ENERGY TECHNOLOGY & SYSTEMS

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Chapter- 1

Energy Technology

The Sun brings much energy to the Earth

Energy technology is an interdisciplinary engineering science having to do with the efficient, safe, environmentally friendly and economical extraction, conversion, transportation, storage and use of energy, targeted towards yielding high efficiency whilst skirting side effects on humans, nature and the environment.

For people, energy is an overwhelming need and as a scarce resource it has been an underlying cause of political conflicts and wars. The gathering and use of energy resources can be harmful to local ecosystems and may have global outcomes.

Interdisciplinary fields

As an interdisciplinary science Energy technology is linked with many interdisciplinary fields in sundry, overlapping ways.

- Physics, for thermodynamics and nuclear physics
- Chemistry for fuel, combustion, air pollution, flue gas, battery technology and fuel cells.
- Electrical engineering
- Engineering, often for fluid energy machines such as combustion engines, turbines, pumps and compressors.
- Geography, for geothermal energy and exploration for resources.
- Mining, for petrochemical and fossil fuels.
- Agriculture and forestry, for sources of renewable energy.
- Meteorology for wind and solar energy.
- Water and Waterways, for hydropower.
- Waste management, for environmental impact.
- Transportation, for energy-saving transportation systems.
- Environmental studies, for studying the effect of energy use and production on the environment, nature and climate change.

Electrical engineering

High-voltage lines for the long distance transportation of electrical energy

Electric power engineering deals with the production and use of electrical energy, which can entail the study of machines such as generators, electric motors and transformers. Infrastructure involves substations and transformer stations, power lines and electrical cable. Load management and power management over networks have meaningful sway on overall energy efficiency. Electric heating is also widely used and researched.

Thermodynamics

Thermodynamics deals with the fundamental laws of energy conversion and is drawn from theoretical Physics.

Thermal and chemical energy

A grate for a wood fire

Thermal and chemical energy are intertwined with chemistry and environmental studies. Combustion has to do with burners and chemical engines of all kinds, grates and incinerators along with their energy efficiency, pollution and operational safety.

Exhaust gas purification technology aims to lessen air pollution through sundry mechanical, thermal and chemical cleaning methods. Emission control technology is a field of process and chemical engineering. Boiler technology deals with the design, construction and operation of steam boilers and turbines, drawn from applied mechanics and materials engineering.

Energy conversion has to do with internal combustion engines, turbines, pumps, fans and so on, which are used for transportation, mechanical energy and power generation. High thermal and mechanical loads bring about operational safety worries which are dealt with through many branches of applied engineering science.

Nuclear energy

A steam turbine.

Nuclear technology deals with nuclear power production from nuclear reactors, along with the processing of nuclear fuel and disposal of radioactive waste, drawing from applied nuclear physics, nuclear chemistry and radiation science.

Nuclear power generation has been politically controversial in many countries for several decades but the electrical energy produced through nuclear fission is of worldwide importance. There are high hopes that fusion technologies will one day replace most fission reactors but this is still a research area of nuclear physics.

Renewable energy

Solar (photovoltaic) panels at a military base in the US.

Renewable energy has many branches.

Solar power

- Photovoltaic power draws electricity from solar radiation through solar cells, either locally or in large photovoltaic power plants and uses semiconductor technology.

- Solar heating uses solar panels which gather heat from sunlight to heat buildings and water.

- Solar thermal power produces electricity by converting solar heat.

Wind power

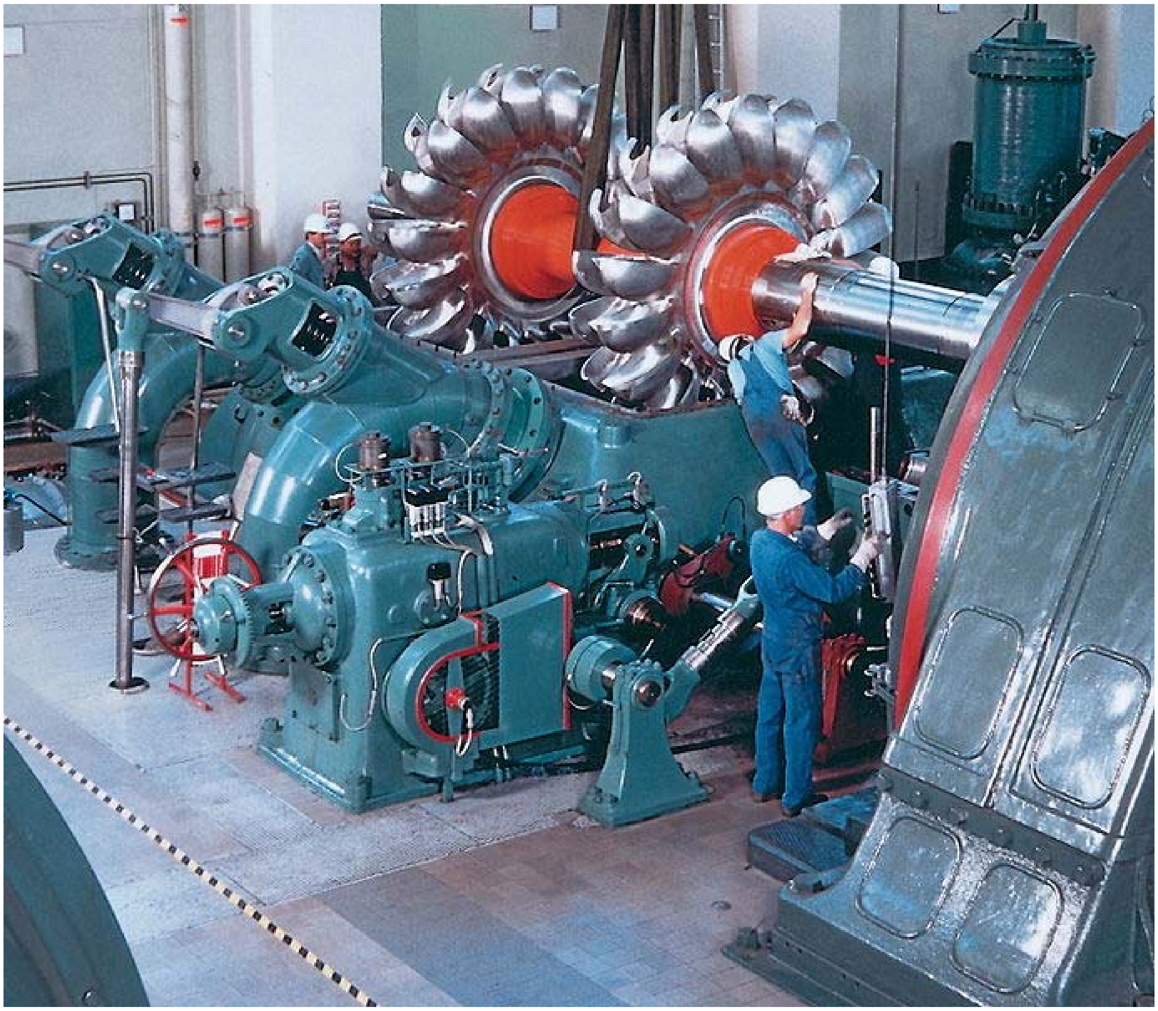
Wind turbines on Inner Mongolian grassland

Wind turbines draw energy from atmospheric currents and are designed using aerodynamics along with knowledge taken from mechanical and electrical engineering.

Geothermal

Where it can be had, geothermal energy is used for heating and electricity.

Hydropower



Building of Pelton water turbines in Germany.

Saint Anthony Falls, United States.

Hydropower, **hydraulic power** or **water power** is power that is derived from the force or energy of moving water, which may be harnessed for useful purposes. Prior to the widespread availability of commercial electric power, hydropower was used for irrigation, and operation of various machines, such as watermills, textile machines, sawmills, dock cranes, and domestic lifts.

Another method used a trompe to produce compressed air from falling water, which could then be used to power other machinery at a distance from the water.

In hydrology, hydropower is manifested in the force of the water on the riverbed and banks of a river. It is particularly powerful when the river is in flood. The force of the water results in the removal of sediment and other materials from the riverbed and banks of the river, causing erosion and other alterations.

History

Early uses of waterpower date back to Mesopotamia and ancient Egypt, where irrigation has been used since the 6th millennium BC and water clocks had been used since the early 2nd millennium BC. Other early examples of water power include the Qanat system in ancient Persia and the Turpan water system in ancient China.

Waterwheels and mills

Hydropower has been used for hundreds of years. In India, water wheels and watermills were built; in Imperial Rome, water powered mills produced flour from grain, and were also used for sawing timber and stone; in China, watermills were widely used since the Han Dynasty. The power of a wave of water released from a tank was used for extraction of metal ores in a method known as hushing. The method was first used at the Dolaucothi gold mine in Wales from 75 AD onwards, but had been developed in Spain at such mines as Las Medulas. Hushing was also widely used in Britain in the Medieval and later periods to extract lead and tin ores. It later evolved into hydraulic mining when used during the California gold rush.

In China and the rest of the Far East, hydraulically operated "pot wheel" pumps raised water into irrigation canals. At the beginning of the Industrial revolution in Britain, water was the main source of power for new inventions such as Richard Arkwright's water frame. Although the use of water power gave way to steam power in many of the larger mills and factories, it was still used during the 18th and 19th centuries for many smaller operations, such as driving the bellows in small blast furnaces (e.g. the Dyfi Furnace) and gristmills, such as those built at Saint Anthony Falls, utilizing the 50-foot (15 m) drop in the Mississippi River.

In the 1830s, at the peak of the canal-building era, hydropower was used to transport barge traffic up and down steep hills using inclined plane railroads.

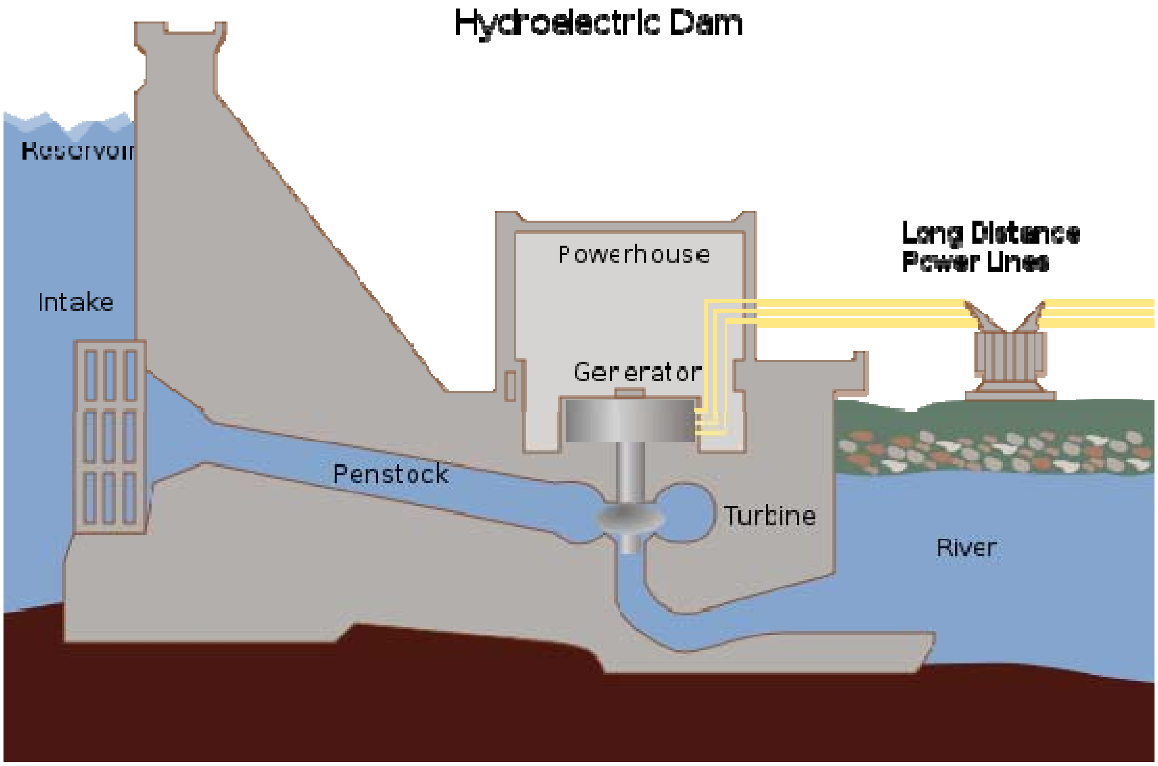
Hydraulic power pipes

Hydraulic power networks also existed, using pipes carrying pressurized liquid to transmit mechanical power from a power source, such as a pump, to end users. These were extensive in Victorian cities in the United Kingdom. A hydraulic power network was also in use in Geneva, Switzerland. The world famous Jet d'Eau was originally the only over pressure valve of this network.

Modern usage

There are several forms of water power currently in use or development. Some are purely mechanical but many primarily generate electricity. Broad categories include:

Hydroelectricity



A conventional dammed-hydro facility (hydroelectric dam) is the most common type of hydroelectric power generation.

- Conventional hydroelectric, referring to hydroelectric dams.
- Run-of-the-river hydroelectricity, which captures the kinetic energy in rivers or streams, without the use of dams.
- Pumped-storage hydroelectricity, to pump up water, and use its head to generate in times of demand.
- Tidal power, which captures energy from the tides in horizontal direction.
    - Tidal stream power, usage of stream generators, somewhat similar to that of a wind turbine.
    - Tidal barrage power, usage of a tidal dam.
    - Dynamic tidal power, utilizing large areas to generate head.

Marine energy

A Pelamis wave device under test at the European Marine Energy Centre (EMEC), Orkney, Scotland.

- Marine current power, which captures the kinetic energy from marine currents.
- Osmotic power, which channels river water into a container separated from sea water by a semi-permeable membrane.
- Ocean thermal energy, which exploits the temperature difference between deep and shallow waters.
- Tidal power, which captures energy from the tides in horizontal direction. Also a popular form of hydroelectric power generation.
    - Tidal stream power, usage of stream generators, somewhat similar to that of a wind turbine.
    - Tidal barrage power, usage of a tidal dam.
    - Dynamic tidal power, utilizing large areas to generate head.
- Wave power, the use ocean surface waves to generate power.

Calculating the amount of available power

A hydropower resource can be measured according to the amount of available power, or energy per unit time. In large reservoirs, the available power is generally only a function of the hydraulic head and rate of fluid flow. In a reservoir, the head is the height of water in the reservoir relative to its height after discharge. Each unit of water can do an amount of work equal to its weight times the head.

The amount of energy, E, released when an object of mass m drops a height h in a gravitational field of strength g is given by

$$E = mgh$$

The energy available to hydroelectric dams is the energy that can be liberated by lowering water in a controlled way. In these situations, the power is related to the mass flow rate.

$$\frac{E}{t} - \frac{m}{t}gh$$

Substituting *P* for $^{E}/_{t}$ and expressing $^{m}/_{t}$ in terms of the volume of liquid moved per unit time (the rate of fluid flow, φ) and the density of water, we arrive at the usual form of this expression:

$$P = \rho \phi g \, h$$

or

A simple formula for approximating electric power production at a hydroelectric plant is:

P = hrgk

where P is Power in kilowatts, h is height in meters, r is flow rate in cubic meters per second, g is acceleration due to gravity of 9.8 m/s2, and k is a coefficient of efficiency ranging from 0 to 1. Efficiency is often higher with larger and more modern turbines.

Some hydropower systems such as water wheels can draw power from the flow of a body of water without necessarily changing its height. In this case, the available power is the kinetic energy of the flowing water.

$$P = \frac{1}{2} \rho \phi v^2$$

where *v* is the speed of the water, or with

$$\phi = A \, v$$

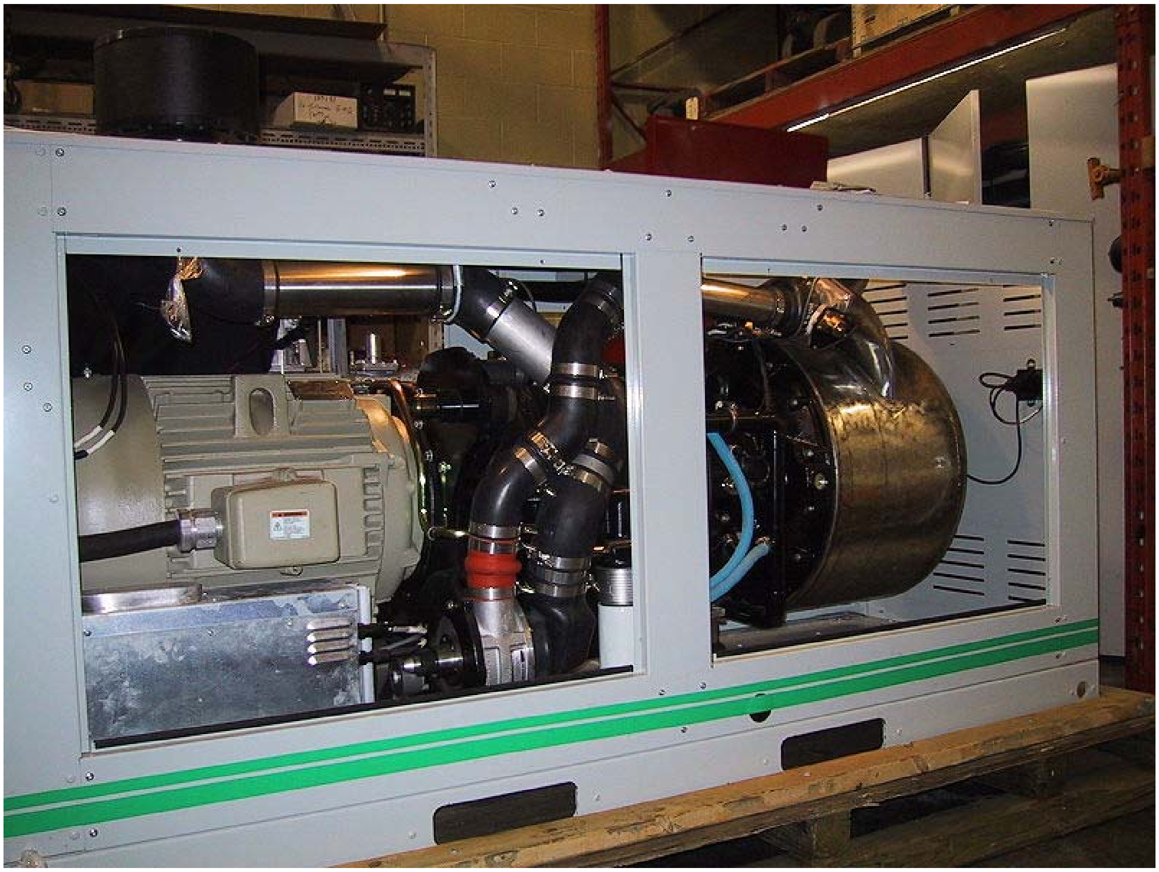
where *A* is the area through which the water passes, also

$$P = \frac{1}{2} \rho A v^3$$

Over-shot water wheels can efficiently capture both types of energy.

Hydropower draws mechanical energy from rivers, ocean waves and tides. Civil engineering is used to study and build dams, tunnels, waterways and manage coastal resources through hydrology and geology. A low speed water turbine spun by flowing water can power an electrical generator to produce electricity.

Bioenergy



Stirling engine capable of producing electricity from biomass combustion heat.

Bioenergy is renewable energy made available from materials derived from biological sources. In its most narrow sense it is a synonym to biofuel, which is fuel derived from biological sources. In its broader sense it includes biomass, the biological material used as a biofuel, as well as the social, economic, scientific and technical fields associated with using biological sources for energy. This is a common misconception, as bioenergy is the energy extracted from the biomass, as the biomass is the fuel and the bioenergy is the energy contained in the fuel.

Biomass is any organic material which has stored sunlight in the form of chemical energy. As a fuel it may include wood, wood waste, straw, manure, sugar cane, and many other byproducts from a variety of agricultural processes.

There is a slight tendency for the word *bioenergy* to be favoured in Europe compared with *biofuel* in North America.

Solid Biomass

Simple use of biomass fuel (Combustion of wood for heat).

Biomass is material derived from recently living organisms, which includes plants, animals and their byproducts. Manure, garden waste and crop residues are all sources of biomass. It is a renewable energy source based on the carbon cycle, unlike other natural resources such as petroleum, coal, and nuclear fuels.

Animal waste is a persistent and unavoidable pollutant produced primarily by the animals housed in industrial-sized farms.

There are also agricultural products being grown for biofuel production. These include corn, and soybeans and to some extend willow and switchgrass on a pre-commercial research level, primarily in the United States; rapeseed, wheat, sugar beet, and willow (15,000 ha in Sweden) primarily in Europe; sugar cane in Brazil; palm oil and miscanthus in Southeast Asia; sorghum and cassava in China; and jatropha in India. Hemp has also been proven to work as a biofuel. Biodegradable outputs from industry, agriculture, forestry and households can be used for biofuel production, using e.g. anaerobic digestion to produce biogas, gasification to produce syngas or by direct combustion. Examples of biodegradable wastes include straw, timber, manure, rice husks, sewage, and food waste.

The use of biomass fuels can therefore contribute to waste management as well as fuel security and help to prevent or slow down climate change, although alone they are not a comprehensive solution to these problems. You can get bioenergy from almost everything, from fire to planting a tree. Fire gives off a fume and needs something to fuel it like grass, trees, and shrub or gas. therefore it can be used for good things or bad things like burning someone's house down or clearing land to farm.

Electricity generation from biomass

Electricity from sugarcane bagasse in Brazil

Sugarcane (*Saccharum officinarum*) plantation ready for harvest, Ituverava, São Paulo State. Brazil.

Sugar/Ethanol Plant located in Piracicaba, São Paulo State. This plant produces the electricity it needs from baggasse residuals from sugarcane left over by the milling process, and it sells the surplus electricity to the public grid.

Sucrose accounts for little more than 30% of the chemical energy stored in the mature plant; 35% is in the leaves and stem tips, which are left in the fields during harvest, and 35% are in the fibrous material (bagasse) left over from pressing.

The production process of sugar and ethanol in Brazil takes full advantage of the energy stored in sugarcane. Part of the baggasse is currently burned at the mill to provide heat for distillation and electricity to run the machinery. This allows ethanol plants to be energetically self-sufficient and even sell surplus electricity to utilities; current production is 600 MW for self-use and 100 MW for sale. This secondary activity is expected to boom now that utilities have been induced to pay "fair price "(about US$10/GJ or US$0.036/kWh) for 10 year contracts. This is approximately half of what the World Bank considers the reference price for investing in similar projects (see below). The energy is especially valuable to utilities because it is produced mainly in the dry season when hydroelectric dams are running low. Estimates of potential power generation from bagasse range from 1,000 to 9,000 MW, depending on technology. Higher estimates assume gasification of biomass, replacement of current low-pressure steam boilers and turbines by high-pressure ones, and use of harvest trash currently left behind in the fields. For comparison, Brazil's Angra I nuclear plant generates 657 MW.

Presently, it is economically viable to extract about 288 MJ of electricity from the residues of one tonne of sugarcane, of which about 180 MJ are used in the plant itself. Thus a medium-size distillery processing 1 million tonnes of sugarcane per year could sell about 5 MW of surplus electricity. At current prices, it would earn US$ 18 million from sugar and ethanol sales, and about US$ 1 million from surplus electricity sales. With advanced boiler and turbine technology, the electricity yield could be increased to 648 MJ per tonne of sugarcane, but current electricity prices do not justify the necessary investment. (According to one report, the World Bank would only finance investments in bagasse power generation if the price were at least US$19/GJ or US$0.068/kWh.)

