged depends on operational strategies • High maintenance • Environmentally hazardous materials	• Backup power • Short-duration power quality • Short-duration peak reduction • Motive power (e.g., forklifts) and deep-cycle stationary applications
Valve-Regulated Lead-Acid (VRLA)	• Cost effective • Mature technology • Lower maintenance than regular lead-acid batteries	• Traditionally have not cycled well • Have not met rated life expectancies	• Backup power • Short-duration power quality • Short-duration peak reduction • Limited motive power applications (e.g., electric wheelchairs)
Flow Batteries			
Vanadium Redox	• Good cycle life • Low-temperature, low-pressure operation • Low maintenance • Power and energy are independently scalable	• Low energy density	• Firming capacity of renewable resources • Remote area power systems • Load management • Peak shifting
Zinc Bromine (Zn/Br)	• Low-temperature, low-pressure operation • Low maintenance • Power and energy are independently scalable	• Low energy density • Requires a zinc-stripping cycle • Medium power density	• Backup power • Peak shaving • Firming capacity of renewables • Remote area power • Load management
Advanced High-Temperature Batteries			
Sodium Sulfur (Na/S)	• High energy density • No emissions • Long calendar life • Long cycle life when deeply discharged • Low maintenance	• Relatively high cost • Requires powered thermal management (heaters) • Environmentally hazardous materials • Rated output available only in 500-kW/600-kWh increments	• Utility grid-integrated renewable generation support • Utility transmission and distribution system optimization • Commercial/industrial peak shaving • Commercial/industrial backup power
"Zebra" Sodium Nickel Chloride (Na/NiCl)	• High energy density • Good cycle life • Tolerant of short circuits • Low-cost materials	• Only one manufacturer • High internal resistance • Molten-sodium electrode • High-operating temperature	• Peak shaving • Electric and hybrid vehicles; locomotives
Other Advanced Batteries			

Nickel Cadmium (NiCd)	• Good energy density
	• Excellent power delivery
	• Long shelf life
	• Abuse tolerant
	• Low maintenance
	• Mature technology
		• Moderately expensive
		• Suffers from charge memory
		• Environmentally hazardous materials
			• Utility grid support
			• Telecommunications backup power
			  • Aircraft cranking, aerospace, military and commercial aircraft applications
			  • Stationary rail
			  • Low-end consumer goods

Nickel Metal Hydride (NiMH)	• Good energy density • Low environmental impact • Good cycle life	• Expensive	• Electric and hybrid vehicles • Commercial technology for small, low-current consumer goods • Emerging market for larger applications
Lithium-ion (Li-ion)	• High energy density • High efficiency	• High production cost • Scale-up proving difficult due to safety concerns	• Electric and hybrid vehicles • Small consumer goods
Lithium Iron Phosphate (Li-FePO)	• Safer than traditional Li-ion • High power density • Lower cost than Li-ion	• Lower energy density than other Li-ion technologies	• Electric and hybrid vehicles • Small consumer goods and tools

Terms and Definitions

Anode – The positive pole or electrode of an electrolytic cell, vacuum tube, etc.

Amp–hours – A measure of the flow of current (in amperes) over one hour.

Cathode – The negative pole or electrode of an electrolytic cell, vacuum tube, etc., where electrons enter (current leaves) the system; the opposite of an anode.

Electrode – A conductor that is brought in conducting contact with a ground.

Electrolyte – A nonmetallic (liquid or solid) conductor that carries current by the movement of ions (instead of electrons) with the liberation of matter at the electrodes of an electrochemical cell.

Energy storage – The process of storing, or converting energy from one form to another, for later use.

Flow battery – a rechargeable battery in which an electrolyte containing one or more dissolved electroactive species flows through an electrochemical cell that reversibly converts chemical energy directly to electricity.

Lead–acid battery – An electrochemical battery that uses lead and lead oxide for electrodes and sulfuric acid for the electrolyte. *Oxidation/reduction potential* – A measure of the oxidation/reduction capability of a solution.

For More Information

Battery Council International
www.batterycouncil.org
A trade association for the lead-acid battery industry.

Battery University
batteryuniversity.com
An educational website that offers hands-on battery information to engineers, educators, media, students and battery users alike.

Energy Storage
www.eere.energy.gov/vehiclesandfuels/technologies/energy_storage
Information from the U.S. Department of Energy about battery technologies and supercapacitors with a focus on vehicle applications.

Flow Batteries
electrochem.cwru.edu/encycl/art-b03-flow-batt.htm
Information from Case Western Reserve University's Electrochemistry Encyclopedia.

Compressed-Air Energy Storage

Compressed-air energy storage (CAES) plants use off-peak electricity to compress and store air in an airtight underground storage cavern. During times of high electricity demand, stored air is released from the cavern, heated by natural gas, and then expanded through a gas turbine to produce electricity.

With conventional gas turbines, the air that drives the turbine is compressed and heated using natural gas. Roughly two-thirds of the fuel consumed by the turbine is actually used by the machine's compressor. In contrast, a CAES plant uses low-cost, off-peak grid electricity to precompress the air using an electric motor; that energy is later used along with some gas to generate electricity at a substantial fuel savings.

A CAES system is essentially a pneumatic battery combined with a peaking gas-turbine power plant that consumes 60% less gas than is used in conventional gas turbine to produce the same amount of electric power.

The underground storage can be in natural aquifers, depleted oil or gas fields, mined salt caverns, or excavated or natural rock caverns. Suitable caverns can also be created by dissolving existing salt deposits, and the Electric Power Research Institute has estimated that more than 85% of the United States has geological characteristics that will accommodate an underground CAES reservoir.

There are currently only two commercial CAES plants operating in the world. One is a 290-MW unit that was built in Germany in 1978. The other is a 110-MW unit that was built in Alabama in 1991. Both use caverns created by salt deposits.

Compressed air is also under consideration as an emissions-free way to power urban vehicles; prototype vehicles have been built but currently have a very limited range.

Terms and Definitions

Compressed air storage – The storage of compressed air in a container for use to operate a prime mover for electricity generation.

Energy storage – The process of storing, or converting energy from one form to another, for later use.

Gas turbine – A type of turbine in which combusted, pressurized gas is directed against a series of blades connected to a shaft, which forces the shaft to turn to produce mechanical energy.

Off–peak – The period of low energy demand, as opposed to maximum, or peak, demand.

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For More Information

Compressed-Air Energy Storage
www.electricitystorage.org/technology/storage_technologies/caes
A list of current CAES developers/suppliers from the Electricity Storage Association.

Open Energy Information: Compressed-Air Energy Storage
en.openei.org/wiki/Compressed_Air_Energy_Storage_%28CAES%29
Information developed by the National Renewable Energy Laboratory for the U.S. Department of Energy.