Bagasse burning is environmentally friendly compared to other fuels like oil and coal. Its ash content is only 2.5% (against 30-50% of coal), and it contains no sulfur. Since it burns at relatively low temperatures, it produces little nitrous oxides. Moreover, bagasse is being sold for use as a fuel (replacing heavy fuel oil) in various industries, including citrus juice concentrate, vegetable oil, ceramics, and tyre recycling. The state of São Paulo alone used 2 million tonnes, saving about US$ 35 million in fuel oil imports.

Researchers working with cellulosic ethanol are trying to make the extraction of ethanol from sugarcane bagasse and other plants viable on an industrial scale.

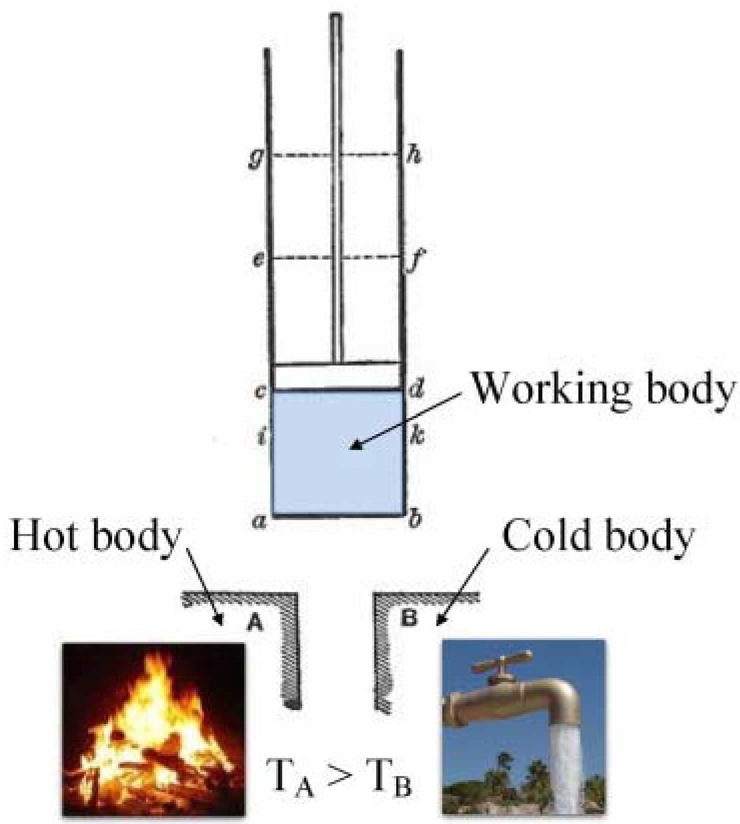
Delhi Technological University has done pioneering research in the sphere of Third Generation Biofuel research. Delhi Technological University(Formerly Delhi College Of Engineering)is also organizing the 1st International Conference On New Frontiers in Bio-fuels.The Conference aims to harbor a platform facilitating the exchange of ideas and experience among scientists involved in various segments of biofuel research.

Bioenergy deals with the gathering, processing and use of biomasses grown in biological manufacturing, agriculture and forestry from which power plants can draw burning fuel. Ethanol, methanol (both controversial) or hydrogen for fuel cells can be had from these technologies and used to generate electricity.

Chapter- 2

Energy & Technology in Physics

Thermodynamics



Annotated color version of the original 1824 Carnot heat engine showing the hot body (boiler), working body (system, steam), and cold body (water), the letters labeled according to the stopping points in Carnot cycle.

Thermodynamics is the science of energy conversion involving heat and other forms of energy, most notably mechanical work. It studies and interrelates the macroscopic variables, such as temperature, volume and pressure, which describe physical, thermodynamic systems.

Historically, thermodynamics developed out of a desire to increase the efficiency of early steam engines, particularly through the work of French physicist Nicolas Léonard Sadi Carnot (1824) who believed that engine efficiency was the key that could help France win the Napoleonic Wars. Scottish physicist Lord Kelvin was the first to formulate a concise definition of thermodynamics when he stated in 1854:

Thermo-dynamics is the subject of the relation of heat to forces acting between contiguous parts of bodies, and the relation of heat to electrical agency.

Two fields of thermodynamics emerged in the following decades. Statistical thermodynamics, or statistical mechanics, (1860) concerned itself with statistical predictions of the collective motion of particles from their microscopic behavior, while chemical thermodynamics (1873) studies the nature of the role of entropy in the process of chemical reaction.

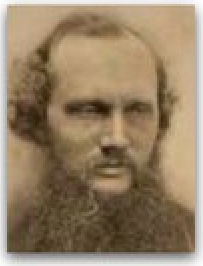
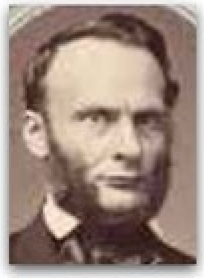
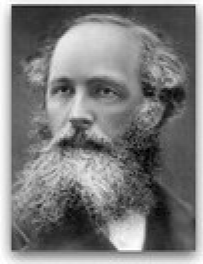
Introduction

The starting point for most thermodynamic considerations are the laws of thermodynamics, which postulate that energy can be exchanged between physical systems as heat or work. They also postulate the existence of a quantity named entropy, which can be defined for any isolated system that is in thermodynamic equilibrium.

In thermodynamics, interactions between large ensembles of objects are studied and categorized. Central to this are the concepts of *system* and *surroundings*. A system is composed of particles, whose average motions define its properties, which in turn are related to one another through equations of state. Properties can be combined to express internal energy and thermodynamic potentials, which are useful for determining conditions for equilibrium and spontaneous processes.

With these tools, thermodynamics can be used to describe how systems respond to changes in their environment. This can be applied to a wide variety of topics in science and engineering, such as engines, phase transitions, chemical reactions, transport phenomena, and even black holes. The results of thermodynamics are essential for other fields of physics and for chemistry, chemical engineering, aerospace engineering, mechanical engineering, cell biology, biomedical engineering, materials science, and economics, to name a few.

The present article is focused mainly on classical thermodynamics, which is concerned with systems in thermodynamic equilibrium. It is wise to distinguish classical thermodynamics from non-equilibrium thermodynamics, which is concerned with systems that are not in thermodynamic equilibrium.

École Polytechnique	Glasgow school	Berlin school	Edinburgh school
			
Sadi Carnot (1796-1832)	William Thomson (1824-1907)	Rudolf Clausius (1822-1888)	James Maxwell (1831-1879)
Vienna school	Gibbsian school	Dresden school	Dutch school
			
Ludwig Boltzmann (1844-1906)	Willard Gibbs (1839-1903)	Gustav Zeuner (1828-1907)	Johannes der Waals (1837-1923)

The thermodynamicists representative of the original eight founding schools of thermodynamics. The schools with the most-lasting effect in founding the modern versions of thermodynamics are the Berlin school, particularly as established in Rudolf Clausius's 1865 textbook *The Mechanical Theory of Heat*, the Vienna school, with the statistical mechanics of Ludwig Boltzmann, and the Gibbsian school at Yale University, American engineer Willard Gibbs' 1876 *On the Equilibrium of Heterogeneous Substances* launching chemical thermodynamics.

History

The history of thermodynamics as a scientific discipline generally begins with Otto von Guericke who, in 1650, built and designed the world's first vacuum pump and demonstrated a vacuum using his Magdeburg hemispheres. Guericke was driven to make a vacuum in order to disprove Aristotle's long-held supposition that 'nature abhors a vacuum'. Shortly after Guericke, the English physicist and chemist Robert Boyle had learned of Guericke's designs and, in 1656, in coordination with English scientist Robert Hooke, built an air pump. Using this pump, Boyle and Hooke noticed a correlation between pressure, temperature, and volume. In time, Boyle's Law was formulated, which states that pressure and volume are inversely proportional. Then, in 1679, based on these concepts, an associate of Boyle's named Denis Papin built a steam digester, which was a closed vessel with a tightly fitting lid that confined steam until a high pressure was generated.

Later designs implemented a steam release valve that kept the machine from exploding. By watching the valve rhythmically move up and down, Papin conceived of the idea of a piston and a cylinder engine. He did not, however, follow through with his design. Nevertheless, in 1697, based on Papin's designs, engineer Thomas Savery built the first engine, followed by Thomas Newcomen in 1712. Although these early engines were crude and inefficient, they attracted the attention of the leading scientists of the time.

The fundamental concepts of heat capacity and latent heat, which were necessary for the development of thermodynamics, were developed by Professor Joseph Black at the University of Glasgow, where James Watt was employed as an instrument maker. Black and Watt performed experiments together, but it was Watt who conceived the idea of the external condenser which resulted in a large increase in steam engine efficiency. Drawing on all the previous work led Sadi Carnot, the "father of thermodynamics", to publish *Reflections on the Motive Power of Fire* (1824), a discourse on heat, power, and engine efficiency. The paper outlined the basic energetic relations between the Carnot engine, the Carnot cycle, and motive power. It marked the start of thermodynamics as a modern science.

The first thermodynamic textbook was written in 1859 by William Rankine, originally trained as a physicist and a civil and mechanical engineering professor at the University of Glasgow. The first and second laws of thermodynamics emerged simultaneously in the 1850s, primarily out of the works of William Rankine, Rudolf Clausius, and William Thomson (Lord Kelvin).

The foundations of statistical thermodynamics were set out by physicists such as James Clerk Maxwell, Ludwig Boltzmann, Max Planck, Rudolf Clausius and J. Willard Gibbs.

During the years 1873-76 the American mathematical physicist Josiah Willard Gibbs published a series of three papers, the most famous being *On the Equilibrium of Heterogeneous Substances*, in which he showed how thermodynamic processes could be graphically analyzed, by studying the energy, entropy, volume, temperature and pressure of the thermodynamic system in such a manner, one can determine if a process would occur spontaneously. During the early 20th century, chemists such as Gilbert N. Lewis, Merle Randall, and E. A. Guggenheim began to apply the mathematical methods of Gibbs to the analysis of chemical processes.

Etymology

The etymology of *thermodynamics* has an intricate history.It was first spelled in a hyphenated form as an adjective (*thermo-dynamic*) and from 1854 to 1868 as the noun *thermo-dynamics* to represent the science of generalized heat engines.

American biophysisist Donald Haynie claims that *thermodynamics* was coined in 1840 from the Greek root θέρμη *therme,* meaning heat and δύναμις,*dynamis,* meaning power. However, this etymology has been cited as unlikely.

Pierre Perrot claims that the term *thermodynamics* was coined by James Joule in 1858 to designate the science of relations between heat and power., however, Joule never used that term, but used instead the term *perfect thermo-dynamic engine* in reference to Thomson's 1849 phraseology.

By 1858, *thermo-dynamics*, as a functional term, was used in William Thomson's paper *An Account of Carnot's Theory of the Motive Power of Heat.*

Interpretations

Thermodynamics has developed into several related branches of science, each with a different focus.

Classical thermodynamics

Classical thermodynamics is the description of the states of thermodynamical systems at near-equilibrium, using macroscopic, empirical properties directly measurable in the laboratory. It is used to model exchanges of energy, work and heat based on the laws of thermodynamics. The qualifier *classical* reflects the fact that it represents the level of knowledge in the early 19th century. An atomic interpretation of these principles was provided later by the development of statistical mechanics.

Statistical mechanics

Statistical mechanics (or statistical thermodynamics) emerged only with the development of atomic and molecular theories in the late 19th century and early 20th century, giving thermodynamics a molecular interpretation. This field relates the microscopic properties of individual atoms and molecules to the macroscopic or bulk properties of materials that can be observed in everyday life, thereby explaining thermodynamics as a natural result of statistics and mechanics (classical and quantum) at the microscopic level. This statistical approach is in contrast to classical thermodynamics, which is a more phenomenological approach.

Chemical thermodynamics

Chemical thermodynamics is the study of the interrelation of energy with chemical reactions or with a physical change of state within the confines of the laws of thermodynamics.

Treatment of equilibrium

Equilibrium thermodynamics is the systematic study of transformations of matter and energy in systems as they approach equilibrium. The word equilibrium implies a state of balance. In an equilibrium state there are no unbalanced potentials, or driving forces, within the system. A central aim in equilibrium thermodynamics is: given a system in a well-defined initial state, subject to accurately specified constraints, to calculate what the state of the system will be once it has reached equilibrium.

Non-equilibrium thermodynamics is a branch of thermodynamics that deals with systems that are not in thermodynamic equilibrium. Most systems found in nature are not in thermodynamic equilibrium because they are not in stationary states, and are continuously and discontinuously subject to flux of matter and energy to and from other systems. The thermodynamic study of non-equilibrium systems requires more general concepts than are dealt with by equilibrium thermodynamics. Many natural systems still today remain beyond the scope of currently known macroscopic thermodynamic methods.

Laws of thermodynamics

Thermodynamics defines four laws which do not depend on the details of the systems under study or how they interact. Hence these laws are generally valid and can be applied to systems about which one knows nothing other than the balance of energy and matter transfer. Examples of such systems include Einstein's prediction of spontaneous emission, and ongoing research into the thermodynamics of black holes.

These four laws are:

- Zeroth law of thermodynamics: *If two systems are in thermal equilibrium with a third, they are also in thermal equilibrium with each other.*

This statement implies that thermal equilibrium is an equivalence relation on the set of thermodynamic systems under consideration. Systems are said to be in equilibrium if the small, random exchanges between them (eg. Brownian motion) do not lead to a net change in energy. This law is tacitly assumed in every measurement of temperature. Thus, if one seeks to decide if two bodies are at the same temperature, it is not necessary to bring them into contact and measure any changes of their observable properties in time. The law provides a fundamental definition of temperature and justification for the construction of practical thermometers.

It is interesting to note that the zeroth law was not initially recognized as a law. The need to for the zeroth law was not initially realized, so the first, second, and third laws were explicitly stated and found common acceptance in the physics community first. Once the importance of the zeroth law was realized, it was impracticable to renumber the other laws, hence the *zeroth.*

- First law of thermodynamics: *The internal energy of an isolated system is constant.*

The first law of thermodynamics is an expression of the principle of conservation of energy. It states that energy can be transformed (changed from one form to another), but cannot be created or destroyed.

The first law is usually formulated by saying that the change in the internal energy of a closed thermodynamic system is equal to the difference between the of heat supplied to the system and the amount of work done by the system on its surroundings. It is important to note that internal energy is a state of the system whereas heat and work modify the state of the system. In other words, a specific internal energy of a system may be achieved by any combination of heat and work; the manner by which a system achieves a specific internal energy is path independent.

- Second law of thermodynamics: *Heat cannot spontaneously flow from a colder location to a hotter location.*

The second law of thermodynamics is an expression of the universal principle of decay observable in nature. The second law is an observation of the fact that over time, differences in temperature, pressure, and chemical potential tend to even out in a physical system that is isolated from the outside world. Entropy is a measure of how much this evening-out process has progressed. The entropy of an isolated system which is not in equilibrium will tend to increase over time, approaching a maximum value at equilibrium.

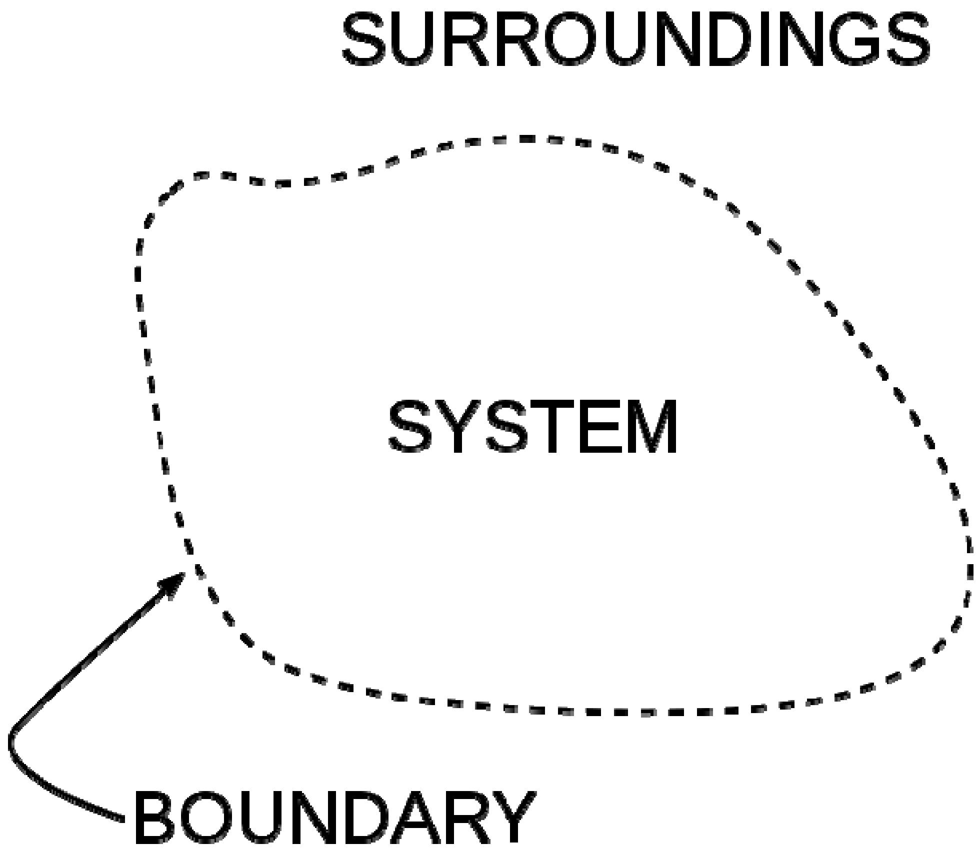
In classical thermodynamics, the second law is a basic postulate applicable to any system involving heat energy transfer; in statistical thermodynamics, the second law is a consequence of the assumed randomness of molecular chaos. There are many versions of the second law, but they all have the same effect, which is to explain the phenomenon of irreversibility in nature.

- Third law of thermodynamics: *As a system approaches absolute zero, all processes cease and the entropy of the system approaches a minimum value.*

The third law of thermodynamics is a statistical law of nature regarding entropy and the impossibility of reaching absolute zero of temperature. This law provides an absolute reference point for the determination of entropy. The entropy determined relative to this point is the absolute entropy. Alternate definitions are, "the entropy of all systems and of all states of a system is smallest at absolute zero," or equivalently "it is impossible to reach the absolute zero of temperature by any finite number of processes".

Absolute zero, at which all activity would stop if it were possible to happen, is −273.15 °C (degrees Celsius), or −459.67 °F (degrees Fahrenheit) or 0 K (kelvin).

System models



A diagram of a generic thermodynamic system

An important concept in thermodynamics is the thermodynamic system, a precisely defined region of the universe under study. Everything in the universe except the system is known as the *surroundings*. A system is separated from the remainder of the universe by a *boundary* which may be notional or not, but which by convention delimits a finite volume. Exchanges of work, heat, or matter between the system and the surroundings take place across this boundary.

In practice, the boundary is simply an imaginary dotted line drawn around a volume when there is going to be a change in the internal energy of that volume. Anything that passes across the boundary that effects a change in the internal energy needs to be accounted for in the energy balance equation. The volume can be the region surrounding a single atom resonating energy, such as Max Planck defined in 1900; it can be a body of steam or air in a steam engine, such as Sadi Carnot defined in 1824; it can be the body of a tropical cyclone, such as Kerry Emanuel theorized in 1986 in the field of atmospheric thermodynamics; it could also be just one nuclide (i.e. a system of quarks) as hypothesized in quantum thermodynamics.

Boundaries are of four types: fixed, moveable, real, and imaginary. For example, in an engine, a fixed boundary means the piston is locked at its position; as such, a constant volume process occurs. In that same engine, a moveable boundary allows the piston to move in and out. For closed systems, boundaries are real while for open system boundaries are often imaginary.

Generally, thermodynamics distinguishes five classes of systems, defined in terms of what is allowed to cross their boundaries:

Interactions of thermodynamic systems

Type of system	Mass flow	Work	Heat
Open	✓	✓	✓
Closed	✗	✓	✓
Isolated	✗	✗	✗

As time passes in an isolated system, internal differences in the system tend to even out and pressures and temperatures tend to equalize, as do density differences. A system in which all equalizing processes have gone to completion is considered to be in a state of thermodynamic equilibrium.

In thermodynamic equilibrium, a system's properties are, by definition, unchanging in time. Systems in equilibrium are much simpler and easier to understand than systems which are not in equilibrium. Often, when analysing a thermodynamic process, it can be assumed that each intermediate state in the process is at equilibrium. This will also considerably simplify the situation. Thermodynamic processes which develop so slowly as to allow each intermediate step to be an equilibrium state are said to be reversible processes.

States and processes

When a system is at equilibrium under a given set of conditions, it is said to be in a definite thermodynamic state. The state of the system can be described by a number of intensive variables and extensive variables. The properties of the system can be described by an equation of state which specifies the relationship between these variables. State may be thought of as the instantaneous quantitative description of a system with a set number of variables held constant.

A thermodynamic process may be defined as the energetic evolution of a thermodynamic system proceeding from an initial state to a final state. Typically, each thermodynamic process is distinguished from other processes in energetic character according to what parameters, such as temperature, pressure, or volume, etc., are held fixed. Furthermore, it is useful to group these processes into pairs, in which each variable held constant is one member of a conjugate pair.

Several commonly studied thermodynamic processes are:

- Isobaric process: occurs at constant pressure
- Isochoric process: occurs at constant volume (also called isometric/isovolumetric)
- Isothermal process: occurs at a constant temperature
- Adiabatic process: occurs without loss or gain of energy by heat
- Isentropic process: a reversible adiabatic process, occurs at a constant entropy
- Isenthalpic process: occurs at a constant enthalpy
- Steady state process: occurs without a change in the internal energy

Instrumentation

There are two types of thermodynamic instruments, the **meter** and the **reservoir**. A thermodynamic meter is any device which measures any parameter of a thermodynamic system. In some cases, the thermodynamic parameter is actually defined in terms of an idealized measuring instrument. For example, the zeroth law states that if two bodies are in thermal equilibrium with a third body, they are also in thermal equilibrium with each other. This principle, as noted by James Maxwell in 1872, asserts that it is possible to measure temperature. An idealized thermometer is a sample of an ideal gas at constant pressure. From the ideal gas law $pV=nRT$, the volume of such a sample can be used as an indicator of temperature; in this manner it defines temperature. Although pressure is defined mechanically, a pressure-measuring device, called a barometer may also be constructed from a sample of an ideal gas held at a constant temperature. A calorimeter is a device which is used to measure and define the internal energy of a system.

A thermodynamic reservoir is a system which is so large that it does not appreciably alter its state parameters when brought into contact with the test system. It is used to impose a particular value of a state parameter upon the system. For example, a pressure reservoir is a system at a particular pressure, which imposes that pressure upon any test system that it is mechanically connected to. The Earth's atmosphere is often used as a pressure reservoir.

Conjugate variables

The central concept of thermodynamics is that of energy, the ability to do work. By the First Law, the total energy of a system and its surroundings is conserved. Energy may be transferred into a system by heating, compression, or addition of matter, and extracted from a system by cooling, expansion, or extraction of matter. In mechanics, for example, energy transfer equals the product of the force applied to a body and the resulting displacement.