Flywheels

A flywheel is a cylinder that spins at very high speeds, storing kinetic (movement) energy. A flywheel energy storage system integrates the flywheel with a device that operates either as (1) an electric motor that accelerates the flywheel to store energy, or (2) as a generator that produces electricity from the energy stored in the flywheel. The faster the flywheel spins, the more energy it retains. Energy can be drawn off as needed, slowing the flywheel.

Flywheels have been around for thousands of years in the form of the potter's wheel. Modern flywheels use rotors made of steel or carbon-fiber composite materials. The rotors have a very high strength-to-density ratio.

The first generation of commercially available flywheels rotate at 4,000 revolutions per minute (rpm) or less and use steel rotors supported on ball bearings. These bearings have to be replaced numerous times during the flywheel's service life. Newer, high-speed flywheel systems use composite rotors spinning at up to 100,000 rpm on electromagnetic bearings that virtually eliminate energy losses through friction. High-speed flywheels rotate in a vacuum chamber to minimize aerodynamic losses and the buildup of heat.

Flywheels are little affected by fluctuations in air temperature, take up relatively little space, have much lower maintenance requirements than batteries, and are very durable. They have a long service life: 15-20 years or tens of thousands of deep cycles.

Flywheels can discharge their power either slowly or quickly, allowing them to serve as backup power systems for low-power applications or as short-term power quality support for high-power applications. They have excellent load-following characteristics. And they can be charged with energy 10 times faster than a conventional lead-acid battery.

Flywheels are used by businesses and industry in UPS applications today and are being optimized for grid-support applications (still in the precommercial stage). They can be daisy-chained in flywheel farms to provide backup power for extended periods of time, over an hour in some instances. Flywheels have also been used to power urban buses, locomotives in coal mines, and have been proposed to improve the range, performance, and energy efficiency of electric vehicles. However, their high kinetic energy could lead to safety issues in the event of a traffic accident, and this concern may limit their application in vehicles.

Terms and Definitions

Energy storage – The process of storing, or converting energy from one form to another, for later use.

Kinetic energy – Energy available as a result of motion that varies directly in proportion to an object's mass and the square of its velocity.

Rotor – An electric generator consists of an armature and a field structure. The armature carries the wire loop, coil, or other windings in which the voltage is induced, whereas the field structure produces the magnetic field. In small generators, the armature is usually the rotating component (rotor) surrounded by the stationary field structure (stator). In large generators in commercial electric power plants the situation is reversed.

Uninterruptible power supply (UPS) – A storage technology mated to control electronics that convert stored energy to AC electricity and dispatch it as needed.

For More Information

Flywheel Project Escalates Grid Efficiency
energy.gov/articles/flywheel-project-escalates-grid-efficiency
An article from the U.S. Department of Energy about Beacon Power Corporation's flywheel energy storage plant.

Pumped Hydro

Hydropower uses the energy of flowing water to turn a turbine that rotates a generator to produce electricity. Pumped-hydro facilities use off-peak electricity to pump water from a lower reservoir into one at a higher elevation, typically using reversible turbine-pumps. When the water stored in the upper reservoir is released, it is passed back through the turbines to generate electricity.

The off-peak electrical energy used to pump the water uphill can be stored indefinitely as gravitational energy in the upper reservoir. Pumped-hydro facilities can be built to almost any size, with discharge times ranging from several hours to several days.

The round-trip efficiency loss in a pumped-hydro scheme ranges from 15% to 30%, meaning that 70% to 85% of the electrical energy used to pump water into the upper reservoir is reclaimed when the water is discharged back through the turbines into the lower reservoir.

Most pumped storage plants use the height difference between two natural bodies of water or artificial reservoirs. But abandoned mines and other subterranean cavities can be used for the lower reservoir, as can the ocean: a 30-MW pumped hydro plant using seawater was built in Japan in 1999.

Pumped-hydro energy storage is used for grid frequency control and to smooth out the demand for electricity from baseload power plants. It can also be used to provide emergency power injection to the grid when a power plant goes offline unexpectedly. Pumped-hydro facilities have extremely fast ramp-up rates, which make them particularly suitable for emergency power injection. They can also be started up when no off-site power is available, providing a critical "black-start" capability for utilities in the event of a power outage.

Pumped hydro has been in use since the 1890s and was the only commercially available storage technology for grid applications until around 1970. Pumped-storage plants require a high initial capital outlay and have long construction times. There are also geographic, geologic, and environmental constraints associated with reservoir design. Currently, efforts aimed at increasing the use of pumped-hydro storage are focused on the development of underground facilities.

Other uses of hydropower are described in the chapter on Renewable Power Generation.

Terms and Definitions

Baseload power plant – A power plant that is normally operated to generate a baseload, and that usually operates at a constant load; examples include coal-fired and nuclear-fueled power plants.

Black start – the process of restoring a power station to operation without relying on the external electric power transmission network.

Energy storage – The process of storing, or converting energy from one form to another, for later use.

Off–peak – The period of low energy demand, as opposed to maximum, or peak, demand.

Pumped–storage facility – A type of power-generating facility that pumps water to a storage reservoir during off–peak periods, and uses the stored water (by allowing it to fall through a hydro turbine) to generate power during peak periods. The pumping energy is typically supplied by lower cost base-power capacity, and the peaking-power capacity is of greater value, even though there is a net loss of power in the process.

For More Information

Pumped Hydro
www.electricitystorage.org/technology/storage_technologies/pumped_hydro/
A list of pumped-hydro developers/suppliers from the Electricity Storage Association.

Pumped Storage
hydro.org/tech-and-policy/technology/pumped-storage
Information on pumped storage technology from the National Hydropower Association.

Supercapacitors

Supercapacitors are electrochemical storage devices that work like large versions of common electrical capacitors. They are also known as ultracapacitors, electrochemical capacitors, and electric double-layer capacitors.

Capacitors, supercapacitors, and batteries all incorporate two electrodes, each of which stores an opposite charge. But they store the charges differently. Batteries are charged when they undergo an internal chemical reaction. They discharge, delivering the absorbed energy, when they reverse the chemical reaction. In contrast, when a supercapacitor is charged, there is no chemical reaction. Instead, the energy is stored as a charge or concentration of electrons on the surface of a material.

In a conventional capacitor, the electrodes (typically metal plates) are separated by insulating material or a very thin layer of metal oxide, and the charge is stored on the surface of the electrodes at the boundary with the insulator. In a supercapacitor, the electrodes (typically porous carbon) are separated by electrolyte, as in a battery, although in this case it is a very thin layer of electrolyte. This electrolyte can be aqueous (e.g., sulfuric acid) or organic (e.g., acetonitrile). Supercapacitors store their energy in an electrostatic field—the supercapacitor polarizes the electrolyte so that energy is stored via charge separation at the electrode-electrolyte interface.