Conjugate variables are pairs of thermodynamic concepts, with the first being akin to a "force" applied to some thermodynamic system, the second being akin to the resulting "displacement," and the product of the two equalling the amount of energy transferred. The common conjugate variables are:

- Pressure-volume (the mechanical parameters);

- Temperature-entropy (thermal parameters);
- Chemical potential-particle number (material parameters).

Potentials

Thermodynamic potentials are different quantitative measures of the stored energy in a system. Potentials are used to measure energy changes in systems as they evolve from an initial state to a final state. The potential used depends on the constraints of the system, such as constant temperature or pressure. For example, the Helmholtz and Gibbs energies are the energies available in a system to do useful work when the temperature and volume or the pressure and temperature are fixed, respectively.

The five most well known potentials are:

Name	Symbol	Formula	Natural variables
Internal energy	U	$\int (T dS - p dV + \sum_i \mu_i dN_i)$	$S, V, \{N_i\}$
Helmholtz free energy	F, A	$U - TS$	$T, V, \{N_i\}$
Enthalpy	H	$U + pV$	$S, p, \{N_i\}$
Gibbs free energy	G	$U + pV - TS$	$T, p, \{N_i\}$
Landau Potential (Grand potential)	Ω, Φ_G	$U - TS - \sum_i \mu_i N_i$	$T, V, \{\mu_i\}$

where T is the temperature, S the entropy, p the pressure, V the volume, μ the chemical potential, N the number of particles in the system, and i is the count of particles types in the system.

Thermodynamic potentials can be derived from the energy balance equation applied to a thermodynamic system. Other thermodynamic potentials can also be obtained through Legendre transformation.

Nuclear physics

Nuclear physics is the field of physics that studies the building blocks and interactions of atomic nuclei. The most commonly known applications of nuclear physics are nuclear power and nuclear weapons, but the research has provided wider applications, including those in medicine (nuclear medicine, magnetic resonance imaging), materials engineering (ion implantation) and archaeology (radiocarbon dating).

The field of particle physics evolved out of nuclear physics and, for this reason, has been included under the same term in earlier times.

History

The history of nuclear physics as a discipline distinct from atomic physics starts with the discovery of radioactivity by Henri Becquerel in 1896, while investigating phosphorescence in uranium salts. The discovery of the electron by J. J. Thomson a year later was an indication that the atom had internal structure. At the turn of the 20th century the accepted model of the atom was J. J. Thomson's "plum pudding" model in which the atom was a large positively charged ball with small negatively charged electrons embedded inside of it. By the turn of the century physicists had also discovered three types of radiation coming from atoms, which they named alpha, beta, and gamma radiation. Experiments in 1911 by Lise Meitner and Otto Hahn, and by James Chadwick in 1914 discovered that the beta decay spectrum was continuous rather than discrete. That is, electrons were ejected from the atom with a range of energies, rather than the discrete amounts of energies that were observed in gamma and alpha decays. This was a problem for nuclear physics at the time, because it indicated that energy was not conserved in these decays.

In 1905, Albert Einstein formulated the idea of mass–energy equivalence. While the work on radioactivity by Becquerel, Pierre and Marie Curie predates this, an explanation of the source of the energy of radioactivity would have to wait for the discovery that the nucleus itself was composed of smaller constituents, the nucleons.

Rutherford's team discovers the nucleus

In 1907 Ernest Rutherford published "Radiation of the α Particle from Radium in passing through Matter." Geiger expanded on this work in a communication to the Royal Society with experiments he and Rutherford had done passing α particles through air, aluminum foil and gold leaf. More work was published in 1909 by Geiger and Marsden and further greatly expanded work was published in 1910 by Geiger, In 1911-2 Rutherford went before the Royal Society to explain the experiments and propound the new theory of the atomic nucleus as we now understand it.

The key experiment behind this announcement happened in 1910 at the University of Manchester, as Ernest Rutherford's team performed a remarkable experiment in which Hans Geiger and Ernest Marsden under his supervision fired alpha particles (helium nuclei) at a thin film of gold foil. The plum pudding model predicted that the alpha particles should come out of the foil with their trajectories being at most slightly bent. Rutherford had the idea to instruct his team to look for something that shocked him to actually observe: a few particles were scattered through large angles, even completely backwards, in some cases. He likened it to firing a bullet at tissue paper and having it bounce off. The discovery, beginning with Rutherford's analysis of the data in 1911, eventually led to the Rutherford model of the atom, in which the atom has a very small, very dense nucleus containing most of its mass, and consisting of heavy positively charged particles with embedded electrons in order to balance out the charge (since the neutron was unknown). As an example, in this model (which is not the modern one) nitrogen-14 consisted of a nucleus with 14 protons and 7 electrons (21 total particles), and the nucleus was surrounded by 7 more orbiting electrons.

The Rutherford model worked quite well until studies of nuclear spin were carried out by Franco Rasetti at the California Institute of Technology in 1929. By 1925 it was known that protons and electrons had a spin of 1/2, and in the Rutherford model of nitrogen-14, 20 of the total 21 nuclear particles should have paired up to cancel each other's spin, and the final odd particle should have left the nucleus with a net spin of 1/2. Rasetti discovered, however, that nitrogen-14 has a spin of 1.

James Chadwick discovers the neutron

In 1932 Chadwick realized that radiation that had been observed by Walther Bothe, Herbert L. Becker, Irène and Frédéric Joliot-Curie was actually due to a neutral particle of about the same mass as the proton, that he called the neutron (following a suggestion about the need for such a particle, by Rutherford). In the same year Dmitri Ivanenko suggested that neutrons were in fact spin 1/2 particles and that the nucleus contained neutrons to explain the mass not due to protons, and that there were no electrons in the nucleus—only protons and neutrons. The neutron spin immediately solved the problem of the spin of nitrogen-14, as the one unpaired proton and one unpaired neutron in this model, each contribute a spin of 1/2 in the same direction, for a final total spin of 1.

With the discovery of the neutron, scientists at last could calculate what fraction of binding energy each nucleus had, from comparing the nuclear mass with that of the protons and neutrons which composed it. Differences between nuclear masses were calculated in this way and—when nuclear reactions were measured—were found to agree with Einstein's calculation of the equivalence of mass and energy to high accuracy (within 1 percent as of in 1934).

Yukawa's meson postulated to bind nuclei

In 1935 Hideki Yukawa proposed the first significant theory of the strong force to explain how the nucleus holds together. In the Yukawa interaction a virtual particle, later called a meson, mediated a force between all nucleons, including protons and neutrons. This force explained why nuclei did not disintegrate under the influence of proton repulsion, and it also gave an explanation of why the attractive strong force had a more limited range than the electromagnetic repulsion between protons. Later, the discovery of the pi meson showed it to have the properties of Yukawa's particle.

With Yukawa's papers, the modern model of the atom was complete. The center of the atom contains a tight ball of neutrons and protons, which is held together by the strong nuclear force, unless it is too large. Unstable nuclei may undergo alpha decay, in which they emit an energetic helium nucleus, or beta decay, in which they eject an electron (or positron). After one of these decays the resultant nucleus may be left in an excited state, and in this case it decays to its ground state by emitting high energy photons (gamma decay).

The study of the strong and weak nuclear forces (the latter explained by Enrico Fermi via Fermi's interaction in 1934) led physicists to collide nuclei and electrons at ever higher energies. This research became the science of particle physics, the crown jewel of which is the standard model of particle physics which unifies the strong, weak, and electromagnetic forces.

Modern nuclear physics

A heavy nucleus can contain hundreds of nucleons which means that with some approximation it can be treated as a classical system, rather than a quantum-mechanical one. In the resulting liquid-drop model, the nucleus has an energy which arises partly from surface tension and partly from electrical repulsion of the protons. The liquid-drop model is able to reproduce many features of nuclei, including the general trend of binding energy with respect to mass number, as well as the phenomenon of nuclear fission.

Superimposed on this classical picture, however, are quantum-mechanical effects, which can be described using the nuclear shell model, developed in large part by Maria Goeppert-Mayer. Nuclei with certain numbers of neutrons and protons (the magic numbers 2, 8, 20, 50, 82, 126, ...) are particularly stable, because their shells are filled.

Other more complicated models for the nucleus have also been proposed, such as the interacting boson model, in which pairs of neutrons and protons interact as bosons, analogously to Cooper pairs of electrons.

Much of current research in nuclear physics relates to the study of nuclei under extreme conditions such as high spin and excitation energy. Nuclei may also have extreme shapes (similar to that of Rugby balls) or extreme neutron-to-proton ratios. Experimenters can create such nuclei using artificially induced fusion or nucleon transfer reactions, employing ion beams from an accelerator. Beams with even higher energies can be used to create nuclei at very high temperatures, and there are signs that these experiments have produced a phase transition from normal nuclear matter to a new state, the quark-gluon plasma, in which the quarks mingle with one another, rather than being segregated in triplets as they are in neutrons and protons.

Modern topics in nuclear physics

Spontaneous changes from one nuclide to another: nuclear decay

There are 80 elements which have at least one stable isotope (defined as isotopes never observed to decay), and in total there are about 255 such stable isotopes. However, there are thousands more well-characterized isotopes which are unstable. These radioisotopes may be unstable and decay in all timescales ranging from fractions of a second to weeks, years, or many billions of years.

For example, if a nucleus has too few or too many neutrons it may be unstable, and will decay after some period of time. For example, in a process called beta decay a nitrogen-16 atom (7 protons, 9 neutrons) is converted to an oxygen-16 atom (8 protons, 8 neutrons) within a few seconds of being created. In this decay a neutron in the nitrogen nucleus is turned into a proton and an electron and antineutrino, by the weak nuclear force. The element is transmuted to another element in the process, because while it previously had seven protons (which makes it nitrogen) it now has eight (which makes it oxygen).

In alpha decay the radioactive element decays by emitting a helium nucleus (2 protons and 2 neutrons), giving another element, plus helium-4. In many cases this process continues through several steps of this kind, including other types of decays, until a stable element is formed.

In gamma decay, a nucleus decays from an excited state into a lower state by emitting a gamma ray. It is then stable. The element is not changed in the process.

Other more exotic decays are possible. For example, in internal conversion decay, the energy from an excited nucleus may be used to eject one of the inner orbital electrons from the atom, in a process which produces high speed electrons, but is not beta decay, and (unlike beta decay) does not transmute one element to another.

Nuclear fusion

When two low mass nuclei come into very close contact with each other it is possible for the strong force to fuse the two together. It takes a great deal of energy to push the nuclei close enough together for the strong or nuclear forces to have an effect, so the process of nuclear fusion can only take place at very high temperatures or high pressures. Once the nuclei are close enough together the strong force overcomes their electromagnetic repulsion and squishes them into a new nucleus. A very large amount of energy is released when light nuclei fuse together because the binding energy per nucleon increases with mass number up until nickel-62. Stars like our sun are powered by the fusion of four protons into a helium nucleus, two positrons, and two neutrinos. The *uncontrolled* fusion of hydrogen into helium is known as thermonuclear runaway. Research to find an economically viable method of using energy from a *controlled* fusion reaction is currently being undertaken by various research establishments.

Nuclear fission

For nuclei heavier than nickel-62 the binding energy per nucleon decreases with the mass number. It is therefore possible for energy to be released if a heavy nucleus breaks apart into two lighter ones. This splitting of atoms is known as nuclear fission.

The process of alpha decay may be thought of as a special type of spontaneous nuclear fission. This process produces a highly asymmetrical fission because the four particles which make up the alpha particle are especially tightly bound to each other, making production of this nucleus in fission particularly likely.

For certain of the heaviest nuclei which produce neutrons on fission, and which also easily absorb neutrons to initiate fission, a self-igniting type of neutron-initiated fission can be obtained, in a so-called chain reaction. (Chain reactions were known in chemistry before physics, and in fact many familiar processes like fires and chemical explosions are chemical chain reactions.) The fission or "nuclear" chain-reaction, using fission-produced neutrons, is the source of energy for nuclear power plants and fission type nuclear bombs such as the two that the United States used against Hiroshima and Nagasaki at the end of World War II. Heavy nuclei such as uranium and thorium may undergo spontaneous fission, but they are much more likely to undergo decay by alpha decay.

For a neutron-initiated chain-reaction to occur, there must be a critical mass of the element present in a certain space under certain conditions (these conditions slow and conserve neutrons for the reactions). There is one known example of a natural nuclear fission reactor, which was active in two regions of Oklo, Gabon, Africa, over 1.5 billion years ago. Measurements of natural neutrino emission have demonstrated that around half of the heat emanating from the Earth's core results from radioactive decay. However, it is not known if any of this results from fission chain-reactions.

Production of heavy elements

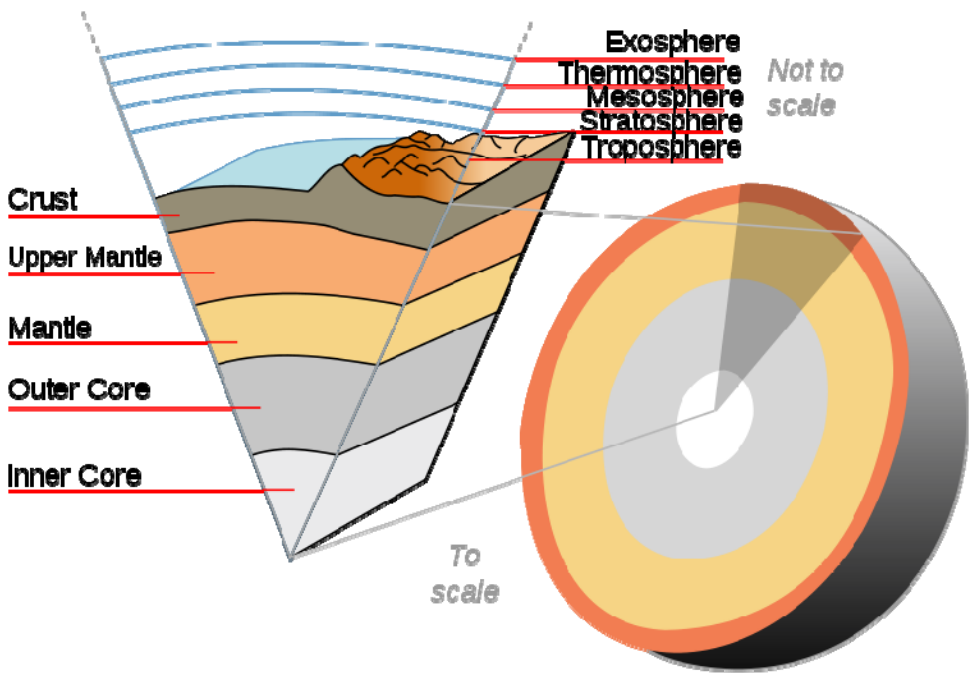
According to the theory, as the Universe cooled after the big bang it eventually became possible for common subatomic particles as we know them (neutrons, protons and electrons) to exist. The most common particles created in the big bang which are still easily observable to us today were protons and electrons (in equal numbers). The protons would eventually form hydrogen atoms. Almost all the neutrons created in the Big Bang were absorbed into helium-4 in the first three minutes after the Big Bang, and this helium accounts for most of the helium in the universe today.

Some fraction of elements beyond helium were created in the Big Bang, as the protons and neutrons collided with each other (lithium, beryllium, and perhaps some boron), but all of the "heavier elements" (heavier than carbon, element number 6) that we see today, were created inside of stars during a series of fusion stages, such as the proton-proton chain, the CNO cycle and the triple-alpha process. Progressively heavier elements are created during the evolution of a star.

Since the binding energy per nucleon peaks around iron, energy is only released in fusion processes occurring below this point. Since the creation of heavier nuclei by fusion costs energy, nature resorts to the process of neutron capture. Neutrons (due to their lack of charge) are readily absorbed by a nucleus. The heavy elements are created by either a *slow* neutron capture process (the so-called *s* process) or by the *rapid*, or *r* process. The *s* process occurs in thermally pulsing stars (called AGB, or asymptotic giant branch stars) and takes hundreds to thousands of years to reach the heaviest elements of lead and bismuth. The *r* process is thought to occur in supernova explosions because the conditions of high temperature, high neutron flux and ejected matter are present. These stellar conditions make the successive neutron captures very fast, involving very neutron-rich species which then beta-decay to heavier elements, especially at the so-called waiting points that correspond to more stable nuclides with closed neutron shells (magic numbers). The *r* process duration is typically in the range of a few seconds.

Chapter- 3

Geothermal Gradient



Earth cutaway from core to exosphere.

The **geothermal gradient** is the rate at which the Earth's temperature increases with depth, indicating heat flowing from the Earth's warm interior to its cooler surface. Away from tectonic plate boundaries, it is 25-30°C per km of depth in most of the world. Strictly speaking, *geo*-thermal necessarily refers to the Earth but the concept may be applied to other planets. The Earth's internal heat comes from a combination of residual heat from planetary accretion (about 20%) and heat produced through radioactive decay (80%). The major heat-producing isotopes in the Earth are potassium-40, uranium-238, uranium-235, and thorium-232. At the center of the planet, the temperature may be up to 7,000 K and the pressure could reach 360 GPa. Because much of the heat is provided by radioactive decay, scientists believe that early in Earth history, before isotopes with short half-lives had been depleted, Earth's heat production would have been much higher. This extra heat production, which was twice that of present-day at approximately 3 billion years ago, would have increased temperature gradients within the Earth, increasing the rates of mantle convection and plate tectonics, and allowing the production of igneous rocks such as komatiites that are not formed today.

Heat sources

Geothermal drill machine in Wisconsin

Temperature within the Earth increases with depth. Highly viscous or partially molten rock at temperatures between 650 to 1,200 °C (1,202 to 2,192 °F) is postulated to exist everywhere beneath the Earth's surface at depths of 50 to 60 miles (80 to 100 kilometers), and the temperature at the Earth's center, nearly 4,000 miles (6,400 km) deep, is estimated to be 5650 ± 600 kelvins. The heat content of the earth is 10^{31} joules.

- Much of the heat is believed to be created by decay of naturally radioactive elements. An estimated 45 to 90 percent of the heat escaping from the Earth originates from radioactive decay of elements within the mantle.
- Heat of impact and compression released during the original formation of the Earth by accretion of in-falling meteorites.
- Heat released as abundant heavy metals (iron, nickel, copper) descended to the Earth's core.
- Some heat may be created by electromagnetic effects of the magnetic fields involved in Earth's magnetic field.

- 10 to 25% of the heat flowing to the surface may be produced by a sustained nuclear fission reaction in Earth's inner core, the "georeactor" hypothesis.
- Heat may be generated by tidal force on the Earth as it rotates; since land cannot flow like water it compresses and distorts, generating heat.

Present-day major heat-producing isotopes

Isotope	Heat release [W/kg isotope]	Half-life [years]	Mean mantle concentration [kg isotope/kg mantle]	Heat release [W/kg mantle]
^{238}U	9.46×10^{-5}	4.47×10^{9}	30.8×10^{-9}	2.91×10^{-12}
^{235}U	5.69×10^{-4}	7.04×10^{8}	0.22×10^{-9}	1.25×10^{-13}
^{232}Th	2.64×10^{-5}	1.40×10^{10}	124×10^{-9}	3.27×10^{-12}
^{40}K	2.92×10^{-5}	1.25×10^{9}	36.9×10^{-9}	1.08×10^{-12}

Heat flow

Sequence of the burning of a shrub by geothermal heat.

Heat flows constantly from its sources within the Earth to the surface. Total heat loss from the earth is 42 TW (4.2×10^{13} watts). This is approximately 1/10 watt/square meter on average, (about 1/10,000 of solar irradiation,) but is much more concentrated in areas where thermal energy is transported toward the crust by Mantle plumes; a form of convection consisting of upwellings of higher-temperature rock. These plumes can produce hotspots and flood basalts. The Earth's crust effectively acts as a thick insulating blanket which must be pierced by fluid conduits (of magma, water or other) in order to release the heat underneath. More of the heat in the Earth is lost through plate tectonics, by mantle upwelling associated with mid-ocean ridges. The final major mode of heat loss is by conduction through the lithosphere, the majority of which occurs in the oceans due to the crust there being much thinner than under the continents.

The heat of the earth is replenished by radioactive decay at a rate of 30 TW. The global geothermal flow rates are more than twice the rate of human energy consumption from all primary sources.

The geothermal gradient has been used for space heating and bathing since ancient roman times, and more recently for generating electricity. About 10 GW of geothermal electric capacity is installed around the world as of 2007, generating 0.3% of global electricity demand. An additional 28 GW of direct geothermal heating capacity is installed for district heating, space heating, spas, industrial processes, desalination and agricultural applications.

Variations

The geothermal gradient varies with location and is typically measured by determining the bottom open-hole temperature after borehole drilling. To achieve accuracy the drilling fluid needs time to reach the ambient temperature. This is not always achievable for practical reasons.

In stable tectonic areas in the tropics a temperature-depth plot will converge to the annual average surface temperature. However, in areas where deep permafrost developed during the Pleistocene a low temperature anomaly can be observed that persists down to several hundred metres. The Suwałki cold anomaly in Poland has led to the recognition that similar thermal disturbances related to Pleistocene-Holocene climatic changes are recorded in boreholes throughout Poland, as well as in Alaska, northern Canada, and Siberia.

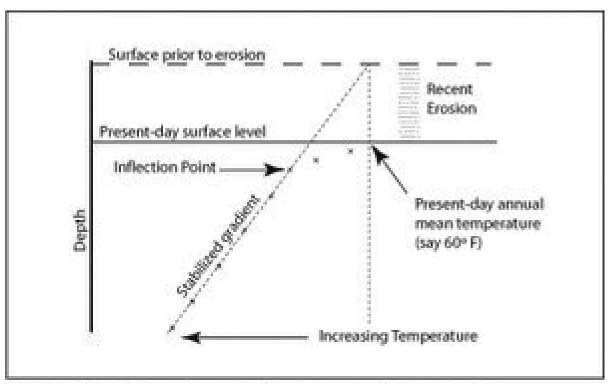


Fig 1. Borehole geothermal gradient in an area of uplift and erosion.

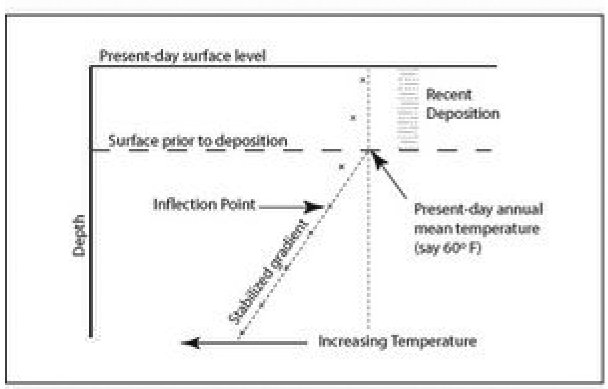


Fig 2. Borehole geothermal gradient in an area of deposition and subsidence.

In areas of Holocene uplift and erosion (Fig. 1) the initial gradient will be higher than the average until it reaches an inflection point where it reaches the stabilized heat-flow regime. If the gradient of the stabilized regime is projected above the inflection point to its intersect with present-day annual average temperature, the height of this intersect above present-day surface level gives a measure of the extent of Holocene uplift and erosion. In areas of Holocene subsidence and deposition (Fig. 2) the initial gradient will be lower than the average until it reaches an inflection point where it joins the stabilized heat-flow regime.