Conventional capacitors have enormous power but store only tiny amounts of energy. Batteries can store lots of energy but have low power—they take a long time to be charged or discharged. Supercapacitors have high power like conventional capacitors, but much higher energy.

Supercapacitors are capable of very fast charges and discharges, and some types can be recharged hundreds of thousands of times, unlike conventional batteries, which last for only a few hundred or a few thousand recharge cycles. But the power of supercapacitors is typically available only for a very short duration, and their self-discharge rate is much higher than that of batteries.

Supercapacitors, especially those using aqueous electrolytes, are typically unaffected by temperature extremes—unlike lead-acid batteries, which can be damaged by high temperatures and which can lose up to 50% of their ability to deliver power at very low temperatures. They are ideal for high-power, short-duration applications because of their deep-discharge capability and their virtually unlimited cycle life.

Common applications include starting diesel trucks and railroad locomotives, and in electric/hybrid-electric vehicles for transient load leveling and capturing the energy used in braking. Small supercapacitors (with power capabilities of a few watts) are commonly found in household electrical devices. Like flywheels, supercapacitors are also used as bridging power sources in a UPS, providing fast-acting short-term power backup. Supercapacitors are used for power quality purposes and grid stability in utility applications.

Terms and Definitions

Capacitor – An electrical device that adjusts the leading current of an applied alternating current to balance the lag of the circuit to provide a high power factor.

Electrode – A conductor that is brought in conducting contact with a ground.

Electrolyte – A nonmetallic (liquid or solid) conductor that carries current by the movement of ions (instead of electrons) with the liberation of matter at the electrodes of an electrochemical cell.

Uninterruptible power supply (UPS) – A storage technology mated to control electronics that convert stored energy to AC electricity and dispatch it as needed.

For More Information

Battery University: Supercapacitor
batteryuniversity.com/learn/article/whats_the_role_of_the_supercapacitor
An overview on supercapacitor technology.

Energy Storage
www.eere.energy.gov/vehiclesandfuels/technologies/energy_storage
Information from the U.S. Department of Energy about battery technologies and supercapacitors with a focus on vehicle applications.

Supercapacitors: Fundamentals of Electrochemical Capacitor Design and Operation
theory.caltech.edu/~politzer/supplements/supercapacitors.pdf
A fact sheet from the California Institute of Technology.

Superconducting Magnetic Energy Storage

A superconducting magnetic energy storage (SMES) system is essentially a magnetic battery. SMES systems store electrical energy in the magnetic field created by the flow of direct current through a large coil of superconducting material that has been cooled to very low temperatures. In such low-temperature superconducting materials, electric currents encounter almost no resistance, greatly enhancing their storage capacity.

Power is available almost instantaneously from SMES systems, and very high power output is provided for a brief period of time. There are no moving parts. However, the energy content of SMES systems is small and short-lived, and the cryogenics (super-cooling technology) can be a challenge. Cryogenic systems also consume energy, decreasing the storage efficiency of SMES systems. Researchers are trying to find ways to maintain the special qualities of SMES without having to keep the systems quite so cold.

Low-temperature [4 Kelvin (K)] SMES systems cooled by liquid helium are commercially available today. “High-temperature” (less cold) SMES systems cooled by liquid nitrogen are in development. High-temperature systems could be operated at 30-70 K, resulting in a 90% cost reduction.

The energy output of an SMES system is much less dependent on the discharge rate than batteries. SMES systems also have a high cycle life and, as a result, are suitable for applications that require constant, full cycling and a continuous mode of operation.

SMES systems are used to address power quality problems and short-term power losses, such as those that may occur while switching from grid electricity to a backup power supply. They have also been used for electricity-grid support, helping to prevent voltage collapse, voltage instability, and system outages.

In Wisconsin, a string of distributed SMES units was deployed to enhance stability on a transmission loop. The transmission line is subject to large, sudden load changes due to the operation of a paper mill, with the potential for uncontrolled fluctuations and voltage collapse. Besides stabilizing the grid, the six SMES units also provide improved power quality to customers served by connected feeders.

Terms and Definitions

Cryogenics – the study of the production of very low temperature (below –150°C, –238°F or 123K) and the behavior of materials at those temperatures.

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Direct current (DC) – A type of electricity transmission and distribution by which electricity flows in one direction through the conductor; usually relatively low voltage and high current.

Energy storage – The process of storing, or converting energy from one form to another, for later use.

Kelvin scale – A scale of temperature that starts at zero and indicates the total absence of heat (absolute zero); zero is equal to minus 273.16°C.

Superconductivity – The abrupt and large increase in electrical conductivity exhibited by some metals as the temperature approaches absolute zero.

For More Information

Superconducting Magnetic Energy Storage System for Improved Dynamic System Performance
scholarsmine.mst.edu/post_prints/pdf/042755_09007dcc8053002e.pdf
An article published by the Institute of Electrical and Electronics Engineers.

Hybrid Power Systems

Hybrid power systems are combinations of two or more energy conversion devices (e.g., electricity generators or storage devices), or two or more fuels for the same device that, when integrated, overcome limitations that may be inherent in either.

Examples of hybrid power systems include:

- Photovoltaic (PV) generation combined with battery storage and/or diesel generation
- Fuel cell generation combined with microturbine generation
- Solar thermal electric generation with natural gas as backup
- Wind generation combined with hydrogen storage.

The U.S. electricity grid is itself one of the world's largest hybrid power systems, incorporating multiple sources of power generation (e.g., coal, nuclear, and renewable power plants) and storage (e.g., pumped hydro and batteries).

Hybrid systems can produce synergistic benefits in which the whole is greater than the sum of its parts.

Potential benefits of hybrid power technologies include:

- **Higher system efficiency** — Systems can be designed so that each component is operating at optimum efficiency, fulfilling the role to which it is best suited. Incorporating heat, power, and highly efficient devices can increase overall efficiency and conserve energy for a hybrid system when compared with individual technologies used separately.
- **Enhanced reliability** — Achieving higher reliability can be accomplished with redundant technologies and/or energy storage. A flywheel can be used to provide instantaneous power until a backup generator comes on-line, for example. Hybrid systems can simultaneously improve the quality and availability of power.
- **Lower emissions** — Hybrid systems can be designed to maximize the use of renewables and gas-fueled generators that have low emissions, such as combustion turbines, resulting in a system with lower emissions than traditional fossil-fueled technologies. Adding wind turbines to a battery bank that is otherwise charged with diesel generators, for example, will reduce the use of diesel fuel and the emissions associated with it.

Terms and Definitions

Fuel cell – An electrochemical device that converts chemical energy directly into electricity.

Hybrid system – A renewable energy system that includes two different types of technologies that produce the same type of energy; e.g., a wind turbine and a solar PV array combined to meet a power demand.

Photovoltaic device – A solid–state electrical device that converts light directly into direct current electricity of voltage–current characteristics that are a function of the characteristics of the light source and the materials in and design of the device.

Solar thermal electric system – A modular mirror system that approximates a parabola and incorporates two–axis tracking to focus the sunlight onto receivers located at the focal point of each dish. The mirror system typically is made from a number of mirror facets, either glass or polymer mirror, or can consist of a single stretched membrane using a polymer mirror.

For More Information

Energy Savers: Small Hybrid Solar and Wind Electric Systems
www.energysavers.gov/your_home/electricity/index.cfm/mytopic=11130
Information for consumers from the U.S. Department of Energy about small hybrid solar and wind systems.

Hybrid Power System Simulation Model
www.ceere.org/rerl/projects/software/hybrid2
A software tool from the University of Massachusetts-Amherst for performing long-term performance and economic analysis on a wide variety of hybrid power systems.

HOMER
analysis.nrel.gov/homer
Information from the National Renewable Energy Laboratory about a computer model that simplifies the task of evaluating design options for remote, stand-alone, and distributed generation applications.

Hydrogen Production and Storage

Hydrogen's great appeal is that it is potentially a completely clean energy carrier for the future. Although hydrogen can be used as a fuel to power vehicles and power-generation equipment, just as electricity can, it is strictly speaking an energy storage medium, not an energy source. Just as with any other storage technology, a source of energy must be tapped to produce the hydrogen before it can be used, and you can't get more energy out of the hydrogen storage system than you put into it.

Assuming that substantial technical hurdles with production and storage can be overcome, hydrogen has some key advantages as an energy carrier and fuel:

- **Potentially no emissions when used** — When burned with pure oxygen, the only byproducts are heat and water vapor. When burned with air, which is about 68% nitrogen, some oxides of nitrogen are formed. The electrochemical conversion of hydrogen in a fuel cell produces only electricity, heat, and water.
- **Potentially no emissions when produced** — This is true if a nonpolluting energy source (e.g., renewable energy) provides the electricity needed to run an electrolyzer, or if the hydrogen is produced via microbial action (see below for an explanation).
- **High energy-conversion efficiency** — The process of converting stored hydrogen to energy using internal combustion engines (ICEs) or fuel cells is much more efficient than the comparable gasoline counterparts. An ICE burning hydrogen is typically 25%-30% more energy efficient than one burning gasoline, for example.

The combination of the first two characteristics is the source of the interest surrounding hydrogen—the promise of a completely pollution-free and sustainable cycle of energy production and use. This is the ultimate goal of what has been dubbed the "hydrogen economy."

In the first stage of the cycle, hydrogen is produced from renewable resources, such as via photoelectrolysis of water, in which energy from the sun is used to convert water into hydrogen and oxygen. The hydrogen is then used to power a fuel cell, in which the stored hydrogen and oxygen from the air combine to produce electricity, heat, and water.

Clean renewable energy is regarded as an enabling technology for the hydrogen economy, but the reverse is also true. Hydrogen energy storage can enable widespread adoption of renewable power-generation technologies, such as solar and wind power, that produce variable power.

The hydrogen economy also represents a potential convergence of vehicle and power technologies, as hydrogen has the capacity to be a truly universal fuel, running vehicles and power plants alike.

The United States currently consumes more than 9 million tons of hydrogen each year, most of which is used in commercial processes, such as fixing nitrogen from the air to produce ammonia for fertilizer. Hydrogen is also used to produce low-sulfur fuels. Hydrogen-powered vehicles are gradually becoming available, but the use of hydrogen for power generation is still in its infancy.

There are significant obstacles to greater adoption of hydrogen:

- **Low natural energy density** — Although hydrogen has very high energy by weight, it has very low energy by volume when in its natural ("free") state. This presents a significant technological obstacle for both storing and transporting it.
- **Low energy-storage efficiency** — There are two aspects to this:
  - It takes a lot more energy to produce and store hydrogen than can be recovered from it. Some methods of production, such as electrolysis, are so inefficient that they make economic sense only when the electricity used to make the hydrogen is virtually free.
  - Existing commercially available storage technologies (compressed gas or cryogenic liquid storage) contribute to this inefficiency due to the amount of energy they consume.
- **Currently a "pollution amplifier"** — Because the production of hydrogen uses far more energy than can later be recovered from it, hydrogen effectively increases the pollution of the energy source used to produce it. Virtually all of the hydrogen used today comes from reforming natural gas. The remainder, high-purity hydrogen from water electrolysis, is primarily produced using electricity that is generated by burning fossil fuels. Both processes release carbon dioxide.

Hydrogen faces particularly difficult challenges in transportation applications. The extreme high pressures used in pressurized hydrogen storage tanks presents a potential safety issue during traffic accidents. Some automakers have avoided this issue by using liquefied hydrogen, but the liquid tends to boil off over time, and the vehicles require proper ventilating to assure that any leaking hydrogen does not cause a risk of fire or explosion.

In addition to efficient methods of producing it and storing it, extensive use of hydrogen in the future will require an infrastructure to deliver it from where it's produced to the point of end use, such as a dispenser at a vehicle refueling station or stationary power site. This infrastructure includes the pipelines, trucks, storage facilities, compressors, and dispensers involved in the process of delivering the fuel. Unfortunately, today's natural gas pipelines could not be converted to hydrogen because they are made of material susceptible to hydrogen embrittlement, which could cause them to crack and catastrophically fail.

The "hydrogen economy" is still several decades away. There have to be some significant advancements in fuel cell technology, electrolyzers, and other hydrogen production methods, storage techniques, and distribution methods before the vision can become a reality.

Production

Hydrogen is the most abundant element in the universe, although it is always chemically bound with other elements here on Earth. To make use of the bound hydrogen, it is necessary to expend energy to extract it from the chemical compounds in which it is found.

Hydrogen can be extracted from a wide variety of resources: coal, oil, natural gas, biomass, and water. Production processes that require electricity can use any generating source—fossil, nuclear, and renewable power—although nuclear and renewable sources are in the forefront due to their lower emissions of greenhouse gases and other pollutants.