In deep boreholes, the temperature of the rock below the inflection point generally increases with depth at rates of the order of 20 K/km or more. Fourier's law of heat flow applied to the Earth gives $q = Mg$ where q is the heat flux at a point on the Earth's surface, M the thermal conductivity of the rocks there, and g the measured geothermal gradient. A representative value for the thermal conductivity of granitic rocks is $M = 3.0$ W/mK. Hence, using the global average geothermal conducting gradient of 0.02 K/m we get that $q = 0.06$ W/m². This estimate, corroborated by thousands of observations of heat flow in boreholes all over the world, gives a global average of 6×10^{-2} W/m². Thus, if the geothermal heat flow rising through an acre of granite terrain could be efficiently captured, it would light four 60 watt light bulbs.

A variation in surface temperature induced by climate changes and the Milankovitch cycle can penetrate below the Earth's surface and produce an oscillation in the geothermal gradient with periods varying from daily to tens of thousands of years and an amplitude which decreases with depth and having a scale depth of several kilometers. Melt water from the polar ice caps flowing along ocean bottoms tends to maintain a constant geothermal gradient throughout the Earth's surface.

If that rate of temperature change were constant, temperatures deep in the Earth would soon reach the point where all known rocks would melt. We know, however, that the Earth's mantle is solid because it transmits S-waves. The temperature gradient dramatically decreases with depth for two reasons. First, radioactive heat production is concentrated within the crust of the Earth, and particularly within the upper part of the crust, as concentrations of uranium, thorium, and potassium are highest there: these three elements are the main producers of radioactive heat within the Earth. Second, the mechanism of thermal transport changes from conduction, as within the rigid tectonic plates, to convection, in the portion of Earth's mantle that convects. Despite its solidity, most of the Earth's mantle behaves over long time-scales as a fluid, and heat is transported by advection, or material transport. Thus, the geothermal gradient within the bulk of Earth's mantle is of the order of 0.3 kelvin per kilometer, and is determined by the adiabatic gradient associated with mantle material (peridotite in the upper mantle).

This heating up can be both beneficial or detrimental in terms of engineering: Geothermal energy can be used as a means for generating electricity, by using the heat of the surrounding layers of rock underground to heat water and then routing the steam from this process through a turbine connected to a generator.

On the other hand, drill bits have to be cooled not only because of the friction created by the process of drilling itself but also because of the heat of the surrounding rock at great depth. Very deep mines, like some gold mines in South Africa, need the air inside to be cooled and circulated to allow miners to work at such great depth.

Chapter- 4

Energy & Technology Systems used in Solar Power

Photovoltaics

Nellis Solar Power Plant at Nellis Air Force Base in the USA. These panels track the sun in one axis.

Photovoltaic system 'tree' in Styria, Austria

Photovoltaics (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels comprising a number of cells containing a photovoltaic material. Materials presently used for photovoltaics include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium selenide/sulfide. Due to the growing demand for renewable energy sources, the manufacturing of solar cells and photovoltaic arrays has advanced considerably in recent years.

As of 2010, solar photovoltaics generates electricity in more than 100 countries and, while yet comprising a tiny fraction of the 4800 GW total global power-generating capacity from all sources, is the fastest growing power-generation technology in the world. Between 2004 and 2009, grid-connected PV capacity increased at an annual average rate of 60 percent, to some 21 GW. Such installations may be ground-mounted (and sometimes integrated with farming and grazing) or built into the roof or walls of a building, known as Building Integrated Photovoltaics or BIPV for short. Off-grid PV accounts for an additional 3–4 GW.

Driven by advances in technology and increases in manufacturing scale and sophistication, the cost of photovoltaics has declined steadily since the first solar cells were manufactured. Net metering and financial incentives, such as preferential feed-in tariffs for solar-generated electricity, have supported solar PV installations in many countries.

Photovoltaic effect

The photovoltaic effect is the creation of a voltage (or a corresponding electric current) in a material upon exposure to light. Though the photovoltaic effect is directly related to the photoelectric effect, the two processes are different and should be distinguished. In the photoelectric effect, electrons are ejected from a material's surface upon exposure to radiation of sufficient energy. The photovoltaic effect is different in that the generated electrons are transferred between different bands (i.e. from the valence to conduction bands) within the material, resulting in the buildup of a voltage between two electrodes.

In most photovoltaic applications the radiation is sunlight and for this reason the devices are known as solar cells. In the case of a p-n junction solar cell, illumination of the material results in the creation of an electric current as excited electrons and the remaining holes are swept in different directions by the built-in electric field of the depletion region.

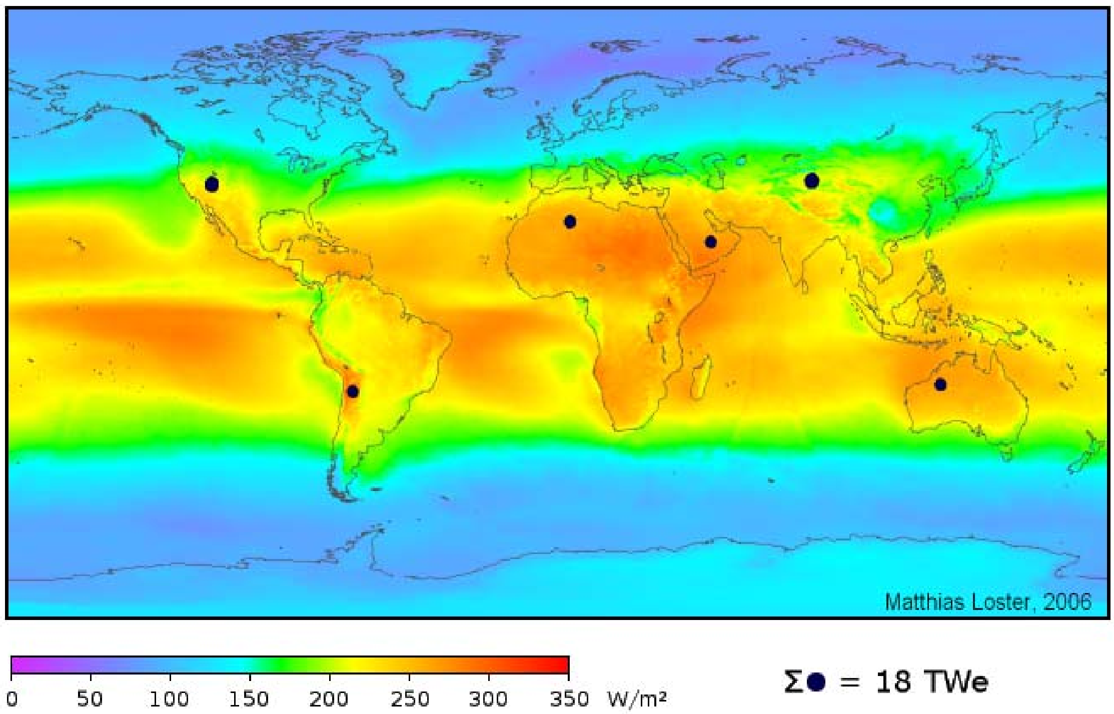
The photovoltaic effect was first observed by Alexandre-Edmond Becquerel in 1839.

Solar cells

Solar cells produce electricity directly from sunlight

Photovoltaics are best known as a method for generating electric power by using solar cells to convert energy from the sun into electricity. The photovoltaic effect refers to photons of light knocking electrons into a higher state of energy to create electricity. The term photovoltaic denotes the unbiased operating mode of a photodiode in which current through the device is entirely due to the transduced light energy. Virtually all photovoltaic devices are some type of photodiode.

Solar cells produce direct current electricity from sun light, which can be used to power equipment or to recharge a battery. The first practical application of photovoltaics was to power orbiting satellites and other spacecraft, but today the majority of photovoltaic modules are used for grid connected power generation. In this case an inverter is required to convert the DC to AC. There is a smaller market for off-grid power for remote dwellings, boats, recreational vehicles, electric cars, roadside emergency telephones, remote sensing, and cathodic protection of pipelines.



Average solar irradiance, watts per square metre. Note that this is for a horizontal surface, whereas solar panels are normally mounted at an angle and receive more energy per unit area. The small black dots show the area of solar panels needed to generate all of the world's energy using 8% efficient photovoltaics.

Cells require protection from the environment and are usually packaged tightly behind a glass sheet. When more power is required than a single cell can deliver, cells are electrically connected together to form photovoltaic modules, or solar panels. A single module is enough to power an emergency telephone, but for a house or a power plant the modules must be arranged in multiples as arrays. Although the selling price of modules is still too high to compete with grid electricity in most places, significant financial incentives in Japan and then Germany, Italy and France triggered a huge growth in demand, followed quickly by production. In 2008, Spain installed 45% of all photovoltaics, but a change in law limiting the feed-in tariff is expected to cause a precipitous drop in the rate of new installations there, from an extra 2500 MW in 2008, to an expected additional 375 MW in 2009.

A significant market has emerged in off-grid locations for solar-power-charged storage-battery based solutions. These often provide the only electricity available. The first commercial installation of this kind was in 1966 on Ogami Island in Japan to transition Ogami Lighthouse from gas torch to fully self-sufficient electrical power. Due to the growing demand for renewable energy sources, the manufacture of solar cells and photovoltaic arrays has advanced dramatically in recent years.

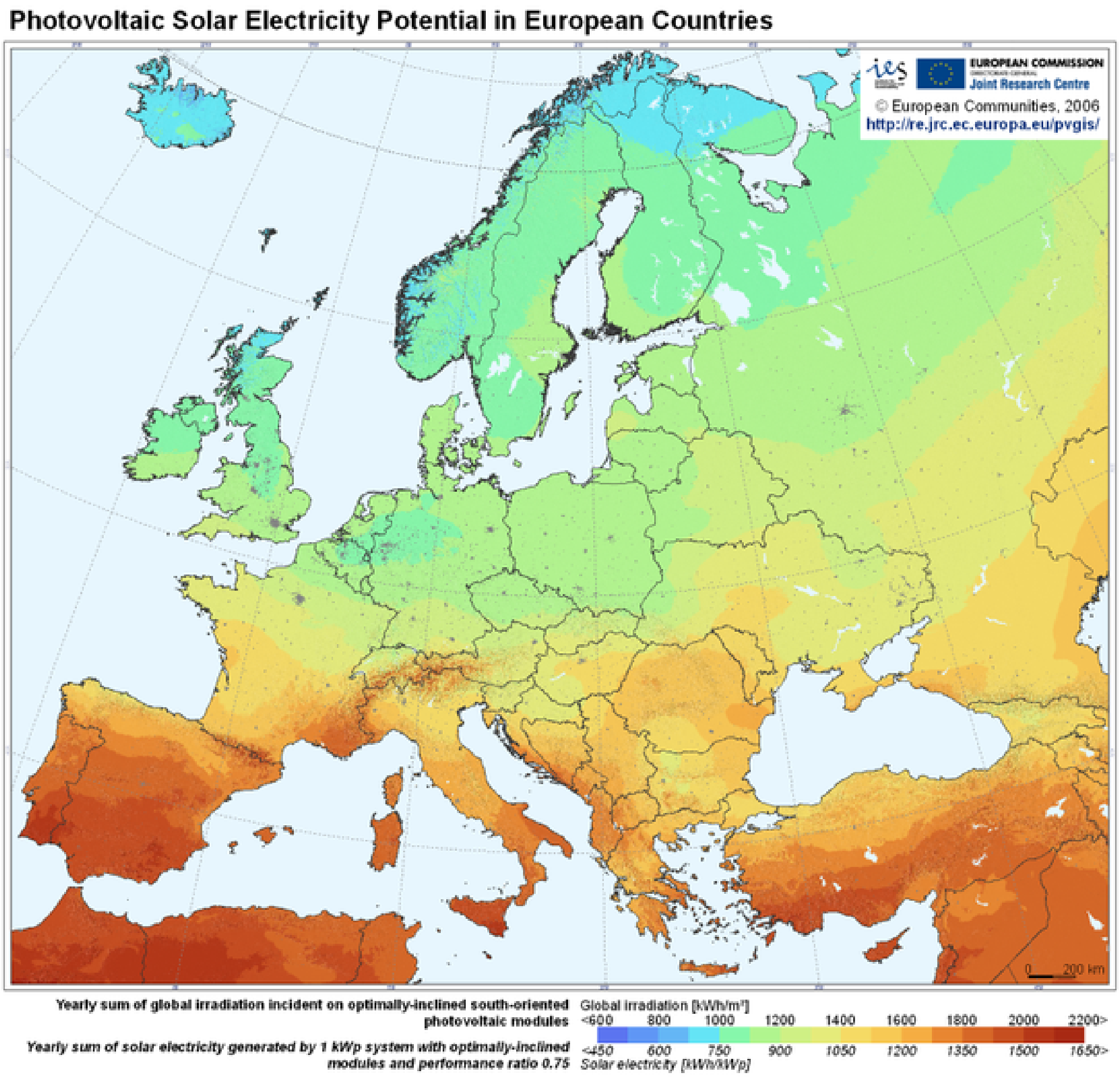
Photovoltaic production has been increasing by an average of more than 20 percent each year since 2002, making it the world's fastest-growing energy technology. At the end of 2009, the cumulative global PV installations surpassed 21,000 megawatts. Germany installed a record 3,800 MW of solar PV in 2009. Roughly 90% of this generating capacity consists of grid-tied electrical systems. Such installations may be ground-mounted (and sometimes integrated with farming and grazing) or built into the roof or walls of a building, known as Building Integrated Photovoltaics or BIPV for short. Solar PV power stations today have capacities ranging from 10–60 MW although proposed solar PV power stations will have a capacity of 150 MW or more.

World solar photovoltaic (PV) installations were 2.826 gigawatts peak (GWp) in 2007, and 5.95 gigawatts in 2008, and 7.5 gigawatts in 2009. The three leading countries (Germany, Japan and the US) represent nearly 89% of the total worldwide PV installed capacity. According to Navigant Consulting and Electronic Trend Publications, the estimated PV worldwide installations outlooks of 2012 are 18.8GW and 12.3GW respectively. Notably, the manufacture of solar cells and modules had expanded in recent years.

Germany installed a record 3,800 MW of solar PV in 2009; in contrast, the US installed about 500 MW in 2009. The previous record, 2,600 MW, was set by Spain in 2008. Germany was also the fastest growing major PV market in the world from 2006 to 2007 industry observers speculate that Germany could install more than 4,500 MW in 2010. The German PV industry generates over 10,000 jobs in production, distribution and installation. By the end of 2006, nearly 88% of all solar PV installations in the EU were in grid-tied applications in Germany. Photovoltaic power capacity is measured as maximum power output under standardized test conditions (STC) in "Wp" (Watts peak). The actual power output at a particular point in time may be less than or greater than this standardized, or "rated," value, depending on geographical location, time of day, weather conditions, and other factors. Solar photovoltaic array capacity factors are typically under 25%, which is lower than many other industrial sources of electricity. Therefore the 2008 installed base peak output would have provided an average output of 3.04 GW (assuming 20% × 15,200 MWp). This represented 0.15 percent of global demand at the time.

The EPIA/Greenpeace Advanced Scenario shows that by the year 2030, PV systems could be generating approximately 1,864 GW of electricity around the world. This means that, assuming a serious commitment is made to energy efficiency, enough solar power would be produced globally in twenty-five years' time to satisfy the electricity needs of almost 14% of the world's population.

Current developments



Map of solar electricity potential in Europe. Germany is the current leader in solar production.

Photovoltaic panels based on crystalline silicon modules are being partially replaced in the market by panels that employ thin-film solar cells (CdTe CIGS, amorphous Si, microcrystalline Si), which are rapidly growing and are expected to account for 31 percent of the global installed power by 2013. Other developments include casting wafers instead of sawing, concentrator modules, 'Sliver' cells, and continuous printing processes. Due to economies of scale solar panels get less costly as people use and buy more — as manufacturers increase production to meet demand, the cost and price is expected to drop in the years to come. By early 2006, the average cost per installed watt for a residential sized system was about USD 7.50 to USD 9.50, including panels, inverters, mounts, and electrical items.

In 2006 investors began offering free solar panel installation in return for a 25 year contract, or Power Purchase Agreement, to purchase electricity at a fixed price, normally set at or below current electric rates. It is expected that by 2009 over 90% of commercial photovoltaics installed in the United States will be installed using a power purchase agreement. An innovative financing arrangement in Berkeley, California, funded by grants from the EPA and the Bay Area Air Quality Management District, lends money to a homeowner for solar system, to be repaid via an additional tax assessment on the property which remains in place for 20 years. This allows installation of the solar system at "relatively little up-front cost to the property owner."

The current market leader in solar panel efficiency (measured by energy conversion ratio) is SunPower, a San Jose based company. Sunpower's cells have a conversion ratio of 24.2%, well above the market average of 12–18%. However, advances past this efficiency mark are being pursued in academia and R&D labs with efficiencies of 42% achieved at the University of Delaware in conjunction with DuPont by means of concentration of light The highest efficiencies achieved without concentration include Sharp Corporation at 35.8% using a proprietary triple-junction manufacturing technology in 2009, and Boeing Spectrolab (40.7% also using a triple layer design). A March 2010 experimental demonstration of a design by a Caltech group which has an absorption efficiency of 85% in sunlight and 95% at certain wavelengths (it is claimed to have near perfect quantum efficiency). However, absorption efficiency should not be confused with the sunlight-to-electricity conversion efficiency.

Applications

Power stations

President Barack Obama speaks at the DeSoto Next Generation Solar Energy Center.

As of October 2010, the largest photovoltaic (PV) power plants in the world are the Sarnia Photovoltaic Power Plant (Canada, 80 MW), the Olmedilla Photovoltaic Park (Spain, 60 MW), the Strasskirchen Solar Park (Germany, 54 MW), the Lieberose Photovoltaic Park (Germany, 53 MW), the Puertollano Photovoltaic Park (Spain, 50 MW), the Moura photovoltaic power station (Portugal, 46 MW), and the Waldpolenz Solar Park (Germany, 40 MW).

World's largest photovoltaic (PV) power plants (40 MW or larger)

Name of PV power plant	Country	Nominal Power (MW_p)	GW·h /year	Capacity factor	Notes
Sarnia Photovoltaic Power Plant	Canada	80			Complete October 2010
Olmedilla Photovoltaic Park	Spain	55	85	0.16	Siliken crystalline silicon modules. Completed September 2008
Strasskirchen Solar Park	Germany	54			
Lieberose Photovoltaic Park	Germany	53	53	0.11	700'000 First Solar CdTe modules, opened 2009
Puertollano Photovoltaic Park	Spain	47.6			231'653 crystalline silicon modules, Suntech and Solaria, opened 2008
Moura photovoltaic power station	Portugal	46	93	0.23	Completed December 2008
Kothen Solar Park	Germany	45			2009
Finsterwalde Solar Park	Germany	41			2009
Waldpolenz Solar Park	Germany	40	40	0.11	550,000 First Solar thin-film CdTe modules. Completed December 2008

Topaz Solar Farm is a proposed 550 MW solar photovoltaic power plant which is to be built northwest of California Valley in the US at a cost of over $1 billion. Built on 9.5 square miles (25 km^2) of ranchland, the project would utilize thin-film PV panels designed and manufactured by OptiSolar in Hayward and Sacramento. The project would deliver approximately 1,100 gigawatt-hours (GW·h) annually of renewable energy. The project is expected to begin construction in 2010, begin power delivery in 2011, and be fully operational by 2013.

High Plains Ranch is a proposed 250 MW solar photovoltaic power plant which is to be built by SunPower in the Carrizo Plain, northwest of California Valley.

In buildings

Photovoltaic arrays are often associated with buildings: either integrated into them, mounted on them or mounted nearby on the ground.

Arrays are most often retrofitted into existing buildings, usually mounted on top of the existing roof structure or on the existing walls. Alternatively, an array can be located separately from the building but connected by cable to supply power for the building. In 2010, more than four-fifths of the 9,000 MW of solar PV operating in Germany was installed on rooftops.

Photovoltaic solar panels on a house roof.

Building-integrated photovoltaics (BIPV) are increasingly incorporated into new domestic and industrial buildings as a principal or ancillary source of electrical power. Typically, an array is incorporated into the roof or walls of a building. Roof tiles with integrated PV cells are also common.

The power output of photovoltaic systems for installation in buildings is usually described in kilowatt-peak units (kWp).

In transport

PV has traditionally been used for electric power in space. PV is rarely used to provide motive power in transport applications, but is being used increasingly to provide auxiliary power in boats and cars. A self-contained solar vehicle would have limited power and low utility, but a solar-charged vehicle would allow use of solar power for transportation. Solar-powered cars have been demonstrated.

Standalone devices

Solar parking meter.

Until a decade or so ago, PV was used frequently to power calculators and novelty devices. Improvements in integrated circuits and low power LCD displays make it possible to power such devices for several years between battery changes, making PV use less common. In contrast, solar powered remote fixed devices have seen increasing use recently in locations where significant connection cost makes grid power prohibitively expensive. Such applications include water pumps, parking meters, emergency telephones, trash compactors, temporary traffic signs, and remote guard posts & signals.

Rural electrification

Developing countries where many villages are often more than five kilometers away from grid power have begun using photovoltaics. In remote locations in India a rural lighting program has been providing solar powered LED lighting to replace kerosene lamps. The solar powered lamps were sold at about the cost of a few month's supply of kerosene. Cuba is working to provide solar power for areas that are off grid. These are areas where the social costs and benefits offer an excellent case for going solar though the lack of profitability could relegate such endeavors to humanitarian goals.

Solar roadways

A 45 mi (72 km) section of roadway in Idaho is being used to test the possibility of installing solar panels into the road surface, as roads are generally unobstructed to the sun and represent about the percentage of land area needed to replace other energy sources with solar power.

Solar Power satellites

Design studies of large solar power collection satellites have been conducted for decades. The idea was first proposed by Peter Glaser, then of Arthur D. Little Inc; NASA conducted a long series of engineering and economic feasibility studies in the 1970s, and interest has revived in first years of the 21st century.

From a practical economic viewpoint, the key issue for such satellites appears to be the launch cost. Additional considerations will include developing space based assembly techniques, but they seem to be less a hurdle than the capital cost. These will be reduced as photovoltaic cell costs are reduced or alternatively efficiency increased.

Performance

Temperature

Generally, temperatures above room temperature reduce the performance of photovoltaics.

Optimum Orientation of Solar Panels

For best performance, terrestrial PV systems aim to maximize the time they face the sun. Solar trackers aim to achieve this by moving PV panels to follow the sun. The increase can be by as much as 20% in winter and by as much as 50% in summer. Static mounted systems can be optimized by analysis of the Sun path. Panels are often set to latitude tilt, an angle equal to the latitude, but performance can be improved by adjusting the angle for summer or winter.

Advantages

The 89 petawatts of sunlight reaching the Earth's surface is plentiful – almost 6,000 times more than the 15 terawatts equivalent of average power consumed by humans. Additionally, solar electric generation has the highest power density (global mean of 170 W/m²) among renewable energies.

Solar power is pollution-free during use. Production end-wastes and emissions are manageable using existing pollution controls. End-of-use recycling technologies are under development and policies are being produced that encourage recycling from producers.