Options for producing hydrogen include the following:

- **Steam reformation of natural gas —** It's the source of 95% of the hydrogen produced in the United States today.
- **Electrolysis —** Electrolysis can electrochemically split water into hydrogen and oxygen in essentially the reverse of the reaction in a fuel cell. To make sense for large-scale use, this process must use an inexpensive source of electricity. Wind energy is the leading candidate because it is currently the lowest-cost renewable technology. It is also a variable source that would benefit from being able to produce hydrogen when its electricity is not needed. When electricity demand exceeds what the wind turbines can provide, a fuel cell can convert the hydrogen back into electricity, serving as a supplemental power source. The combination also benefits because electrolyzers require direct current and wind turbines output direct current before conversion to alternating current suitable for the electric grid.
- **Thermochemical processing —** Heating biomass or fossil fuels with limited or no oxygen present can either (1) gasify it to a mixture of hydrogen and carbon monoxide known as synthesis gas or syngas, or (2) liquefy/pyrolyze it to a liquid known as pyrolysis oil or bio-oil. Syngas can then be catalytically converted to increase the amount of hydrogen with a "water-gas-shift reaction." Pyrolysis oil can be converted to hydrogen using steam reformation and the water-gas-shift reaction.
- **Electrochemical photolysis —** It uses solar power to produce hydrogen directly by immersing a solar cell in water. This is also referred to as photoelectrolysis or photoelectrochemical hydrogen production. It involves replacing one electrode of an electrolyzer with PV semiconductor material to generate the electricity needed for the water-splitting reaction. This avoids the efficiency loss of two-step processes in which the PV cells and electrolyzer are separate components of the system. However, the challenge of finding a PV cell capable of splitting water and also able to be immersed in water has thus far proved formidable.
- **Biological photolysis —** It involves harnessing microalgae and photosynthetic bacteria that sometimes use photosynthesis to make hydrogen instead of sugar and oxygen. Among challenges here is the fact that the algal enzyme that triggers the hydrogen production is inhibited by oxygen, which the organism also normally produces.
- **Fermentation —** Another biological conversion method that is being researched, this involves developing microorganisms that will ferment sugars or cellulose to hydrogen instead of alcohol.

Storage

Hydrogen is a poorly compressing, low-density gas. It is very difficult to liquefy. The challenges with storing hydrogen for stationary power applications are substantial, although not as great as in transportation applications.

The technologies for storing hydrogen fall into three broad categories:

- **Gaseous-physical storage** — This involves compressing hydrogen in pressurized tanks, like the ones that transport propane and natural gas, except that hydrogen is generally pressurized at higher pressures, requiring tanks made from super-strong materials such as carbon fibers. Pressurized tanks have a large volume that can make them difficult to accommodate on site.
- **Liquid-physical storage** — This involves cooling hydrogen for storage in highly insulated liquid tanks. Liquefying the hydrogen more than doubles the fuel density, but uses up substantial amounts of energy to lower the temperature sufficiently (-253°C at atmospheric pressure), and requires expensive insulated tanks to maintain that temperature.
- **Materials-based storage —** There are three mechanisms:
  - Absorption — Hydrogen is absorbed directly into the material. In simple metal hydrides, for example, the hydrogen is stored in the spaces within the crystalline structure of the hydride, resulting in a much higher density than free hydrogen. Heat is used to release the hydrogen. This method shows some promise but is still prohibitively expensive.
  - Adsorption — Molecules of hydrogen gas will adhere to the surface of the solids or liquids with which they are in contact. Sorptive processes typically require highly porous materials in order to maximize the surface area available for hydrogen sorption, and to allow for easy uptake and release of hydrogen from the material.
  - Chemical reactions — This involves chemically converting hydrogen and storing it in compounds that readily release their hydrogen. Examples include sodium-alanate-based complex metal hydrides and sodium borohydride.

A third type of storage mechanism shows great promise for the long-term future: carbon nanotube physical storage. Carbon nanotubes are microscopically tiny carbon cylinders, each of which has a diameter equal to several hydrogen molecules. It has been demonstrated in the lab that hydrogen can be drawn up into these carbon tubes just as water is drawn up into a drinking straw. Once bundles of aligned nanotubes can be fabricated, they can act as lightweight hydrogen "sponges." This approach is still in the early stages of development.

Energy efficiency is a challenge for all hydrogen storage approaches. The energy required to get hydrogen in and out is an issue for both reversible solid-state materials and chemical hydride storage. And the energy associated with compression and liquefaction must be considered for those storage approaches.

Terms and Definitions

Absorption – The passing of a substance or force into the body of another substance.

Electrochemical cell – A device containing two conducting electrodes, one positive and the other negative, made of dissimilar materials (usually metals) that are immersed in a chemical solution (electrolyte) that transmits positive ions from the negative to the positive electrode and thus forms an electrical charge. One or more cells constitute a battery.

Electrode – A conductor that is brought in conducting contact with a ground.

Electrolysis – A chemical change in a substance that results from the passage of an electric current through an electrolyte. The production of commercial hydrogen by separating the elements of water, hydrogen, and oxygen, by charging the water with an electrical current.

Fermentation – The decomposition of organic material to alcohol, methane, etc., by organisms, such as yeast or bacteria, usually in the absence of oxygen.

Hydrogen – A chemical element that can be used as a fuel because it has a very high energy content.

Photoelectrochemical cell – A type of PV device in which the electricity induced in the cell is used immediately within the cell to produce a chemical, such as hydrogen, which can then be withdrawn for use.

Photoelectrolysis – The production of hydrogen using a photoelectrochemical cell.

Pyrolysis – The breaking apart of complex molecules by heating in the absence of oxygen, producing solid, liquid, and gaseous fuels.

For More Information

Fuel Cell and Hydrogen Energy Association
www.fchea.org
An advocacy organization dedicated to the commercialization of fuel cells and hydrogen energy technologies.

U.S. Department of Energy Hydrogen and Fuel Cells Program
www.hydrogen.energy.gov
A program providing research and development in hydrogen production, delivery, storage, and fuel cells, as well as activities in technology validation, systems analysis and integration, safety codes and standards, and education.

SYSTEMS INTEGRATION AND LOAD CONTROL

For distributed generation systems, this chapter features information on grid-tied and stand-alone power generation; connecting to the grid; maintaining grid stability; power quality and reliability issues; communication technologies and demand response; and utility policies.

Grid-Tied vs. Stand-Alone Power Generation

Customer-owned renewable power systems and other forms of distributed generation can be operated either in stand-alone mode or connected to the electrical grid. For remote locations, off-grid systems are the best choice when the cost of extending a distribution line to the property is prohibitive. Some utilities will even finance such systems to avoid having to extend their power lines into areas that are difficult to access.

Stand-Alone Systems

Except for a handful of applications, such as water pumping, off-grid renewable power systems require energy storage in batteries. Battery storage systems allow variable energy sources, such as the sun and wind, to provide a continual supply of electricity. Off-grid systems with battery storage are an attractive option in locations with inaccessible or unreliable power supplies.