PV installations can operate for many years with little maintenance or intervention after their initial set-up, so after the initial capital cost of building any solar power plant, operating costs are extremely low compared to existing power technologies.

Solar electric generation is economically superior where grid connection or fuel transport is difficult, costly or impossible. Long-standing examples include satellites, island communities, remote locations and ocean vessels.

When grid-connected, solar electric generation replaces some or all of the highest-cost electricity used during times of peak demand (in most climatic regions). This can reduce grid loading, and can eliminate the need for local battery power to provide for use in times of darkness. These features are enabled by net metering. Time-of-use net metering can be highly favorable, but requires newer electronic metering, which may still be impractical for some users.

Grid-connected solar electricity can be used locally thus reducing transmission/distribution losses (transmission losses in the US were approximately 7.2% in 1995).

Compared to fossil and nuclear energy sources, very little research money has been invested in the development of solar cells, so there is considerable room for improvement. Nevertheless, experimental high efficiency solar cells already have efficiencies of over 40% in case of concentrating photovoltaic cells and efficiencies are rapidly rising while mass-production costs are rapidly falling.

Disadvantages

Photovoltaics are costly to install. While the modules are often warranteed for upwards of 20 years, much of the investment in a home-mounted system may be lost if the home-owner moves and the buyer puts less value on the system than the seller.

Solar electricity is seen to be expensive. With the UK Feed-In Tariff for green solar energy, Solar PV has been made more accessible to homeowners. Under the scheme, homeowners can generate both free electricity, and a fee per kWh sold to the grid "Solar PV as a Domestic Investment Opportunity

Solar electricity is not produced at night and is much reduced in cloudy conditions. Therefore, a storage or complementary power system is required.

Solar electricity production depends on the limited power density of the location's insolation. Average daily output of a flat plate collector at latitude tilt in the contiguous US is 3–7 kilowatt·h/m^2 and on average lower in Europe.

Solar cells produce DC which must be converted to AC (using a grid tie inverter) when used in existing distribution grids. This incurs an energy loss of 4–12%.

Chapter- 5

Solar Thermal Energy

Solar thermal system for water heating in Santorini, Greece.

Solar thermal energy (**STE**) is a technology for harnessing solar energy for thermal energy (heat). Solar thermal collectors are classified by the USA Energy Information Administration as low-, medium-, or high-temperature collectors. Low temperature collectors are flat plates generally used to heat swimming pools. Medium-temperature collectors are also usually flat plates but are used for heating water or air for residential and commercial use. High temperature collectors concentrate sunlight using mirrors or lenses and are generally used for electric power production. STE is different from photovoltaics, which convert solar energy directly into electricity. While only 600 megawatts of solar thermal power is up and running worldwide in October 2009 according to Dr David Mills of Ausra, another 400 megawatts is under construction and there are 14,000 megawatts of the more serious concentrating solar thermal (CST) projects being developed.

Low-temperature collectors

Of the 21,000,000 square feet (2,000,000 m^2) of solar thermal collectors produced in the United States in 2006, 16,000,000 square feet (1,500,000 m^2) were of the low-temperature variety. Low-temperature collectors are generally installed to heat swimming pools, although they can also be used for space heating. Collectors can use air or water as the medium to transfer the heat to their destination.

Heating, cooling, and ventilation

MIT's Solar House #1 built in 1939 used seasonal thermal storage for year round heating.

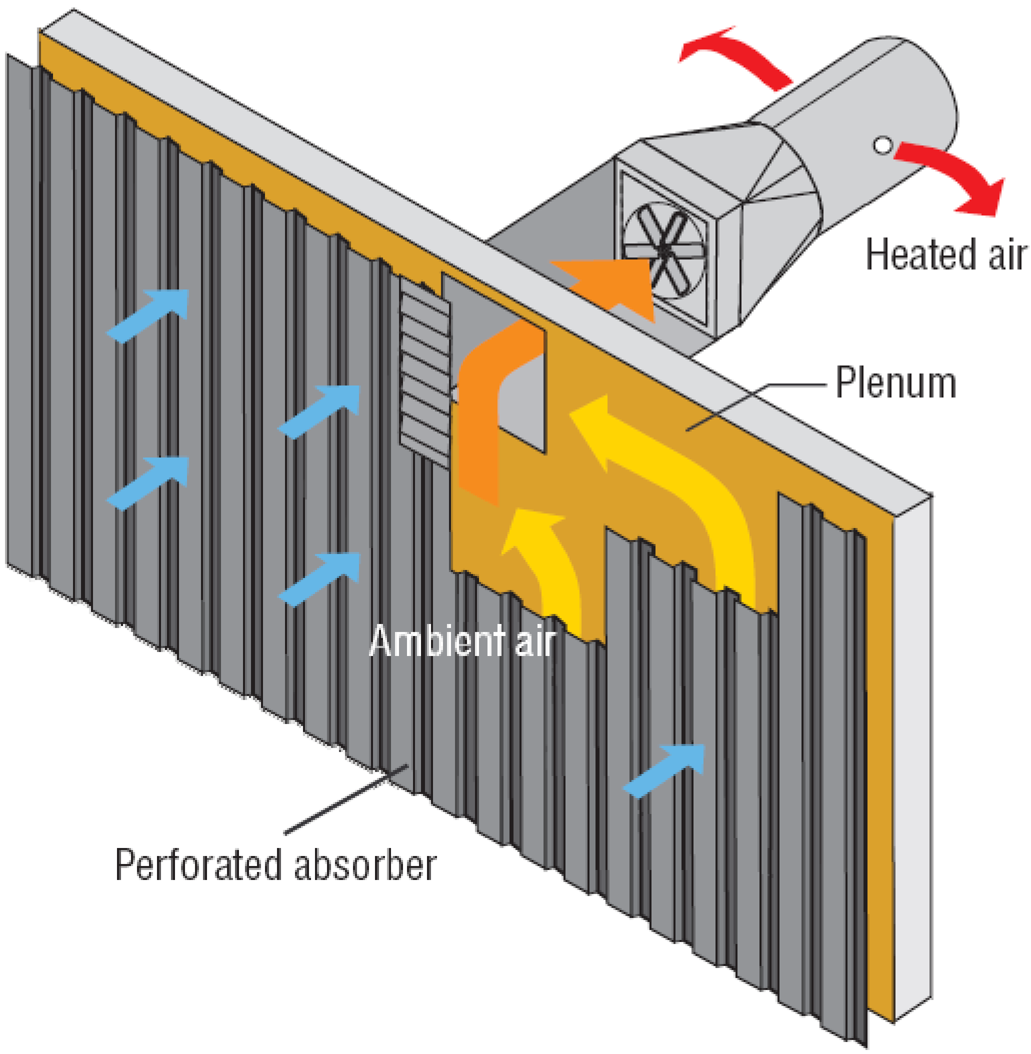
In the United States, heating, ventilation, and air conditioning (HVAC) systems account for over 25 percent (4.75 EJ) of the energy used in commercial buildings and nearly half (10.1 EJ) of the energy used in residential buildings. Solar heating, cooling, and ventilation technologies can be used to offset a portion of this energy.

Thermal mass materials store solar energy during the day and release this energy during cooler periods. Common thermal mass materials include stone, concrete, and water. The proportion and placement of thermal mass should consider several factors such as climate, daylighting, and shading conditions. When properly incorporated, thermal mass can passively maintain comfortable temperatures while reducing energy consumption. A solar chimney (or thermal chimney) is a passive solar ventilation system composed of a hollow thermal mass connecting the interior and exterior of a building. As the chimney warms, the air inside is heated causing an updraft that pulls air through the building.

These systems have been in use since Roman times and remain common in the Middle East.

Solar space heating with solar air heat collectors is more popular in USA and Canada than heating with solar liquid collectors since most buildings already have a ventilation system for heating and cooling. The two main types of solar air panels are glazed and unglazed.

Glazed Solar Collectors are designed primarily for space heating and they recirculate building air through a solar air panel where the air is heated and then directed back into the building. These solar space heating systems require at least two penetrations into the building and only perform when the air in the solar collector is warmer than the building room temperature. Most glazed collectors are used in the residential sector.



Unglazed, "transpired" air collector

Unglazed Solar Collectors are primarily used to pre-heat make-up ventilation air in commercial, industrial and institutional buildings with a high ventilation load. They turn building walls or sections of walls into low cost, high performance, unglazed solar collectors. Also called, "transpired solar panels", they employ a painted perforated metal solar heat absorber that also serves as the exterior wall surface of the building. Heat conducts from the absorber surface to the thermal boundary layer of air 1 mm thick on the outside of the absorber and to air that passes behind the absorber. The boundary layer of air is drawn into a nearby perforation before the heat can escape by convection to the outside air. The heated air is then drawn from behind the absorber plate into the building's ventilation system.

A Trombe wall is a passive solar heating and ventilation system consisting of an air channel sandwiched between a window and a sun-facing thermal mass. During the ventilation cycle, sunlight stores heat in the thermal mass and warms the air channel causing circulation through vents at the top and bottom of the wall. During the heating cycle the Trombe wall radiates stored heat.

Solar roof ponds are unique solar heating and cooling systems developed by Harold Hay in the 1960s. A basic system consists of a roof-mounted water bladder with a movable insulating cover. This system can control heat exchange between interior and exterior environments by covering and uncovering the bladder between night and day. When heating is a concern the bladder is uncovered during the day allowing sunlight to warm the water bladder and store heat for evening use. When cooling is a concern the covered bladder draws heat from the building's interior during the day and is uncovered at night to radiate heat to the cooler atmosphere. The Skytherm house in Atascadero, California uses a prototype roof pond for heating and cooling.

Active solar cooling can be achieved via absorption refrigeration cycles, desiccant cycles, and solar mechanical processes. In 1878, Auguste Mouchout pioneered solar cooling by making ice using a solar steam engine attached to a refrigeration device. Thermal mass, smart windows and shading methods can also be used to provide cooling. The leaves of deciduous trees provide natural shade during the summer while the bare limbs allow light and warmth into a building during the winter. The water content of trees will also help moderate local temperatures.

Process heat

Solar Evaporation Ponds in the Atacama Desert.

Solar process heating systems are designed to provide large quantities of hot water or space heating for nonresidential buildings.

Evaporation ponds are shallow ponds that concentrate dissolved solids through evaporation. The use of evaporation ponds to obtain salt from sea water is one of the oldest applications of solar energy. Modern uses include concentrating brine solutions used in leach mining and removing dissolved solids from waste streams. Altogether, evaporation ponds represent one of the largest commercial applications of solar energy in use today.

Unglazed transpired collectors (UTC) are perforated sun-facing walls used for preheating ventilation air. UTCs can raise the incoming air temperature up to 22 °C and deliver outlet temperatures of 45-60 °C. The short payback period of transpired collectors (3 to 12 years) make them a more cost-effective alternative to glazed collection systems. As of 2009, over 1500 systems with a combined collector area of 300,000 m² had been installed worldwide. Representatives include an 860 m² collector in Costa Rica used for drying coffee beans and a 1300 m² collector in Coimbatore, India used for drying marigolds.

A food processing facility in Modesto, California uses parabolic troughs to produce steam used in the manufacturing process. The 5,000 m² collector area is expected to provide 4.3 GJ per year.

Medium-temperature collectors

These collectors could be used to produce approximately 50% and more of the hot water needed for residential and commercial use in the United States. In the United States, a typical system costs $4000–$6000 retail ($1400 to $2200 wholesale for the materials) and 30% of the system qualifies for a federal tax credit + additional state credit exists in about half of the states. Labor for a simple open loop system in southern climates can take 3-5 hours for the installation and 4- 6 hours in Northern areas. Northern system require more collector area and more complex plumbing to protect the collector form freezing. With this incentive, the payback time for a typical household is four to nine years, depending on the state. Similar subsidies exist in parts of Europe. A crew of one solar plumber and two assistants with minimal training can install a system per day. Thermosiphon installation have negligible maintenance costs (costs rise if antifreeze and mains power are used for circulation) and in the US reduces a households' operating costs by $6 per person per month. Solar water heating can reduce CO_2 emissions of a family of four by 1 ton/year (if replacing natural gas) or 3 ton/year (if replacing electricity). Medium-temperature installations can use any of several designs: common designs are pressurized glycol, drain back, batch systems and newer low pressure freeze tolerant systems using polymer pipes containing water with photovoltaic pumping. European and International standards are being reviewed to accommodate innovations in design and operation of medium temperature collectors. Operational innovations include "permanently wetted collector" operation. This innovation reduces or even eliminates the occurrence of no-flow high temperature stresses called stagnation which would otherwise reduce the life expectancy of collectors.

Solar Drying

Solar thermal energy can be very useful in drying wood for construction and wood fuels such as wood chips for combustion. Solar is also used for food products such as fruits, grains, and fish. Crop drying by solar means is environmentally friendly as well as cost effective while improving the quality. The less money it takes to make a product, the less it can be sold for, pleasing both the buyers and the sellers. Technologies in solar drying include ultra low cost pumped transpired plate air collectors based on black fabrics. Solar thermal energy is helpful in the process of drying products such as wood chips and other forms of biomass by raising the heat while allowing air to pass through and get rid of the moisture.

Cooking

The Solar Bowl above the Solar Kitchen in Auroville, India concentrates sunlight on a movable receiver to produce steam for cooking.

Solar cookers use sunlight for cooking, drying and pasteurization. Solar cooking offsets fuel costs, reduces demand for fuel or firewood, and improves air quality by reducing or removing a source of smoke.

The simplest type of solar cooker is the box cooker first built by Horace de Saussure in 1767. A basic box cooker consists of an insulated container with a transparent lid. These cookers can be used effectively with partially overcast skies and will typically reach temperatures of 50–100 °C.

Concentrating solar cookers use reflectors to concentrate light on a cooking container. The most common reflector geometries are flat plate, disc and parabolic trough type. These designs cook faster and at higher temperatures (up to 350 °C) but require direct light to function properly.

The Solar Kitchen in Auroville, India uses a unique concentrating technology known as the solar bowl. Contrary to conventional tracking reflector/fixed receiver systems, the solar bowl uses a fixed spherical reflector with a receiver which tracks the focus of light as the Sun moves across the sky. The solar bowl's receiver reaches temperature of 150 °C that is used to produce steam that helps cook 2,000 daily meals.

Many other solar kitchens in India use another unique concentrating technology known as the Scheffler reflector. This technology was first developed by Wolfgang Scheffler in

1986. A Scheffler reflector is a parabolic dish that uses single axis tracking to follow the Sun's daily course. These reflectors have a flexible reflective surface that is able to change its curvature to adjust to seasonal variations in the incident angle of sunlight. Scheffler reflectors have the advantage of having a fixed focal point which improves the ease of cooking and are able to reach temperatures of 450-650 °C. Built in 1999, the world's largest Scheffler reflector system in Abu Road, Rajasthan India is capable of cooking up to 35,000 meals a day. By early 2008, over 2000 large cookers of the Scheffler design had been built worldwide.

Distillation

Solar stills can be used to make drinking water in areas that clean water is not common. Solar distillation is necessary in these situations to provide people with purified water. Solar energy heats up the water in the still. The water then evaporates and condenses on the bottom of the covering glass.

High-temperature collectors

The solar furnace at Odeillo in the French Pyrenees-Orientales can reach temperatures up to 3,800 degrees Celsius.

Concentrated solar power plant using parabolic trough design.

Where temperatures below about 95 °C are sufficient, as for space heating, flat-plate collectors of the nonconcentrating type are generally used. Because of the relatively high heat losses through the glazing, flat plate collectors will not reach temperatures much above 200 °C even when the heat transfer fluid is stagnant. Such temperatures are too low for efficient conversion to electricity.

The efficiency of heat engines increases with the temperature of the heat source. To achieve this in solar thermal energy plants, solar radiation is concentrated by mirrors or lenses to obtain higher temperatures — a technique called Concentrated Solar Power (CSP). The practical effect of high efficiencies is to reduce the plant's collector size and total land use per unit power generated, reducing the environmental impacts of a power plant as well as its expense.

As the temperature increases, different forms of conversion become practical. Up to 600 °C, steam turbines, standard technology, have an efficiency up to 41%. Above this, gas turbines can be more efficient. Higher temperatures are problematic because different materials and techniques are needed. One proposal for very high temperatures is to use liquid fluoride salts operating between 700 °C to 800 °C, using multi-stage turbine systems to achieve 50% or more thermal efficiencies. The higher operating temperatures permit the plant to use higher-temperature dry heat exchangers for its thermal exhaust, reducing the plant's water use — critical in the deserts where large solar plants are practical. High temperatures also make heat storage more efficient, because more watt-hours are stored per unit of fluid.

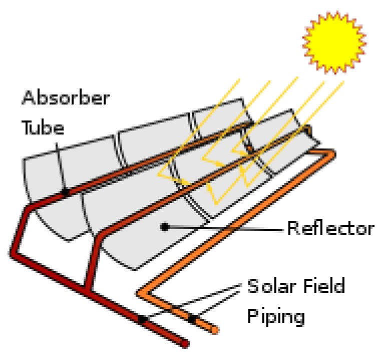
Since the CSP plant generates heat first of all, it can store the heat before conversion to electricity. With current technology, storage of heat is much cheaper and more efficient than storage of electricity. In this way, the CSP plant can produce electricity day and night. If the CSP site has predictable solar radiation, then the CSP plant becomes a reliable power plant. Reliability can further be improved by installing a back-up system that uses fossil energy. The back-up system can reuse most of the CSP plant, which decreases the cost of the back-up system.

With reliability, unused desert, no pollution, and no fuel costs, the obstacles for large deployment for CSP are cost, aesthetics, land use and similar factors for the necessary connecting high tension lines. Although only a small percentage of the desert is necessary to meet global electricity demand, still a large area must be covered with mirrors or lenses to obtain a significant amount of energy. An important way to decrease cost is the use of a simple design.

System designs

During the day the sun has different positions. If the mirrors or lenses do not move, then the focus of the mirrors or lenses changes. Therefore it seems unavoidable that there needs to be a tracking system that follows the position of the sun (for solar photovoltaic a solar tracker is only optional). The tracking system increases the cost and complexity. With this in mind, different designs can be distinguished in how they concentrate the light and track the position of the sun.

Parabolic trough designs



Sketch of a parabolic trough design. A change of position of the sun parallel to the receiver does not require adjustment of the mirrors.

Parabolic trough power plants use a curved, mirrored trough which reflects the direct solar radiation onto a glass tube containing a fluid (also called a receiver, absorber or collector) running the length of the trough, positioned at the focal point of the reflectors. The trough is parabolic along one axis and linear in the orthogonal axis. For change of the daily position of the sun perpendicular to the receiver, the trough tilts east to west so that the direct radiation remains focused on the receiver. However, seasonal changes in the in angle of sunlight parallel to the trough does not require adjustment of the mirrors, since the light is simply concentrated elsewhere on the receiver. Thus the trough design does not require tracking on a second axis.

The receiver may be enclosed in a glass vacuum chamber. The vacuum significantly reduces convective heat loss.

A fluid (also called heat transfer fluid) passes through the receiver and becomes very hot. Common fluids are synthetic oil, molten salt and pressurized steam. The fluid containing the heat is transported to a heat engine where about a third of the heat is converted to electricity.

Andasol 1 in Gaudix, Spain uses the Parabolic Trough design which consists of long parallel rows of modular solar collectors. Tracking the sun from East to West by rotation on one axis, the high precision reflector panels concentrate the solar radiation coming directly from the sun onto an absorber pipe located along the focal line of the collector. A heat transfer medium, a synthetic oil like in car engines, is circulated through the absorber pipes at temperatures up to 400 °C and generates live steam to drive the steam turbine generator of a conventional power block.

Concentrating solar power systems are a fast growing source of sustainable energy.

Full-scale parabolic trough systems consist of many such troughs laid out in parallel over a large area of land. Since 1985 a solar thermal system using this principle has been in full operation in California in the United States. It is called the SEGS system. Other CSP designs lack this kind of long experience and therefore it can currently be said that the parabolic trough design is the most thoroughly proven CSP technology.

The Solar Energy Generating System (SEGS) is a collection of nine plants with a total capacity of 350MW. It is currently the largest operational solar system (both thermal and non-thermal). A newer plant is Nevada Solar One plant with a capacity of 64MW. Under construction are Andasol 1 and Andasol 2 in Spain with each site having a capacity of 50MW. Note however, that those plants have heat storage which requires a larger field of solar collectors relative to the size of the steam turbine-generator to store heat and send heat to the steam turbine at the same time. Heat storage enables better utilization of the steam turbine. With day and some nighttime operation of the steam-turbine Andasol 1 at 50MW peak capacity produces more energy than Nevada Solar One at 64 MW peak capacity, due to the former plant's thermal energy storage system and larger solar field.

553MW new capacity is proposed in Mojave Solar Park, California. Furthermore, 59MW hybrid plant with heat storage is proposed near Barstow, California . Near Kuraymat in Egypt, some 40MW steam is used as input for a gas powered plant. Finally, 25MW steam input for a gas power plant in Hassi R'mel, Algeria.

Power tower designs

Solar Two. Flat mirrors focus the light on the top of the tower. The white surfaces below the receiver are used for calibrating the mirror positions.

eSolar's 5 MW Sierra SunTower facility features arrays of heliostats (mirrors with sun-tracking motion) to concentrate sunlight on to a central receiver mounted at the top of a tower. Sierra SunTower is located in Lancaster, California.

Power towers (also known as 'central tower' power plants or 'heliostat' power plants) capture and focus the sun's thermal energy with thousands of tracking mirrors (called heliostats) in roughly a two square mile field. A tower resides in the center of the heliostat field. The heliostats focus concentrated sunlight on a receiver which sits on top of the tower. Within the receiver the concentrated sunlight heats molten salt to over 1,000 °F (538 °C). The heated molten salt then flows into a thermal storage tank where it is stored, maintaining 98% thermal efficiency, and eventually pumped to a steam generator. The steam drives a standard turbine to generate electricity. This process, also known as the "Rankine cycle" is similar to a standard coal-fired power plant, except it is fueled by clean and free solar energy.

The advantage of this design above the parabolic trough design is the higher temperature. Thermal energy at higher temperatures can be converted to electricity more efficiently and can be more cheaply stored for later use. Furthermore, there is less need to flatten the ground area. In principle a power tower can be built on a hillside. Mirrors can be flat and plumbing is concentrated in the tower. The disadvantage is that each mirror must have its own dual-axis control, while in the parabolic trough design one axis can be shared for a large array of mirrors.

SolarReserve, a Santa Monica, CA-based solar developer, uses this technology for the development of its concentrated solar thermal plants with storage. The plants were designed by United Technologies Corporation. United Technologies' subsidiary, Rocketdyne, demonstrated the technology at the Solar One (1982–1986) and Solar Two (1995–1999) power tower plants in Southern California, although these plants were designed by the Department of Energy (DOE), Southern California Edison, LA Dept of Water and Power, and California Energy Commission. United Technologies has granted SolarReserve an exclusive worldwide license to develop such power plants.

In November 2009, SolarReserve and a Madrid-based renewable energy developer, Preneal, received the key environmental permit that is necessary for the construction of their 50 megawatt solar plant in Spain. This project will generate more than 300,000 megawatt hours of electricity per year, or enough electricity to power almost 70,000 houses in the region. The Alcazar Solar Thermal Power Project will use molten salt as a coolant, which is exclusively licensed to SolarReserve by United Technologies Corporation (UTC).

In December 2009, SolarReserve announced two power contracts in the United States. The first was with Pacific Gas and Electric (PG&E) for the sale of electricity from SolarReserve's Rice Solar Energy Project. The 150-megawatt solar energy project will be located 30 miles (48 km) northwest of the city of Blythe in eastern Riverside County, California. When completed, SolarReserve's facility will supply approximately 450,000 megawatt-hours annually of clean, reliable electricity—enough to power up to 68,000 homes during peak electricity periods—and will use thermal energy storage for nighttime power generation. The second power contract was a 25-year power purchase agreement with NV Energy for the sale of electricity from SolarReserve's Crescent Dunes Solar Energy Project. Developed and owned by SolarReserve's subsidiary, Tonopah Solar Energy, LLC, the project will be located near the town of Tonopah in Nye County, Nevada. When completed, Tonopah Solar Energy's facility will supply approximately 480,000 megawatt hours annually.

In June 2008, eSolar, a Pasadena, CA-based company founded by Idealab CEO Bill Gross with funding from Google, announced a power purchase agreement (PPA) with the utility Southern California Edison to produce 245 megawatts of power. Also, in February 2009, eSolar announced it had licensed its technology to two development partners, the Princeton, N.J.-based NRG Energy, Inc., and the India-based ACME Group. In the deal with NRG, the companies announced plans to jointly build 500 megawatts of concentrating solar thermal plants throughout the United States. The target goal for the ACME Group was nearly double; ACME plans to start construction on its first eSolar power plant this year, and will build a total of 1 gigawatt over the next 10 years.

eSolar's proprietary sun-tracking software coordinates the movement of 24,000 1 meter-square mirrors per 1 tower using optical sensors to adjust and calibrate the mirrors in real time. This allows for a high density of reflective material which enables the development of modular concentrating solar thermal (CSP) power plants in 46 megawatt (MW) units on approximately π square mile parcels of land, resulting in a land-to-power ratio of 4 acres (16,000 m^2) per 1 megawatt.

BrightSource Energy entered into a series of power purchase agreements with Pacific Gas and Electric Company in March 2008 for up to 900MW of electricity, the largest solar power commitment ever made by a utility. BrightSource is currently developing a number of solar power plants in Southern California, with construction of the first plant planned to start in 2009.

In June 2008, BrightSource Energy dedicated its 4-6 MW Solar Energy Development Center (SEDC) in Israel's Negev Desert. The site, located in the Rotem Industrial Park, features more than 1,600 heliostats that track the sun and reflect light onto a 60 meter-high tower. The concentrated energy is then used to heat a boiler atop the tower to 550 degrees Celsius, generating superheated steam.

A working tower power plant is PS10 in Spain with a capacity of 11MW.

The 15MW Solar Tres plant with heat storage is under construction in Spain. In South Africa, a 100MW solar power plant is planned with 4000 to 5000 heliostat mirrors, each having an area of 140 m^2. A 10MW power plant in Cloncurry, Australia (with purified graphite as heat storage located on the tower directly by the receiver).

Out of commission are the 10MW Solar One (later redeveloped and made into Solar Two) and the 2MW Themis plants.

A cost/performance comparison between power tower and parabolic trough concentrators was made by the NREL which estimated that by 2020 electricity could be produced from power towers for 5.47 ₡/kWh and for 6.21 ₡/kWh from parabolic troughs. The capacity factor for power towers was estimated to be 72.9% and 56.2% for parabolic troughs. There is some hope that the development of cheap, durable, mass producible heliostat power plant components could bring this cost down.

Dish designs

A parabolic solar dish concentrating the sun's rays on the heating element of a Stirling engine. The entire unit acts as a solar tracker.

A dish system uses a large, reflective, parabolic dish (similar in shape to satellite television dish). It focuses all the sunlight that strikes the dish up onto to a single point above the dish, where a receiver captures the heat and transforms it into a useful form. Typically the dish is coupled with a Stirling engine in a Dish-Stirling System, but also sometimes a steam engine is used. These create rotational kinetic energy that can be converted to electricity using an electric generator.

The advantage of a dish system is that it can achieve much higher temperatures due to the higher concentration of light (as in tower designs). Higher temperatures leads to better conversion to electricity and the dish system is very efficient on this point. However, there are also some disadvantages. Heat to electricity conversion requires moving parts and that results in maintenance. In general, a centralized approach for this conversion is better than the dencentralized concept in the dish design. Second, the (heavy) engine is part of the moving structure, which requires a rigid frame and strong tracking system. Furthermore, parabolic mirrors are used instead of flat mirrors and tracking must be dual-axis.

In 2005 Southern California Edison announced an agreement to purchase solar powered Stirling engines from Stirling Energy Systems over a twenty year period and in quantities (20,000 units) sufficient to generate 500 megawatts of electricity. Stirling Energy Systems announced another agreement with San Diego Gas & Electric to provide between 300 and 900 megawatts of electricity. In January 2010, Stirling Energy Systems and Tessera Solar commissioned the first demonstration 1.5-megawatt power plant ("Maricopa Solar") using Stirling technology in Peoria, Arizona.

Fresnel reflectors

Wind load is avoided by the low position of the mirrors. Light construction of tracking system due to separation from the receiver.

A linear Fresnel reflector power plant uses a series of long, narrow, shallow-curvature (or even flat) mirrors to focus light onto one or more linear receivers positioned above the mirrors. On top of the receiver a small parabolic mirror can be attached for further focusing the light. These systems aim to offer lower overall costs by sharing a receiver between several mirrors (as compared with trough and dish concepts), while still using the simple line-focus geometry with one axis for tracking. This is similar to the trough design (and different from central towers and dishes with dual-axis). The receiver is stationary and so fluid couplings are not required (as in troughs and dishes). The mirrors also do not need to support the receiver, so they are structurally simpler. When suitable aiming strategies are used (mirrors aimed at different receivers at different times of day), this can allow a denser packing of mirrors on available land area.

Recent prototypes of these types of systems have been built in Australia (CLFR) and by Solarmundo in Belgium.

The Solarmundo research and development project, with its pilot plant at Liège, was closed down after successful proof of concept of the Linear Fresnel technology. Subsequently, Solar Power Group GmbH (SPG), based in Munich, Germany, was founded by some Solarmundo team members. A Fresnel-based prototype with direct steam generation was built by SPG in conjunction with the German Aerospace Center (DLR).

Based on the Australian prototype, a 177MW plant had been proposed near San Luis Obispo in California and would be built by Ausra. But Ausra sold its planned California solar farm to First Solar. First Solar will not build the Carrizo project, and the deal has resulted in the cancellation of Ausra's contract to provide 177 megawatts to P.G.& E . Small capacity plants are an enormous economical challenge with conventional parabolic trough and drive design — few companies build such small projects. There are plans for SHP Europe, former Ausra subsidiary, to build a 6.5 MW combined cycle plant in Portugal. The German company SK Energy]) has plans to build several small 1-3 MW plants in Southern Europe (esp. in Spain) using Fresnel mirror and steam drive technology (Press Release).

In May 2008, the German Solar Power Group GmbH and the Spanish Laer S.L. agreed the joint execution of a solar thermal power plant in central Spain. This will be the first commercial solar thermal power plant in Spain based on the Fresnel collector technology of the Solar Power Group. The planned size of the power plant will be 10 MW a solar thermal collector field with a fossil co-firing unit as backup system. The start of constructions is planned for 2009. The project is located in Gotarrendura, a small renewable energy pioneering village, about 100 km northwest of Madrid, Spain.

A Multi-Tower Solar Array (MTSA) concept, that uses a *point-focus* Fresnel reflector idea, has also been developed, but has not yet been prototyped.

Since March 2009, the Fresnel solar power plant PE 1 of the German company Novatec Biosol is in commercial operation in southern Spain . The solar thermal power plant is based on linear Fresnel collector technology and has an electrical capacity of 1.4 MW. Beside a conventional power block, PE 1 comprises a solar boiler with mirror surface of around 18,000m². The steam is generated by concentrating direct solar irradiation onto a linear receiver which is 7.40m above the ground. An absorber tube is positioned in the focal line of the mirror field in which water is evaporated directly into saturated steam at 270 °C and at a pressure of 55 bar by the concentrated solar energy.

Linear Fresnel Reflector (LFR) and compact-LFR Technologies

Fresnel solar power plant PE 1 in southern Spain

Rival single axis tracking technologies include the relatively new Linear Fresnel reflector (LFR) and compact-LFR (CLFR) technologies. The LFR differs from that of the parabolic trough in that the absorber is fixed in space above the mirror field. Also, the reflector is composed of many low row segments, which focus collectively on an elevated long tower receiver running parallel to the reflector rotational axis.

This system offers a lower cost solution as the absorber row is shared among several rows of mirrors. However, one fundamental difficulty with the LFR technology is the avoidance of shading of incoming solar radiation and blocking of reflected solar radiation by adjacent reflectors. Blocking and shading can be reduced by using absorber towers elevated higher or by increasing the absorber size, which allows increased spacing between reflectors remote from the absorber. Both these solutions increase costs, as larger ground usage is required.

The compact linear Fresnel reflector (CLFR) offers an alternate solution to the LFR problem. The classic LFR has only one linear absorber on a single linear tower. This prohibits any option of the direction of orientation of a given reflector. Since this technology would be introduced in a large field, one can assume that there will be many linear absorbers in the system. Therefore, if the linear absorbers are close enough, individual reflectors will have the option of directing reflected solar radiation to at least two absorbers. This additional factor gives potential for more densely packed arrays, since patterns of alternative reflector inclination can be set up such that closely packed reflectors can be positioned without shading and blocking.

CLFR power plants offer reduced costs in all elements of the solar array. These reduced costs encourage the advancement of this technology. Features that enhance the cost effectiveness of this system compared to that of the parabolic trough technology include minimized structural costs, minimized parasitic pumping losses, and low maintenance. Minimized structural costs are attributed to the use of flat or elastically curved glass reflectors instead of costly sagged glass reflectors are mounted close to the ground. Also, the heat transfer loop is separated from the reflector field, avoiding the cost of flexible high pressure lines required in trough systems. Minimized parasitic pumping losses are due to the use of water for the heat transfer fluid with passive direct boiling. The use of glass-evacuated tubes ensures low radiative losses and is inexpensive. Studies of existing CLFR plants have been shown to deliver tracked beam to electricity efficiency of 19% on an annual basis as a preheater.

Fresnel lenses

Prototypes of Fresnel lens concentrators have been produced for the collection of thermal energy by International Automated Systems. No full-scale thermal systems using Fresnel lenses are known to be in operation, although products incorporating Fresnel lenses in conjunction with photovoltaic cells are already available.

The advantage of this design is that lenses are cheaper than mirrors. Furthermore, if a material is chosen that has some flexibility, then a less rigid frame is required to withstand wind load. A new concept of a lightweight, 'non-disruptive' solar concentrator technology using asymmetric Fresnel lenses that occupies minimal ground surface area and allows for large amounts of concentrated solar energy per concentrator is seen in the 'Desert Blooms' project, though a prototype has yet to be made.

MicroCSP

"MicroCSP" references solar thermal technologies in which concentrating solar power (CSP) collectors are based on the designs used in traditional Concentrating Solar Power systems found in the Mojave Desert but are smaller in collector size, lighter and operate at lower thermal temperatures usually below 315 °C (600 °F). These systems are designed for modular field or rooftop installation where they are easy to protect from high winds, snow and humid deployments. Solar manufacturer Sopogy completed construction on a 1MW CSP plant at the Natural Energy Laboratory of Hawaii.

MicroCSP is used for community-sized power plants (1MW to 50MW), for industrial, agricultural and manufacturing 'process heat' applications, and when large amounts of hot water are needed, such as resort swimming pools, water parks, large laundry facilities, sterilization, distillation and other such uses.

Heat exchange

Heat in a solar thermal system is guided by five basic principles: heat gain; heat transfer; heat storage; heat transport; and heat insulation. Here, heat is the measure of the amount of thermal energy an object contains and is determined by the temperature, mass and specific heat of the object. Solar thermal power plants use heat exchangers that are designed for constant working conditions, to provide heat exchange.

Heat gain is the heat accumulated from the sun in the system. Solar thermal heat is trapped using the greenhouse effect; the greenhouse effect in this case is the ability of a reflective surface to transmit short wave radiation and reflect long wave radiation. Heat and infrared radiation (IR) are produced when short wave radiation light hits the absorber plate, which is then trapped inside the collector. Fluid, usually water, in the absorber tubes collect the trapped heat and transfer it to a heat storage vault.

Heat is transferred either by conduction or convection. When water is heated, kinetic energy is transferred by conduction to water molecules throughout the medium. These molecules spread their thermal energy by conduction and occupy more space than the cold slow moving molecules above them. The distribution of energy from the rising hot water to the sinking cold water contributes to the convection process. Heat is transferred from the absorber plates of the collector in the fluid by conduction. The collector fluid is circulated through the carrier pipes to the heat transfer vault. Inside the vault, heat is transferred throughout the medium through convection.

Heat storage enables solar thermal plants to produce electricity during hours without sunlight. Heat is transferred to a thermal storage medium in an insulated reservoir during hours with sunlight, and is withdrawn for power generation during hours lacking sunlight. Thermal storage mediums will be discussed in a heat storage section. Rate of heat transfer is related to the conductive and convection medium as well as the temperature differences. Bodies with large temperature differences transfer heat faster than bodies with lower temperature differences.

Heat transport refers to the activity in which heat from a solar collector is transported to the heat storage vault. Heat insulation is vital in both heat transport tubing as well as the storage vault. It prevents heat loss, which in turn relates to energy loss, or decrease in the efficiency of the system.

Heat storage

Heat storage allows a solar thermal plant to produce electricity at night and on overcast days. This allows the use of solar power for baseload generation as well as peak power generation, with the potential of displacing both coal and natural gas fired power plants. Additionally, the utilization of the generator is higher which reduces cost.

Heat is transferred to a thermal storage medium in an insulated reservoir during the day, and withdrawn for power generation at night. Thermal storage media include pressurized steam, concrete, a variety of phase change materials, and molten salts such as sodium and potassium nitrate.

Steam accumulator

The PS10 solar power tower stores heat in tanks as pressurized steam at 50 bar and 285 °C. The steam condenses and flashes back to steam, when pressure is lowered. Storage is for one hour. It is suggested that longer storage is possible, but that has not been proven yet in an existing power plant.

Molten salt storage

A variety of fluids have been tested to transport the sun's heat, including water, air, oil, and sodium, but molten salt was selected as best. Molten salt is used in solar power tower systems because it is liquid at atmosphere pressure, it provides an efficient, low-cost medium in which to store thermal energy, its operating temperatures are compatible with today's high-pressure and high-temperature steam turbines, and it is non-flammable and nontoxic. In addition, molten salt is used in the chemical and metals industries as a heat-transport fluid, so experience with molten-salt systems exists in non-solar settings.

The molten salt is a mixture of 60 percent sodium nitrate and 40 percent potassium nitrate, commonly called saltpeter. New studies show that calcium nitrate could be included in the salts mixture to reduce costs and with technical benefits. The salt melts at 220 °C (430 °F) and is kept liquid at 290 °C (550 °F) in an insulated storage tank. The uniqueness of this solar system is in de-coupling the collection of solar energy from producing power, electricity can be generated in periods of inclement weather or even at night using the stored thermal energy in the hot salt tank. Normally tanks are well insulated and can store energy for up to a week. As an example of their size, tanks that provide enough thermal storage to power a 100-megawatt turbine for four hours would be about 9 m (30 ft) tall and 24 m (80 ft) in diameter.

The Andasol power plant in Spain is the first commercial solar thermal power plant to utilize molten salt for heat storage and nighttime generation. It came online March 2009.

Graphite heat storage

Direct

The proposed power plant in Cloncurry Australia will store heat in purified graphite. The plant has a power tower design. The graphite is located on top of the tower. Heat from the heliostats goes directly to the storage. Heat for energy production is drawn from the graphite. This simplifies the design.

Indirect

Molten salt coolants are used to transfer heat from the reflectors to heat storage vaults.

The heat from the salts are transferred to a secondary heat transfer fluid via a heat exchanger and then to the storage media, or alternatively, the salts can be used to directly heat graphite. Graphite is used as it has relatively low costs and compatibility with liquid fluoride salts. The high mass and volumetric heat capacity of graphite provide an efficient storage medium.

Phase-change materials for storage

Phase Change Material (PCMs) offer an alternate solution in energy storage. Using a similar heat transfer infrastructure, PCMs have the potential of providing a more efficient means of storage. PCMs can be either organic or inorganic materials. Advantages of organic PCMs include no corrosives, low or no undercooling, and chemical and thermal stability. Disadvantages include low phase-change enthalpy, low thermal conductivity, and flammability. Inorganics are advantageous with greater phase-change enthalpy, but exhibit disadvantages with undercooling, corrosion, phase separation, and lack of thermal stability. The greater phase-change enthalpy in inorganic PCMs make hydrate salts a strong candidate in the solar energy storage field.

Use of water

A design which requires water for condensation or cooling may conflict with location of solar thermal plants in desert areas with good solar radiation but limited water resources. The conflict is illustrated by plans of Solar Millennium, a German company, to build a plant in the Amargosa Valley of Nevada which would require 20% of the water available in the area. Some other projected plants by the same and other companies in the Mojave Desert of California may also be affected by difficulty in obtaining adequate and appropriate water rights. California water law currently prohibits use of potable water for cooling.

Other designs require less water. The proposed Ivanpah Solar Power Facility in south-eastern California will conserve scarce desert water by using air-cooling to convert the steam back into water. Compared to conventional wet-cooling, this results in a 90 percent reduction in water usage . The water is then returned to the boiler in a closed process which is environmentally friendly.

Conversion rates from solar energy to electrical energy

Of all of these technologies the solar dish/stirling engine has the highest energy efficiency. A single solar dish-Stirling engine installed at Sandia National Laboratories National Solar Thermal Test Facility produces as much as 25 kW of electricity, with a conversion efficiency of 31.25%.

Solar parabolic trough plants have been built with efficiencies of about 20%. Fresnel reflectors have an efficiency that is slightly lower (but this is compensated by the denser packing).

The gross conversion efficiencies (taking into account that the solar dishes or troughs occupy only a fraction of the total area of the power plant) are determined by net generating capacity over the solar energy that falls on the total area of the solar plant. The 500-megawatt (MW) SCE/SES plant would extract about 2.75% of the radiation that falls on its 4,500 acres (18.2 km²). For the 50 MW AndaSol Power Plant that is being built in Spain (total area of 1,300×1,500 m = 1.95 km²) gross conversion efficiency comes out at 2.6%

Furthermore, efficiency does not directly relate to cost: on calculating total cost, both efficiency and the cost of construction and maintenance should be taken into account.

Levelised cost

Since a solar power plant does not use any fuel, the cost consists mostly of capital cost with minor operational and maintenance cost. If the lifetime of the plant and the interest rate is known, then the cost per kWh can be calculated. This is called the levelised energy cost.

The first step in the calculation is to determine the investment for the production of 1 kWh in a year. Example, the fact sheet of the Andasol 1 project shows a total investment of 310 million euros for a production of 179 GWh a year. Since 179 GWh is 179 million kWh, the investment per kWh a year production is 310 / 179 = 1.73 euro. Another example is Cloncurry solar power station in Australia. It is planned to produce 30 million kWh a year for an investment of 31 million Australian dollars. So, if this is achieved in reality, the cost would be 1.03 Australian dollar for the production of 1 kWh in a year. This would be significantly cheaper than Andasol 1, which can partially be explained by the higher radiation in Cloncurry over Spain. The investment per kwh cost for one year should not be confused with the cost per kwh over the complete lifetime of such a plant.

In most cases the capacity is specified for a power plant (for instance Andasol 1 has a capacity of 50MW). This number is not suitable for comparison, because the capacity factor can differ. If a solar power plant has heat storage, then it can also produce output after sunset, but that will not change the capacity factor, it simply displaces the output. The average capacity factor for a solar power plant, which is a function of tracking, shading and location, is about 20%, meaning that a 50MW capacity power plant will typically provide a yearly output of 50 MW × 24 hrs × 365 days × 20% = 87,600 MWh/year, or 87.6 GWh/yr.

Although the investment for one kWh year production is suitable for comparing the price of different solar power plants, it does not give the price per kWh yet. The way of financing has a great influence on the final price. If the technology is proven, an interest rate of 7% should be possible. However, for a new technology investors want a much higher rate to compensate for the higher risk. This has a significant negative effect on the price per kWh. Independent of the way of financing, there is always a linear relation between the investment per kWh production in a year and the price for 1 kWh (before adding operational and maintenance cost). In other words, if by enhancements of the technology the investments drop by 20%, then the price per kWh also drops by 20%.

If a way of financing is assumed where the money is borrowed and repaid every year, in such way that the debt and interest decreases, then the following formula can be used to calculate the division factor: (1 - (1 + interest / 100) ^ -lifetime) / (interest / 100). For a lifetime of 25 years and an interest rate of 7%, the division factor is 11.65. For example, the investment of Andasol 1 was 1.73 euro per kWh, divided by 11.65 results in a price of 0.15 euro per kWh. If one cent operation and maintenance cost is added, then the levelized cost is 0.16 euro per kWh. Other ways of financing, different way of debt repayment, different lifetime expectation, different interest rate, may lead to a significantly different number.

If the cost per kWh may follow the inflation, then the inflation rate can be added to the interest rate. If an investor puts his money on the bank for 7%, then he is not compensated for inflation. However, if the cost per kWh is raised with inflation, then he is compensated and he can add 2% (a normal inflation rate) to his return. The Andasol 1 plant has a guaranteed feed-in tariff of 0.21 euro for 25 years. If this number is fixed, after 25 years with 2% inflation, 0.21 euro will have a value comparable with 0.13 euro now.

Finally, there is some gap between the first investment and the first production of electricity. This increases the investment with the interest over the period that the plant is not active yet. The modular solar dish (but also solar photovoltaic and wind power) have the advantage that electricity production starts after first construction.

Given the fact that solar thermal power is reliable, can deliver peak load and does not cause pollution, a price of US$0.10 per kWh starts to become competitive. Although a price of US$0.06 has been claimed With some operational cost a simple target is 1 dollar (or lower) investment for 1 kWh production in a year.