Solar power and small wind systems were chiefly pioneered for homes that were not connected to the grid. However, the cost of a battery storage system can be prohibitive for homeowners. Instead, off-grid systems are gaining in popularity for a number of other applications where their benefits are clear, such as traffic signs and signals, farming and ranching, remote telecommunications relays, and emergency response systems.

Grid-Connected Systems

Throughout much of the United States, grid-connected systems are much more economically feasible and practical for both homes and businesses. Such systems don't require the expensive batteries of the off-grid systems, so they're cheaper, require less maintenance, and can provide a benefit to utilities by feeding excess power generation back into the grid.

Net Metering

To improve the economics of customer-owned distributed generation systems and to encourage their connection to the grid, most states now offer net metering.

Net metering involves giving credit to the customer for power fed into the grid. Customers usually are not paid for any net power generation; they just receive a credit against their own electricity bill. This means that they are billed only for their net electricity use, hence the term net metering.

With some net metering arrangements, customer-generated electricity is valued the same as electricity supplied to the customer from the grid. In this case, customers who generate more electricity than they use will actually reduce their electricity bill to near zero, although some service and facility charges may still apply. The simplest net metering arrangement is to have a single meter that runs forward when the customer uses grid electricity and backward when the customer is supplying electricity to the grid. Newer digital meters simply subtract from their total when electricity is supplied to the grid.

In practice, net metering varies widely from state to state and utility to utility, with some utilities giving lower credits for power fed into the grid, or requiring the installation of an expensive second meter. Another common difference is whether any net energy balance can be carried over from month to month or from year to year. In some cases, customers can be paid for annual net energy balances, but in most cases, utilities pay the avoided cost of power, which is much lower than the residential cost of power, so the benefit to the consumer is usually minimal.

Net metering can be problematic for businesses with multiple meters, such as farms, where the electrical load may be on several meters because one meter could indicate net generation while another meter incurs significant energy charges. Some states are allowing a group of meters to be aggregated under one net-metering agreement to address this issue. Net metering can also be a poor choice for business customers who pay demand charges, as it only takes a brief downtime of the customer's generator to incur a significant demand charge that may wipe out any benefits of net metering.

Feed-In Tariffs

California has established a "feed-in tariff" for two of its largest utilities: Southern California Edison and Pacific Gas and Electric Company. The tariff pays customers a set rate for power fed into the grid (as opposed to just giving a credit, as under net metering), so it encourages the installation of customer-owned systems that are larger than the customer needs. Such tariffs could also prove beneficial for businesses with multiple meters. But the economics are uncertain, as customers taking advantage of the feed-in tariff must decline other state incentives. Several other states are considering instituting a feed-in tariff.

Grid-Tied Systems with Battery Storage

Even with a grid-connected system under a net metering agreement or a feed-in tariff, some customers will still want the security of a battery storage system, which can continue to provide power during a blackout. Other grid-connected customers may choose to size their power generation and energy storage systems so that they are essentially self-contained, using the grid more as a backup source of power.

Power System Design

To help homeowners and businesses design off-grid and grid-connected systems that will meet their needs, DOE's National Renewable Energy Laboratory (NREL) has developed a software tool called HOMER (see For More

Information below). HOMER allows people to evaluate the economic and technical feasibility of a large number of options, including renewable energy systems, fuel cells, generators, and battery storage systems.

Terms and Definitions

Demand charge – A charge for the maximum rate at which energy is used during peak hours of a billing period. That part of a power provider service charged for on the basis of the possible demand as distinguished from the energy actually consumed.

Feed–in tariff – An energy supply policy that promotes the rapid deployment of renewable energy resources. It offers a guarantee of payments to renewable energy developers for the electricity they produce.

Net metering – The practice of using a single meter to measure consumption and generation of electricity by a small generation facility (such as a house with a wind or solar photovoltaic system). The net energy produced or consumed is purchased from or sold to the power provider, respectively.

Stand–alone generator – A power source/generator that operates independently of or is not connected to an electric transmission and distribution network; used to meet a load(s) physically close to the generator.

For More Information

State and Utility Net Metering Rules for Distributed Generation
www.irecusa.org/irec-programs/connecting-to-the-grid/net-metering
A state-by-state table from the Interstate Renewable Energy Council.

HOMER
analysis.nrel.gov/home
Information from NREL about a computer model that simplifies the task of evaluating design options for remote, stand-alone, and distributed generation applications.

Connecting to the Grid

To connect to the grid, distributed generation systems require inverters and an interconnection agreement with the local utility.

Inverters

Solar power is the most common renewable power system installed by homeowners and businesses, but it produces direct current (DC), whereas most appliances and the grid run on alternating current (AC). Many small wind turbines also produce DC. It is possible to wire a home for DC and to use all-DC appliances, but this approach may run counter to building codes and could reduce the market value of the home. To match DC power sources with the building's AC power requires the use of an inverter, which converts DC power to AC power.

Inverters are one part of the power-conditioning equipment needed to connect to the grid. This equipment, which is typically sold as a package, includes a computer-controlled device to manage the system's connection to the grid and may also include a charge controller for a battery storage system. Today's systems are able to automatically disconnect from the grid in the event of a power outage (to avoid feeding power into a line that a utility worker needs to access) and can maintain power to critical loads in the building after disconnecting from the grid.

Interconnection Agreements

Connecting a distributed generation system to the grid requires an interconnection agreement with the local utility. While model interconnection agreements have been established by organizations such as the National Association of Regulatory Utility Commissioners, there remains a great deal of inconsistency in how utilities handle interconnection.

Most utilities require an external disconnect switch for distributed generation systems, even though modern inverters will automatically disconnect from the grid. Some utilities also require expensive liability insurance that can make interconnecting such systems uneconomical. For large systems, utilities may try to recoup the cost of upgrades to the distribution system that are needed to handle the extra power. Most utilities also place an upper limit on the size of self-generation systems, or have a two-tiered system that imposes less restrictions on smaller generators.

Western Area Power Administration Agreement

The Western Area Power Administration has established an interconnection agreement for generators up to 20 megawatt in capacity. Customers must supply initial specifications for their system at least 180 days before interconnecting, and final specifications must be submitted at least 90 days in advance. Western requires customers to pay for any needed system upgrades to accommodate the new generation, but also credits customers for unnecessary transmission charges. Western requires liability insurance, but does not specify the dollar amount of coverage.