Chapter- 6

Energy Technology Applications in Wind Power Generation

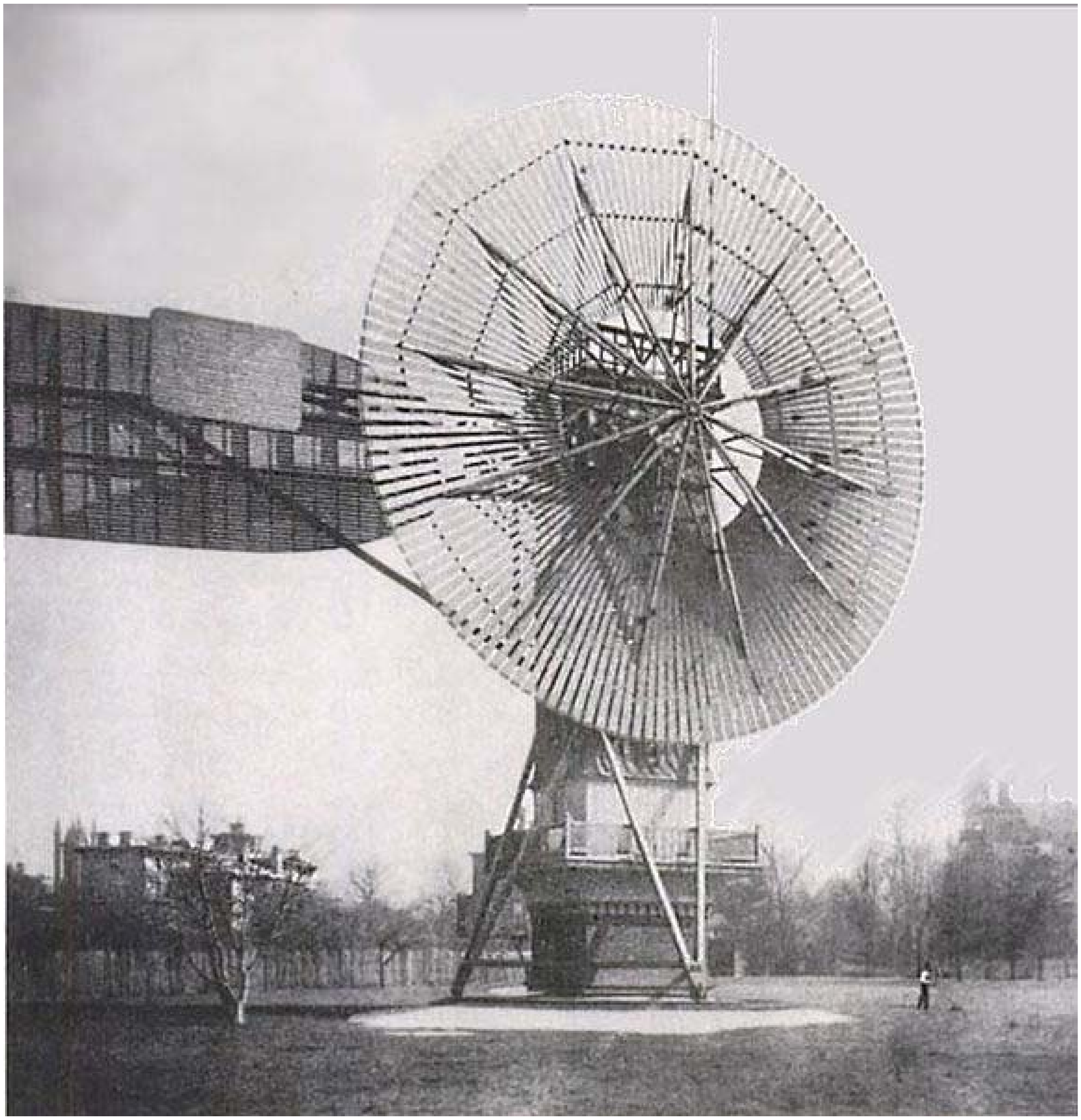
Wind Turbine

Offshore wind farm using 5MW turbines REpower M5 in the North Sea off Belgium

A **wind turbine** is a rotary machine that converts kinetic energy from the wind into mechanical energy. If the mechanical energy is used to produce electricity, the machine is sometimes called a wind generator. If, instead, the mechanical energy is used to drive machinery, such as for pumping water or grinding grain, the machine is called a windmill.

History

Windmills were used in Persia (present-day Iran) as early as 200 B.C. The windwheel of Heron of Alexandria marks one of the first known instances of wind powering a machine in history. However, the first practical windmills were built in Sistan, a region between Afghanistan and Iran, from the 7th century. These were vertical axle windmills, which had long vertical driveshafts with rectangular blades. Made of six to twelve sails covered in reed matting or cloth material, these windmills were used to grind corn or draw up water, and were used in the gristmilling and sugarcane industries.



The world's first automatically operated wind turbine was built in Cleveland in 1888 by Charles F. Brush. It was 60 feet (18 m) tall, weighed 4 tons (3.6 metric tonnes) and powered a 12kW generator.

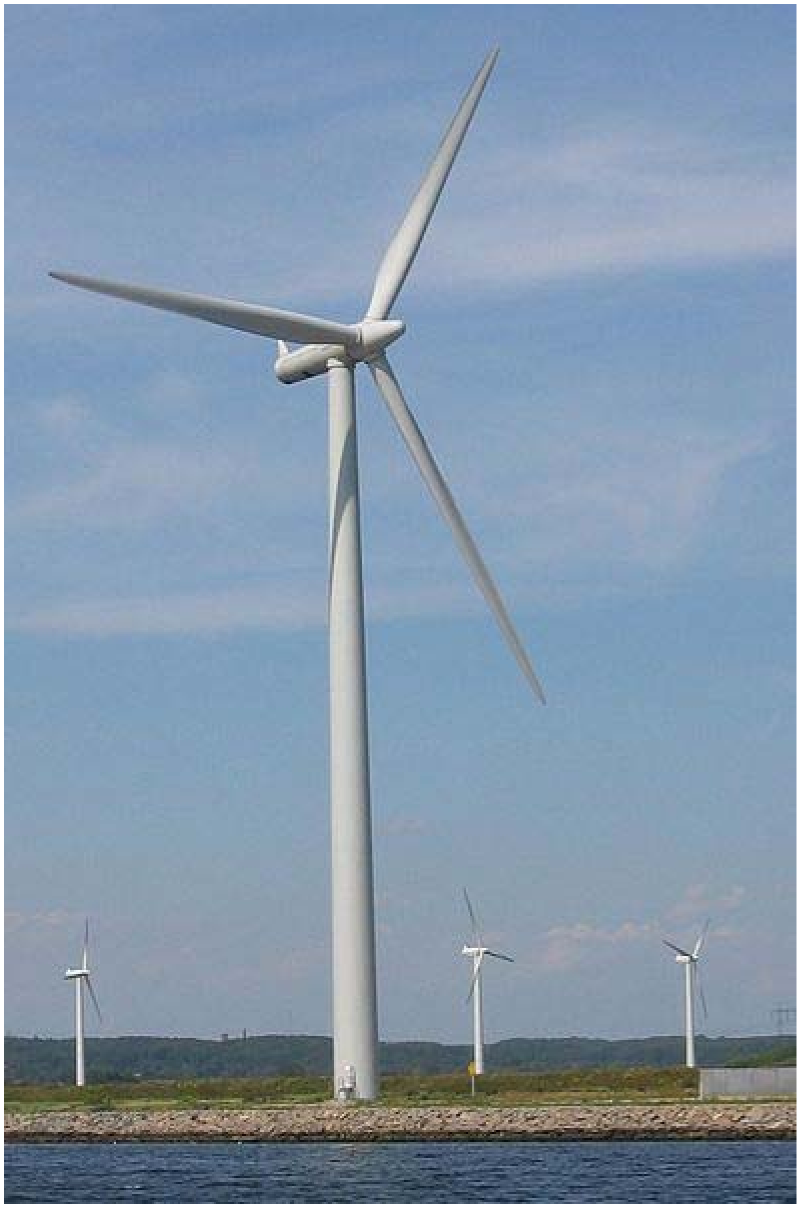
By the 14th century, Dutch windmills were in use to drain areas of the Rhine River delta. In Denmark by 1900, there were about 2500 windmills for mechanical loads such as pumps and mills, producing an estimated combined peak power of about 30 MW. The first known electricity generating windmill operated, was a battery charging machine installed in 1887 by James Blyth in Scotland. The first windmill for electricity production in the United States was built in Cleveland, Ohio by Charles F Brush in 1888, and in 1908 there were 72 wind-driven electric generators from 5 kW to 25 kW. The largest machines were on 24-metre (79 ft) towers with four-bladed 23-metre (75 ft) diameter rotors. Around the time of World War I, American windmill makers were producing

100,000 farm windmills each year, mostly for water-pumping. By the 1930s, windmills for electricity were common on farms, mostly in the United States where distribution systems had not yet been installed. In this period, high-tensile steel was cheap, and windmills were placed atop prefabricated open steel lattice towers.

A forerunner of modern horizontal-axis wind generators was in service at Yalta, USSR in 1931. This was a 100 kW generator on a 30-metre (98 ft) tower, connected to the local 6.3 kV distribution system. It was reported to have an annual capacity factor of 32 per cent, not much different from current wind machines. In the fall of 1941, the first megawatt-class wind turbine was synchronized to a utility grid in Vermont. The Smith-Putnam wind turbine only ran for 1,100 hours before suffering a critical failure. Due to war time material shortages the unit was not repaired.

The first utility grid-connected wind turbine operated in the U.K. was built by John Brown & Company in 1954 in the Orkney Islands. It had an 18-metre (59 ft) diameter, three-bladed rotor and a rated output of 100 kW.

Resources

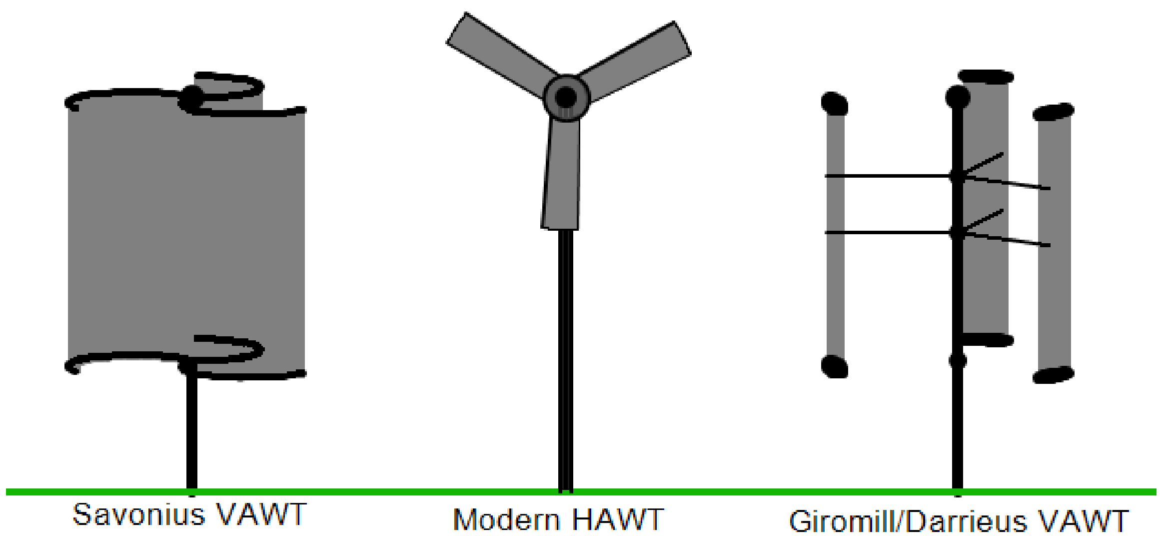


Wind turbines near Aalborg, Denmark

A quantitative measure of the wind energy available at any location is called the Wind Power Density (WPD) It is a calculation of the mean annual power available per square meter of swept area of a turbine, and is tabulated for different heights above ground. Calculation of wind power density includes the effect of wind velocity and air density. Color-coded maps are prepared for a particular area described, for example, as "Mean Annual Power Density at 50 Meters." In the United States, the results of the above calculation are included in an index developed by the U.S. National Renewable Energy Lab and referred to as "NREL CLASS." The larger the WPD calculation, the higher it is rated by class. Classes range from Class 1 (200 watts/square meter or less at 50 meters altitude) to Class 7 (800 to 2000 watts/square meter). Commercial wind farms generally are sited in Class 3 or higher areas, although isolated points in an otherwise Class 1 area may be practical to exploit.

Types

Wind turbines can rotate about either a horizontal or a vertical axis, the former being both older and more common.



The three primary types:VAWT Savonius, HAWT towered; VAWT Darrieus as they appear in operation.

Horizontal axis

Components of a horizontal axis wind turbine (gearbox, rotor shaft and brake assembly) being lifted into position

Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker rotation that is more suitable to drive an electrical generator.

Since a tower produces turbulence behind it, the turbine is usually positioned upwind of its supporting tower. Turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted forward into the wind a small amount.

Downwind machines have been built, despite the problem of turbulence (mast wake), because they don't need an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since cyclical (that is repetitive) turbulence may lead to fatigue failures, most HAWTs are of upwind design.

Subtypes

Doesburger windmill, Ede, The Netherlands.
12th-century windmills

These squat structures, typically (at least) four bladed, usually with wooden shutters or fabric sails, were developed in Europe. These windmills were pointed into the wind manually or via a tail-fan and were typically used for grinding grain. In the Netherlands they were also used for pumping water from low-lying land, and were instrumental in keeping its polders dry.

In Schiedam, the Netherlands, a traditional style windmill (the *Noletmolen*) was built in 2005 to generate electricity. The mill is one of the tallest Tower mills in the world, being some 42.5 metres (139 ft) tall.

19th-century windmills

The Eclipse windmill factory was set up around 1866 in Beloit, Wisconsin and soon became successful building mills for pumping water on farms and for filling railroad tanks. Other firms like Star, Dempster, and Aeromotor also entered the market. Hundreds of thousands of these mills were produced before rural electrification and small numbers continue to be made. They typically had many blades, operated at tip speed ratios not better than one, and had good starting torque. Some had small direct-current generators used for charging storage batteries, to provide power to lights, or to operate a radio receiver. The American rural electrification connected many farms to centrally generated power and replaced individual windmills as a primary source of farm power by the 1950s. They were also produced in other countries like South Africa and Australia (where an American design was copied in 1876). Such devices are still used in locations where it is too costly to bring in commercial power.

Modern wind turbines

An onshore wind farm using 7.5MW Enercon E-126 turbines at Estinnes, Belgium during construction in July 2010. Note the unique 2 part turbine blades.

Turbine blade convoy passing through Edenfield in the UK

Turbines used in wind farms for commercial production of electric power are usually three-bladed and pointed into the wind by computer-controlled motors. These have high tip speeds of over 320 kilometres per hour (200 mph), high efficiency, and low torque ripple, which contribute to good reliability. The blades are usually colored light gray to blend in with the clouds and range in length from 20 to 40 metres (66 to 130 ft) or more. The tubular steel towers range from 60 to 90 metres (200 to 300 ft) tall. The blades rotate at 10-22 revolutions per minute. At 22 rotations per minute the tip speed exceeds 300 feet per second (91 m/s). A gear box is commonly used for stepping up the speed of the generator, although designs may also use direct drive of an annular generator. Some models operate at constant speed, but more energy can be collected by variable-speed turbines which use a solid-state power converter to interface to the transmission system. All turbines are equipped with protective features to avoid damage at high wind speeds, by feathering the blades into the wind which ceases their rotation, supplemented by brakes.

Vertical axis design

Vertical-axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable.

With a vertical axis, the generator and gearbox can be placed near the ground, so the tower doesn't need to support it, and it is more accessible for maintenance. Drawbacks are that some designs produce pulsating torque.

The NEG Micon M700 wind turbine at the Great River Energy headquarters in Maple Grove, Minnesota

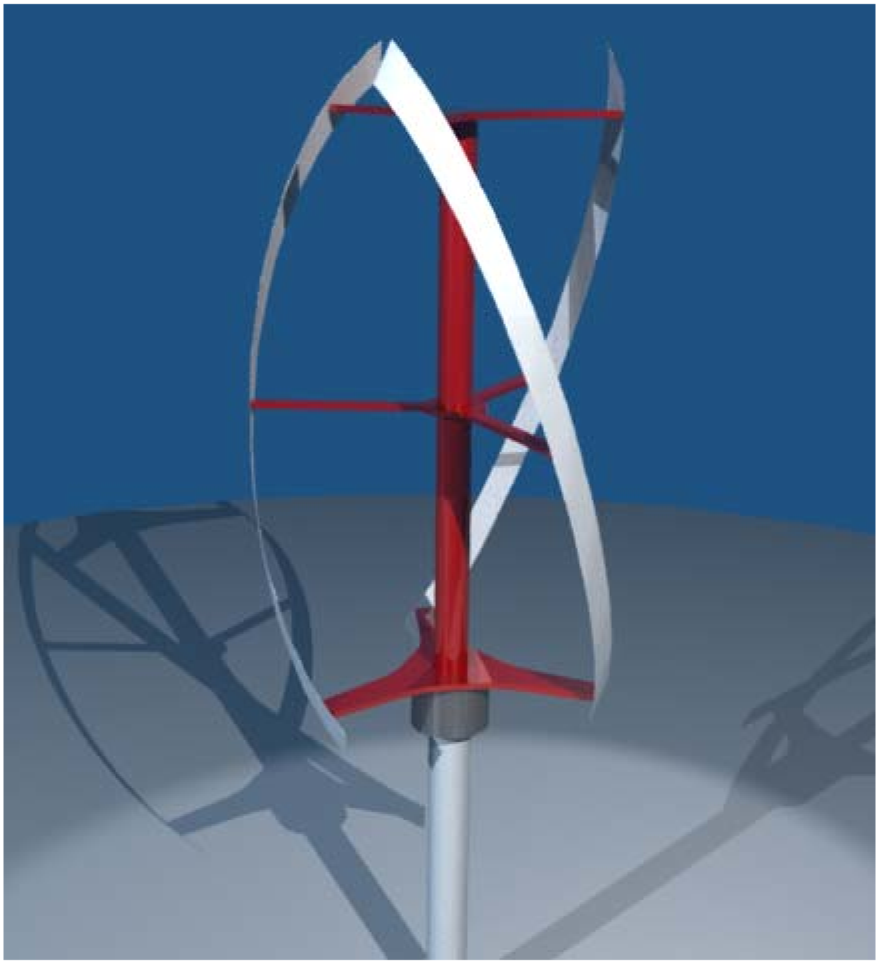
It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine. Air flow near the ground and other objects can create turbulent flow, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten the service life. However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof and this can double the wind speed at the turbine. If the height of the rooftop mounted turbine tower is approximately 50% of the building height, this is near the optimum for maximum wind energy and minimum wind turbulence.

Subtypes

Darrieus wind turbine of 30 m in the Magdalen Islands

Darrieus wind turbine

"Eggbeater" turbines, or Darrieus turbines, were named after the French inventor, Georges Darrieus. They have good efficiency, but produce large torque ripple and cyclical stress on the tower, which contributes to poor reliability. They also generally require some external power source, or an additional Savonius rotor to start turning, because the starting torque is very low. The torque ripple is reduced by using three or more blades which results in a higher solidity for the rotor. Solidity is measured by blade area divided by the rotor area. Newer Darrieus type turbines are not held up by guy-wires but have an external superstructure connected to the top bearing.



A helical twisted VAWT.

Giromill

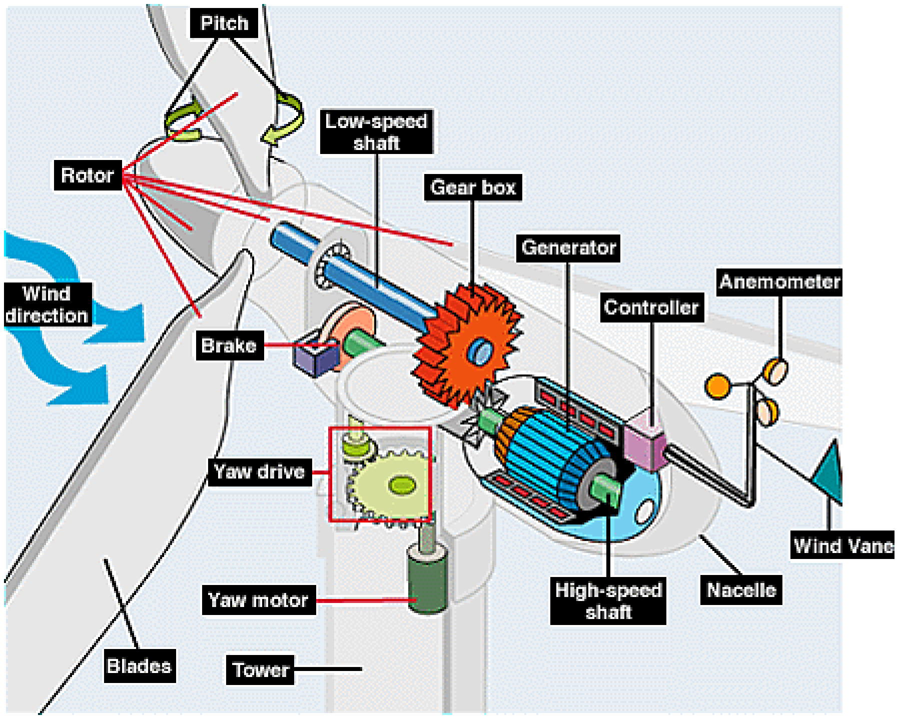
A subtype of Darrieus turbine with straight, as opposed to curved, blades. The cycloturbine variety has variable pitch to reduce the torque pulsation and is self-starting. The advantages of variable pitch are: high starting torque; a wide, relatively flat torque curve; a lower blade speed ratio; a higher coefficient of performance; more efficient operation in turbulent winds; and a lower blade speed ratio which lowers blade bending stresses. Straight, V, or curved blades may be used.

Windmill with rotating sails

Savonius wind turbine

These are drag-type devices with two (or more) scoops that are used in anemometers, *Flettner* vents (commonly seen on bus and van roofs), and in some high-reliability low-efficiency power turbines. They are always self-starting if there are at least three scoops. They sometimes have long helical scoops to give a smooth torque.

Turbine design and construction



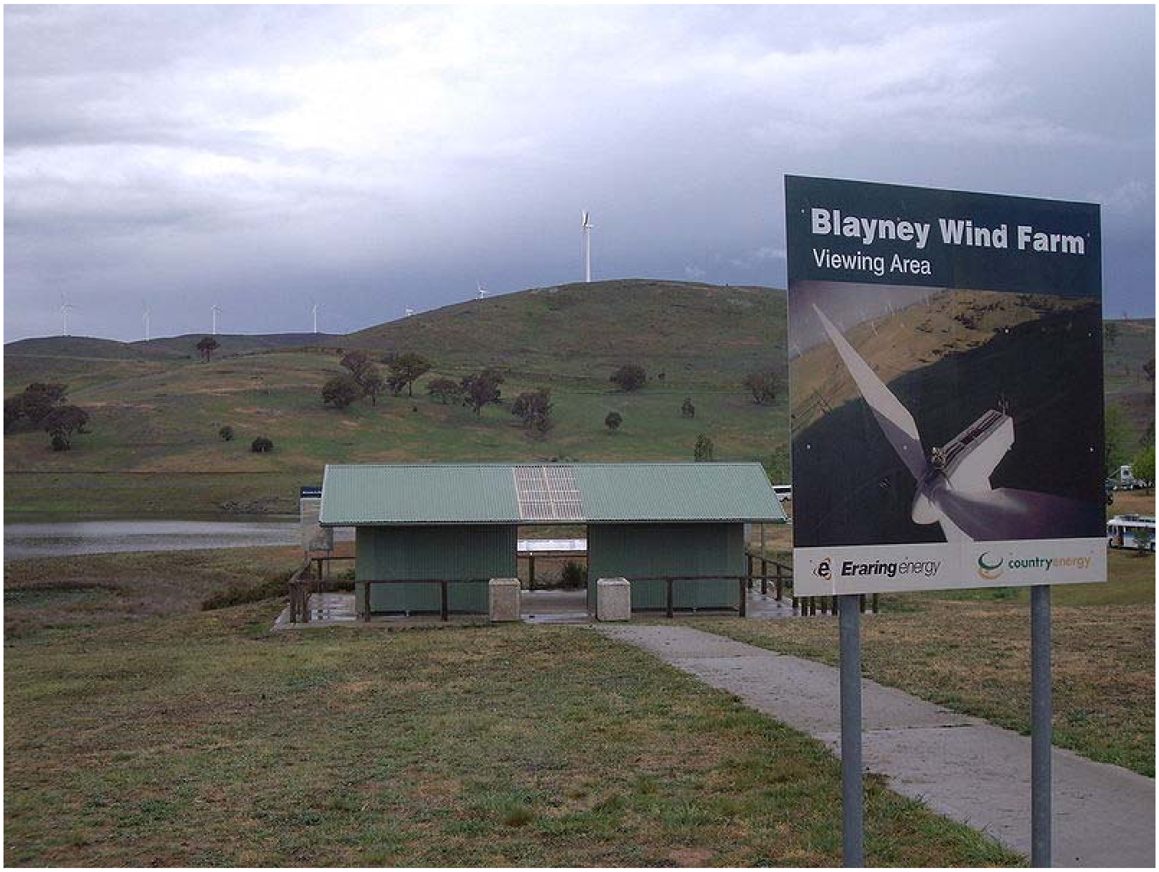
Components of a horizontal-axis wind turbine

Wind turbines are designed to exploit the wind energy that exists at a location. Aerodynamic modeling is used to determine the optimum tower height, control systems, number of blades and blade shape.