For More Information

Connecting to the Grid: A Guide to Distributed Generation Interconnection Issues
recusa.org/wp-content/uploads/2009/11/Connecting-to-the-Grid-Guide-6th-edition.pdf
A publication developed by the Interstate Renewable Energy Council and the North Carolina Solar Center

IEEE 1547: Standard for Interconnecting Distributed Resources with Electric Power Systems
standards.ieee.org/findstds/standard/1547-2003.html
A standard established by the Institute of Electrical and Electronics Engineers (IEEE).

National Association of Regulatory Utility Commissioners
www.naruc.org
A national association representing state public service commissioners who regulate essential utility services, including energy, telecommunications, and water.

NFPA 70: National Electrical Code
www.nfpa.org/aboutthecodes/AboutTheCodes.asp?DocNum=70
A code established by the National Fire Protection Association (NFPA)

UL 1741: Inverters, Converters, Controllers and Interconnection System Equipment for Use with Distributed Energy Resources
http://ulstandardsinfonet.ul.com/scopes/1741.html
Requirements established by UL, a global independent safety science company.

Western's Interconnection Process
ww2.wapa.gov/sites/Western/transmission/interconn/Pages/Process.aspx
Information on the eight steps in the interconnection process.

Maintaining Grid Stability

The U.S. power grid consists of three regional power grids, which are only weakly interconnected with each other. Those three grids are the Western Interconnect, the Eastern Interconnect, and the Texas Interconnect. The Texas Interconnect includes most of Texas and is connected to the other two systems only by direct-current lines. The Western and Eastern interconnects are divided by a line that runs roughly north-south through the border between Colorado and Kansas. The three U.S. regional grids also connect to the Mexican and Canadian grids where they are geographically contiguous. The three interconnects are controlled by roughly 150 control area operators distributed throughout the United States in 12 independent system operators (ISOs).

Today, the idea of "controlling" the electricity grid consists primarily of balancing the fluctuating demand for electricity with an equal amount of power generation. Grid operators monitor the electrical loads on transmission lines and may request that utilities bring additional generation sources on-line near loads to reduce stresses on transmission lines. Grid operators can also work with power generators to adjust the amount of reactive power fed into the grid. Reactive power is needed to drive induction motors at industrial facilities, but it can only be transmitted relatively short distances.

When a power grid is under stress, grid operators typically have agreements in place with large commercial and industrial facilities to reduce loads during power emergencies. Such facilities might shut down for a shift or stop using a particularly energy-intensive process, typically in exchange for discounted power for the month. Facilities with such agreements may also have to pay penalties if they do not reduce their load when called upon to do so. Grid operators also use the media and other channels to call for voluntary conservation. The California ISO, for instance, has "Flex Alerts" to call for voluntary conservation, and the alerts are sent out via the media and directly to consumers via email and mobile phones.

During emergency situations, grid operators can disconnect remaining loads or transmission lines to ease the strain on the transmission system and to limit the spread of a blackout. If the grid event involves insufficient generation to meet the load, operators generally have two tools available to them: reducing the system voltage to cause a "brownout," or sequentially shutting off portions of the grid to lower the power demand, known as "rolling blackouts."

What grid operators currently cannot do, however, is to physically control the flow of electricity through the grid. Electricity flows freely through the grid, like water flowing through an interconnected series of pipes. As a result, it may be theoretically possible to transmit a large amount of power through a large transmission line, but in reality some of that power will also flow through redundant power lines and could overload them.

This limits the functionality of the grid and can lead to contractual difficulties when a large amount of power is transferred from a generator to a distant load—known as "wheeling." For instance, the power purchaser may sign a contract with the owner of a large transmission line to wheel the power from a distant generator, but that power transfer could also impact nearby transmission lines owned by another company. That other company is often not compensated for the impact of the power transfer.

In rare instances, companies have signed wheeling agreements with the owners of smaller transmission lines that could theoretically carry the power from the generator to the load, knowing full well that, in reality, a larger, more direct transmission line would actually carry the majority of the power. Such contractual games have led to lawsuits between transmission system owners and the companies attempting to wheel the power.

The Smart Grid

The limitations of today's electricity grid have been leading utility companies, utility research groups, electric industry trade groups, and policymakers toward the concept of a "Smart Grid," which is envisioned as a more interactive and potentially "self-healing" power grid. Utilities are gradually moving towards this Smart Grid concept as they install and integrate many of the components to their power grids.

The August 2003 blackout in the Northeast and Canada gave much higher visibility to smart grid technologies as a way to create a more stable grid without over-investing in a grid designed to accommodate worst-case operating scenarios.

A Smart Grid would include, among other things, technologies for providing greater control of the transmission and distribution systems. The first step is to add advanced power electronics (based on high-current and high-voltage thyristors) to substations to allow actual control of the power flows through that substation. In fact, many utilities have already added automation technologies to their substations. Utilities are also installing new monitoring devices to help them understand how the grid is performing, including everything from transmission line monitors to smart meters, which help utilities to determine the extent of power outages.

In addition, storage technologies, such as batteries or superconducting magnetic energy storage systems, can provide voltage support and can inject reactive power into the grid to maintain frequency stability despite the drain caused by heavy industrial loads, such as pumps and motors.

Control and storage technologies exist today, but are in limited use among U.S. utilities. When used for grid control, these technologies are sometimes referred to as flexible AC transmission system technologies.

Enforcing Grid Reliability Standards

Another change brought about by the August 2003 blackout was a shift from voluntary grid reliability standards to mandated requirements for grid stability. Previously, the North American Electric Reliability Corporation (NERC) provided voluntary guidelines and assessments of grid reliability, but after the blackout, NERC began policing the reliability of the grid in its role as the nation's official electric reliability organization. In its new role, NERC proposes standards to the Federal Energy Regulatory Commission (FERC), which has the power to promulgate the standards as federal rules. NERC also reports violations and proposes penalties to FERC, which has the authority to impose penalties on utilities.

Terms and Definitions

Blackout – A power loss affecting many electricity consumers over a large geographical area for a significant period of time.

Brownout – A controlled power reduction in which the utility decreases the voltage on the power lines, so customers receive weaker electric current. Brownouts can be used if total power demand exceeds the maximum available supply. The typical household does not notice the difference.

Independent system operator (ISO) – An organization formed at the direction or recommendation of FERC.

Smart grid – a digitally enabled electrical grid that gathers, distributes, and acts on information about the behavior of all participants (suppliers and consumers) to improve the efficiency, reliability, economics, and sustainability of electricity services.

Wheeling – The process of transmitting electricity over one or more separately owned electric transmission and distribution systems.

For More Information

FERC
www.ferc.gov
Regulates interstate transmission of electricity, natural gas and oil; licenses hydropower projects.

NERC
www.nerc.com
The electric reliability organization certified by FERC to establish and enforce reliability standards for the bulk-power system.

SmartGrid.gov
www.smartgrid.gov
Information from the U.S. Department of Energy (DOE) on the Smart Grid concept, initiatives, and projects funded through the American Recovery and Reinvestment Act.

Smart Grid Information Clearinghouse
www.sgiclearinghouse.org

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A portal funded by DOE for providing information on demonstration projects, use cases, standards, legislation, policy and regulation, lessons learned and best practices, and advanced topics dealing with research and development.

Power Quality and Reliability Issues

Today's computer systems and other electronic devices have an increased sensitivity to the quality of power available on the grid. Our growing reliance on computers is also pushing up the economic impact of a loss of power. These issues are driving computer-intensive industries, such as data centers and financial institutions, to demand high-quality and highly reliable power from their utilities. In the face of uncertain power quality, some of these industries are installing backup power systems; others are installing primary power systems that can meet all of their needs, relegating the utility power to a backup position. The latter approach can lead to a failing business model for tomorrow's utilities.

Due to that concern, one goal of the Smart Grid concept is to provide high-quality and highly reliable power. A key part of meeting that goal is the "self-healing" grid, which combines smart-grid control capabilities with extensive measurement and computer-analysis capabilities to automatically maintain the grid in its most stable configuration. If such a system were in operation prior to the August 2003 blackout, it may have been able to dampen the oscillations in voltage and frequency sufficiently to stabilize the grid prior to the grid's collapse.

Another aspect of this more reliable grid would be improved security from external attack. Today's supervisory control and data acquisition (SCADA) systems in use by utilities are Internet-based and are vulnerable to cyber attack, but smart-grid systems are being built with such cybersecurity issues in mind. The self-healing grid will also be less vulnerable to physical attacks.

Communication Technologies and Demand Response

An additional component of the Smart Grid is a system to allow two-way communication with the customer. Today's approach to that challenge is the use of advanced meters, commonly called "smart meters," that can communicate with the utility, typically through the Internet or via wireless technologies.

Advanced meters offer labor savings for utilities by eliminating the need for meter readers. They also allow utilities to quickly and accurately determine the extent of a power outage, allowing utility crews to be deployed more efficiently. With distribution control technologies, utilities can even limit the scope of outages by rerouting power manually. Although many utilities are now installing advanced meters for these reasons, the meters also open the door to more advanced two-way communications.

Advanced meters can also provide benefits to utility customers, particularly if they can get real-time access to their energy-use information, which can be recorded on timescales of minutes or even fractions of minutes. Such immediate feedback can allow customers to notice trends in energy use and to see immediately the impact of, for instance, unplugging a rarely used appliance or electrical device.

As the utility interaction with the customer becomes more complex, it may require the use of building energy management systems for residential customers. Such systems are common for commercial and industrial facilities, but under the Smart-Grid scheme, the commercial and industrial energy management systems would need to be integrated with the smart electric meter. Such integrated systems would have to balance customer preferences (such as acceptable ranges in building temperatures, or the need to drive their plug-in hybrid for 30 miles starting at 7 a.m.) with information from the utility about power prices and power grid needs.

Advanced meters also enable the use of time-of-day pricing, in which customers are billed different rates depending on whether they use electricity at peak or off-peak times. Advanced meters are also capable of relaying real-time price signals to the customer, allowing customers to reduce their demand at times when electricity prices spike.

Real-time price signals could also improve the economics of customer-owned distributed generation. A utility company could, for example, pay higher prices for customer-generated power at times when power prices are peaking, that is, during times of limited power supplies. Customers could then earn a premium at these times, helping to minimize the utility's need to buy higher-priced power on the wholesale market.

Communication technologies are also dramatically expanding the capabilities of demand-side management. Today's systems allow customers to earn a bonus or a reduced rate by permitting utilities to, for example, remotely adjust the customer's thermostat or delay the cycling time on the customer's air conditioner. These adjustments are often unnoticeable to the customer but can add up to huge demand reductions for the utility. Such controls may eventually be incorporated into a variety of "smart" home appliances, including refrigerators and freezers.

Such customer interactions may expand dramatically if all-electric and plug-in hybrid electric vehicles become common. Because of the large amount of electricity stored in these vehicles, they can be seen as a distributed form of utility energy storage. Interactive systems can control the charging of the vehicles to avoid peak-power times and to take the greatest advantage of low-cost, off-peak power. Theoretically, interactive systems could also draw on the batteries of such vehicles during periods of peak demand.

Utility Policies: Integrated Resource Planning and Other Approaches

U.S. electric utilities were once highly regulated monopolies, and in many states they still are. As companies that are in the business of building power plants and selling power to their customers, utilities were sometimes reluctant to invest in unfamiliar technologies or to encourage energy efficiency. Integrated resource planning (IRP) is an approach meant to address that, in which a utility plans for the future by examining all of the options available to meet its future needs and selecting the options that best meet its goals. The IRP process usually has multiple goals—such as increased reliability, reduced cost, greater diversity of power supply, and reduced environmental impacts—that are typically set either by legislation or by the state's utility commission.

Energy efficiency is often the lowest-cost option for meeting future power needs, so IRP should lead to a greater use of energy efficiency. Renewable energy also has advantages for fuel diversity and the environment, so IRP should lead to a greater use of renewable energy.

IRP is much less effective in a restructured utility environment, where market factors drive individual companies to develop power plants. In this case, an oversight body for the state or region can apply the principals of IRP as it reviews individual project proposals, in an attempt to steer the completed projects in a direction that meets the goals that would typically be set by the IRP process.

However, most states have now taken a much more direct approach to resource planning by requiring a specific percentage of renewable energy to be included in the power mix for each entity that sells electricity within the state. Although, some states limit such requirements to investor-owned utilities, or set different requirements for municipal or rural utilities. This concept, called a renewables portfolio standard, is meant to guarantee the development of renewable resources within a state. Some states have also extended that concept to include energy efficiency.

Terms and Definitions

Integrated resource plan (IRP) – A plan developed by an electric power provider, sometimes as required by a public regulatory commission or agency, that defines the short- and long-term capacity additions (supply side) and demand-side management programs that it will undertake to meet projected energy demands.

Renewable portfolio standard (RPS) – A regulatory mandate to increase production of energy from renewable sources such as wind, solar, biomass, and other alternatives to fossil and nuclear electric generation. Also known as a renewable electricity standard.

For More Information

Integrated Resource Planning
www.wapa.gov/es/irp/default.htm
Information on IRP from the Western Area Power Administration.

The Renewable Portfolio Standard: A Practical Guide
www.naruc.affiniscape.com/associations/1773/files/rps.pdf
A publication prepared for the National Association of Regulatory Utility Commissioners.