Wind turbines convert wind energy to electricity for distribution. Conventional horizontal axis turbines can be divided into three components.

- The rotor component, which is approximately 20% of the wind turbine cost, includes the blades for converting wind energy to low speed rotational energy.
- The generator component, which is approximately 34% of the wind turbine cost, includes the electrical generator, the control electronics, and most likely a gearbox (e.g. planetary gearbox, adjustable-speed drive or continuously variable transmission) component for converting the low speed incoming rotation to high speed rotation suitable for generating electricity.
- The structural support component, which is approximately 15% of the wind turbine cost, includes the tower and rotor yaw mechanism.

Unconventional wind turbines



Blayney Wind Farm, New South Wales viewing area

As of 2010, the most common type of **wind turbine** is the three-bladed horizontal-axis wind turbine (HAWT).

Modified HAWT

Ducted rotor

Still something of a research project, the ducted rotor consists of a turbine inside a duct which flares outwards at the back. They are also referred as Diffuser-Augmented Wind Turbines (i.e. DAWT). The main advantage of the ducted rotor is that it can operate in a wide range of winds and generate a higher power per unit of rotor area. Another advantage is that the generator operates at a high rotation rate, so it doesn't require a bulky gearbox, so the mechanical portion can be smaller and lighter. A disadvantage is that (apart from the gearbox) it is more complicated than the unducted rotor and the duct is usually quite heavy, which puts an added load on the tower. The Éolienne Bollée is an example of a DAWT.

Wattle Point Wind Farm's information centre

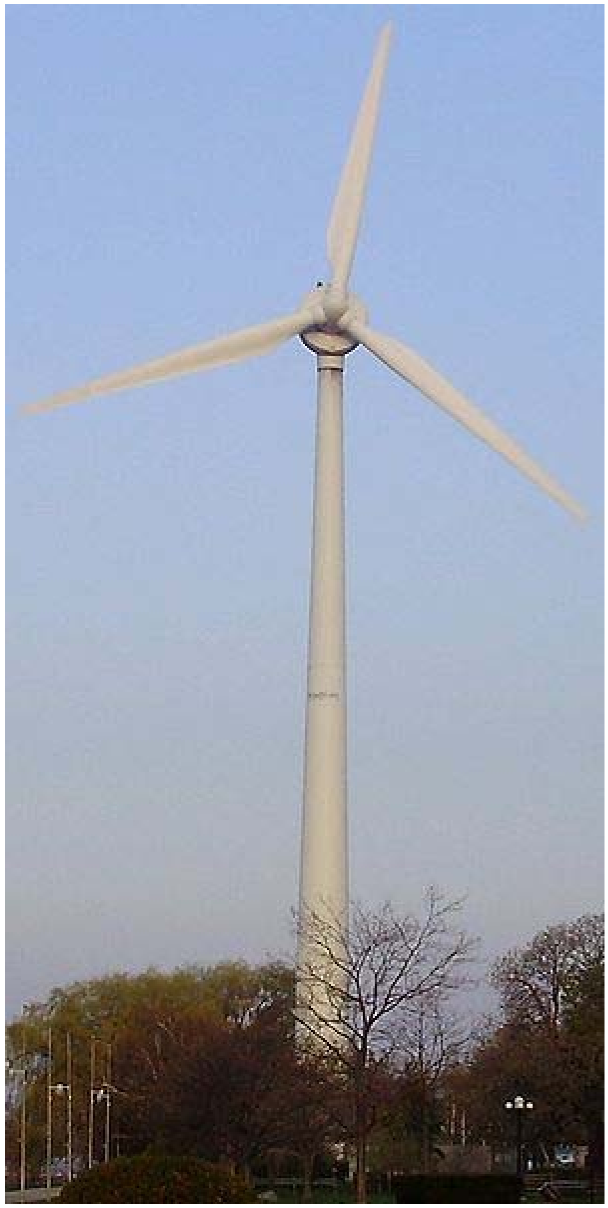
Co-axial, multi-rotor horizontal-axis turbines

Two or more rotors may be mounted to the same driveshaft, with their combined co-rotation together turning the same generator — fresh wind is brought to each rotor by sufficient spacing between rotors combined with an offset angle (alpha) from the wind direction. Wake vorticity is recovered as the top of a wake hits the bottom of the next rotor. Power has been multiplied several times using co-axial, multiple rotors in testing conducted by inventor and researcher Douglas Selsam, for the California Energy Commission in 2004. The first commercially available co-axial multi-rotor turbine is the patented dual-rotor American Twin Superturbine from Selsam Innovations in California, with 2 propellers separated by 12 feet. It is the most powerful 7-foot-diameter (2.1 m) turbine available, due to this extra rotor.

Vestas V47 wind turbine at American Wind Power Center in Lubbock, Texas

Counter-rotating horizontal-axis turbines

When a system expels or accelerates mass in one direction, the accelerated mass will cause a proportional but opposite force on that system. A single rotor wind turbine causes a significant amount of tangential or rotational air flow to be created by the spinning blades. The energy of this tangential air flow is wasted in a single-rotor propeller design. To use this wasted effort, the placement of a second rotor behind the first takes advantage of the disturbed airflow. Contra-rotation wind energy collection with two rotors, one behind the other, can gain up to 40% more energy from a given swept area as compared with a single rotor. Much work has been done recently on this in the USA. A patent application dated 1992 exists based on work done with the Trimblemill. Ability to be point suspended, thus reducing support structure overturning moments theoretical ability to be “grid linked” without electronics, thus giving the possibility of "arrays".



WindShare 750 kW, direct drive, Lagerwey Wind model LW 52 wind turbine in Toronto, Ontario

Counter-rotating turbines can be used to increase the rotation speed of the electrical generator. As of 2005, no large practical counter-rotating HAWTs are commercially sold. When the counter-rotating turbines are on the same side of the tower, the blades in front are angled forwards slightly so as to avoid hitting the rear ones. If the turbine blades are on opposite sides of the tower, it is best that the blades at the back be smaller than the blades at the front and set to stall at a higher wind speed. This allows the generator to function at a wider wind speed range than a single-turbine generator for a given tower. To reduce sympathetic vibrations, the two turbines should turn at speeds with few common multiples, for example 7:3 speed ratio. Overall, this is a more complicated design than the single-turbine wind generator, but it taps more of the wind's energy at a wider range of wind speeds.

Vestas V27 at the Great Lakes Science Center in Cleveland, Ohio

Appa designed and demonstrated a contra-rotor wind turbine in FY 2000–2002 funded by California Energy Commission. This study showed 30 to 40% more power extraction than a comparable single-rotor system. Further, it was observed that the slower the rotor speed, the better the performance. Consequently, Megawatt machines benefit most. This also cancels the gyroscopic forces.

Vestas V29 wind turbine at Beaufort Court, Kings Langley, UK

Furling tail and twisting blades turbines

In addition to variable pitch blades, furling tails and twisting blades are other improvements on wind turbines. Similar to the variable pitch blades, they may also greatly increase the efficiency of the turbine and be used in "do-it-yourself" construction

Telescopic blades

The next step in making improvements to wind turbines is the use of telescopic blades. Telescopic blades can change the blade's length, thus increasing or decreasing the turbine's swept area. Telescopic blades make a turbine more productive by increasing the turbine's rotor diameter during low-wind conditions. In high-wind conditions, when the turbine is in need of reducing loads, the blades can be retracted to make the rotor smaller.

Modified VAWT

Aerogenerator

The Aerogenerator is a special design of vertical axis wind turbine which could allow greater energy outputs.

Savonius wind turbine

The Savonius wind turbine is another special design wind turbine.

Augmented "G" model VAWT: "G" Model Wind Turbine (GMWT)

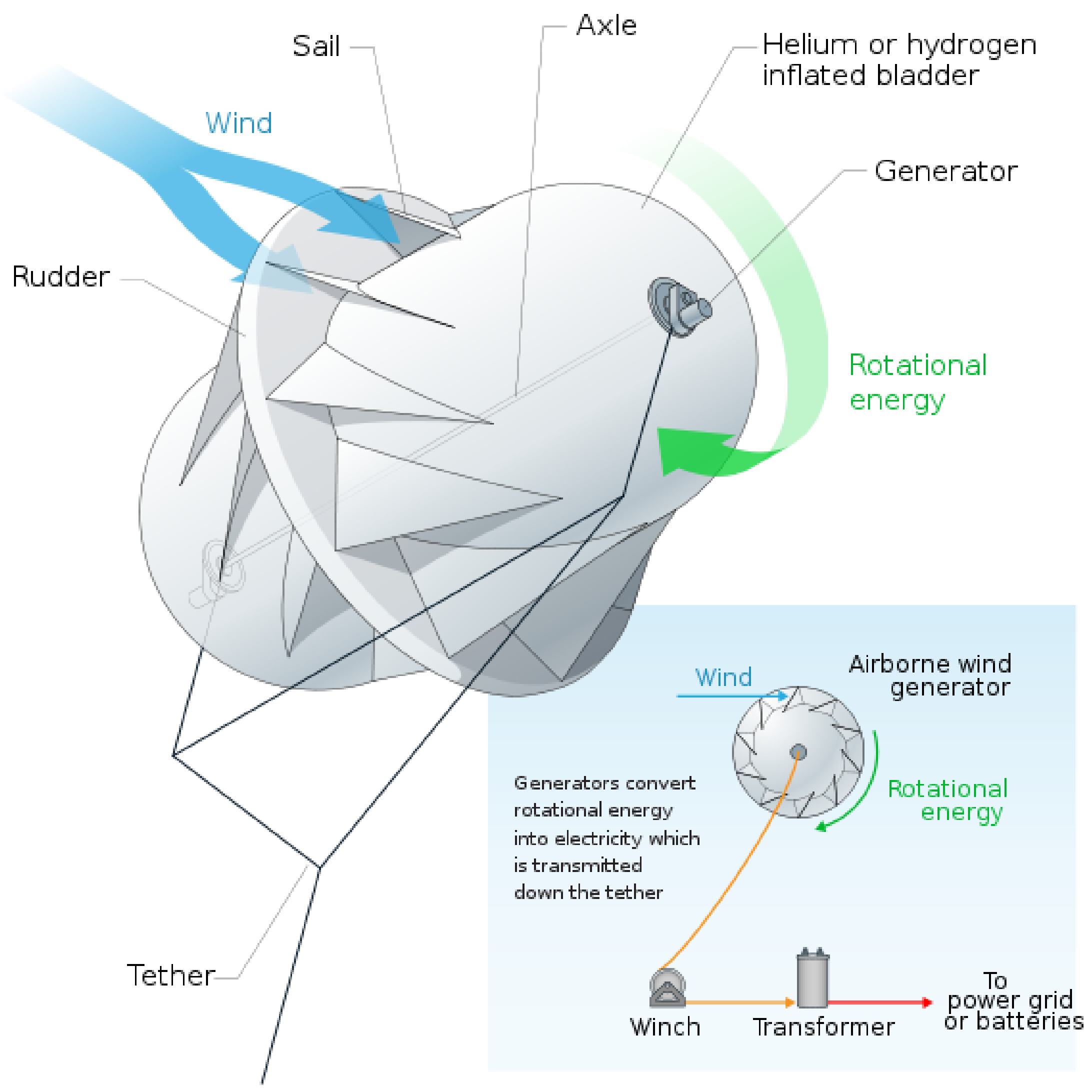
The "G" Model VAWT Turbine is equipped with three self-positioning "Augmentation And Directioning Wings=AADW" placed as the outer sections of classical Darrieus blades. The GMWT can increase almost fivefold the efficiency of classical Darrieus Blades: AADWs adjust themselves to the wind direction without any external power. The resulting combination ("G" Model Wind Turbine) works with very low cut-in wind speed, has self starting ability, together with a high capacity factor.

"Fuller" wind turbine

The "Fuller" wind turbine is a fully enclosed wind turbine which uses boundary layers instead of blades.

Imagine a stack of CDs on a central shaft with a small air gap in between, the surface tension of moving air as it passes through the small gaps creates friction and using this energy causes the CDs to rotate around the shaft. The Fuller has addition vanes to help direct the air for improved performance, hence it isn't totally bladeless, as has been suggested.

Aerial



Concept for an airborne wind generator.

It has been suggested that wind turbines could be flown in high-speed winds using high altitude wind power tactics, taking advantage of the steadier winds at high altitudes. A system of automatically controlled tethered kites could also be used to capture energy from high-altitude winds.

H-rotor

Another type is the H-rotor

Wind belt

Invented by Shawn Frayne. A belt vibrates by the passing flow of air. A magnet is mounted at one end of the belt.

Vaneless ion wind generator

Piezoelectric wind turbines

Another special type of wind turbines are the piezoelectric wind turbines. Turbines with diameters on the scale of 10 centimeters work by flexing piezoelectric crystals as they rotate, sufficient to power small electronic devices.

Enercon E-70 at GreenPark Business Park, UK

Traffic-driven wind generator

A few proposals call for generating power from the otherwise wasted energy in the draft created by traffic.

Blade Tip Power System (BTPS)

Designed by Imad Mahawili with Honeywell/WindTronics. This design uses many nylon blades and turns a permanent magnet generator inside out. The magnets are on the tips of the blades, and the stator is on the outside of the generator.

Wind turbine technology used to harness other power sources

Wind turbines may also be used in conjunction with a solar collector to extract the energy due to air heated by the Sun and rising through a large vertical Solar updraft tower. Wind turbines are part of experimental wave powered generators where air displaced by waves drives turbines.

Wind turbines with two blades

Nearly all modern wind turbines uses rotors with three blades. However, there are and were also designs with another blade count. The most common other blade count is 2. This was used at GROWIAN, some other prototypes and several wind turbine types manufactured by NedWind. A wind park only using wind turbines with 2 blades is Eemmeerdijk Wind Park. Wind turbines with 2 blades are manufactured by Nordic Wind Power (Model N 1000) and by GC China.

Wind turbines on public display

The Nordex N50 wind turbine and visitor centre of Lamma Winds in Hong Kong.

Kiosk at the base of the Lamma Winds Nordex N50/800kW wind turbine on Lamma Island with displays showing current power output and cumulative energy produced.

Scroby Sands wind farm off the coast of Great Yarmouth, UK

The great majority of wind turbines around the world belong to individuals or corporations who use them to generate electric power or to perform mechanical work. As such, wind turbines are primarily designed to be working devices. However, the large size and height above surroundings of modern industrial wind turbines, combined with their moving rotors, often makes them among the most conspicuous objects in their areas. A few localities have exploited the attention-getting nature of wind turbines by placing them on public display, either with visitor centers around their bases, or with viewing areas farther away. The wind turbines themselves are generally of conventional horizontal-axis, three-bladed design, and generate power to feed electrical grids, but they also serve the unconventional roles of technology demonstration, public relations, and education.

- Australia
    - Blayney Wind Farm, New South Wales has a viewing area and interpretive centre
    - Wattle Point Wind Farm, South Australia has an information centre
- Canada
    - OPG 7 commemorative turbine is a Vestas V80-1.8MW wind turbine on the site of the Pickering Nuclear Generating Station
    - Toronto Hydro - WindShare features a Lagerwey Wind model LW 52 wind turbine at Exhibition Place
- China
    - Inner Mongolia's Huitengxile Wind Farm has 14 visitor centers to accommodate wind power tourists to the remote region
    - Lamma Winds in Hong Kong has a single Nordex N50/800 kW model with a rotor diameter of 50m and a nameplate capacity of 800 kW
- New Zealand
    - Brooklyn, Wellington, New Zealand has a 230 kW wind turbine
- United Kingdom
    - GreenPark Business Park has an Enercon E-70 2 MW wind turbine adjacent to the M4 motorway, billed as *the UK's most visible turbine*
    - Renewable Energy Systems has a Vestas V29 225 kW wind turbine visible from the M25 motorway at its headquarters at Beaufort Court, Kings Langley, Hertfordshire
    - Scroby Sands wind farm has a visitor center at Great Yarmouth open during the tourist season (May-October)
    - Scout Moor Wind Farm "has become a real tourist attraction" since its 2008 opening

Visitor Centre at Scroby Sands wind farm

- United States
    - Dorchester, Massachusetts - Local 103 of the International Brotherhood of Electrical Workers installed the first commercial-scale wind turbine within the City of Boston, a 100 kW unit from Fuhrlaender on a 35-meter tower with rotor diameter of 21 meters, visible from the John F. Kennedy Library
    - The Great Lakes Science Center in Cleveland, Ohio has a reconditioned Vestas V27 wind turbine with a nameplate capacity of 225 kW
    - Great River Energy's headquarters in Maple Grove, Minnesota has a NEG Micon M700 wind turbine, visible from Interstate 94
    - Laurel, New York has a Northern Power Systems 100kW turbine at the Half Hollow Nursery and private tours of the operating turbine are provided by Eastern Energy Systems Inc. of Mattituck, New York.
    - Lubbock, Texas has a Vestas V47 at the American Wind Power Center
    - McKinney, Texas has a Wal-Mart store with several sustainability features, including two wind turbines manufactured by Bergey Windpower, of 1 kW and 50 kW nameplate capacity respectively
    - Sweetwater, Texas has a 2 MW 60Hz DeWind D8.2 prototype wind turbine for training students in the Texas State Technical College wind energy program

Observation deck

Some wind turbines on public display go one further, with observation decks beneath their nacelles.

- Canada
  - Grouse Mountain Resorts in North Vancouver, British Columbia installed a Leitwind 1.5MW wind turbine with an observation deck, atop a 65m tower, at an elevation of 1,300m, opening just before the 2010 Winter Olympics.
- Germany
  - One wind turbine of the type Enercon E-66 at Windpark Holtriem, Germany carries an observation deck, open for visitors.
- Netherlands
  - The Siemens plant in Zoetermeer features a wind turbine with 40m blade length and an observation deck.
- United Kingdom
  - Another Enercon E-66 wind turbine with an observation deck belonging to Ecotricity is in the English town of Swaffham.

Enercon E-66 at Swaffham's Ecotech centre, showing observation deck below nacelle

Closeup of the Enercon E-66 at Swaffham

Wind turbine with observation deck at Siemens plant in Zoetermeer

Rooftop wind-turbines

Wind-turbines can be installed on the top of a roof of a building. This is not as common as may first be assumed. Some examples include Marthalen Landi-Silo in Switzerland and Council House 2 in Melbourne, Australia. Discovery Tower is an office building in Houston, Texas, scheduled for opening in 2010, that incorporates 10 wind turbines in its architecture.

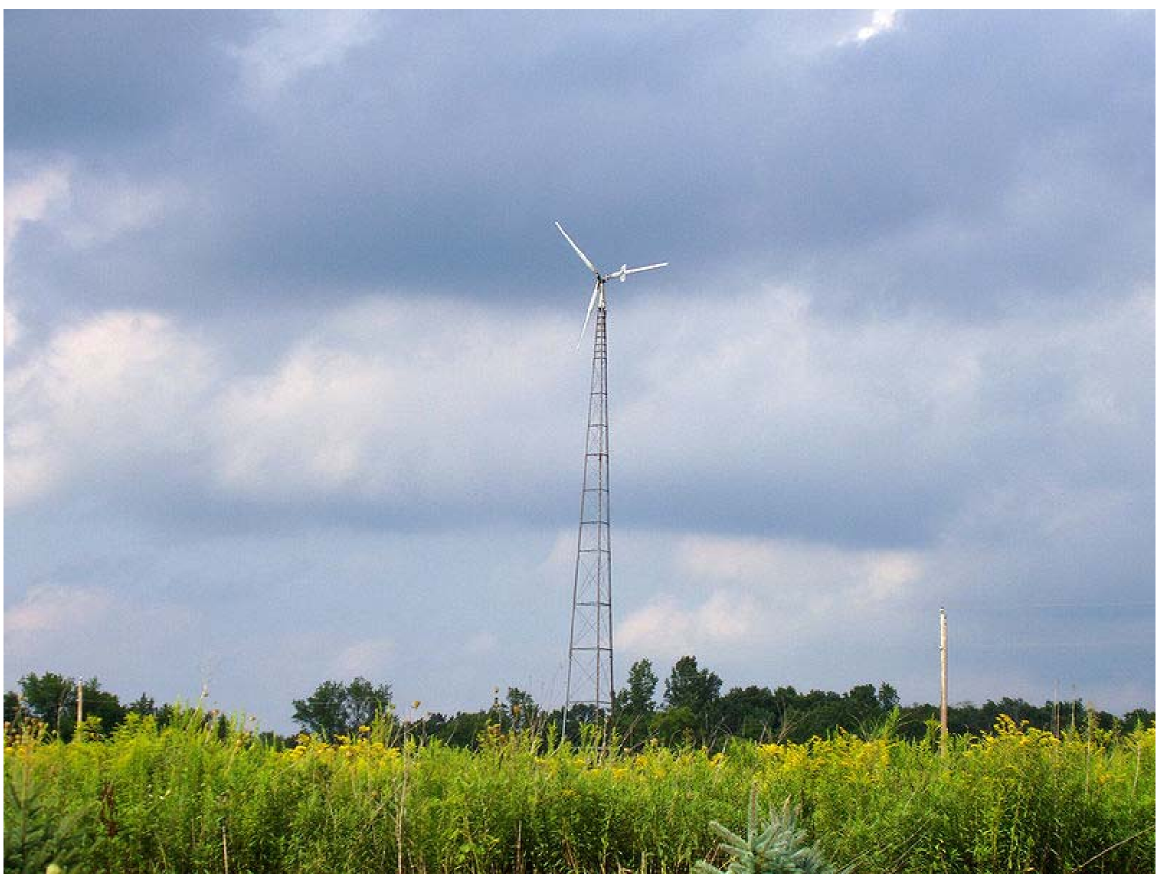
The Museum of Science in Boston, Massachusetts began constructing a rooftop Wind Turbine Lab in 2009. The Lab will test nine wind turbines from five different manufacturers on the roof of the Museum. Rooftop wind turbines may suffer from turbulence, especially in cities, which reduces power output and accelerates turbine wear. The lab seeks to address the general lack of performance data for urban wind turbines.

Due to the structural limitations of buildings, the limited space in urban areas, and safety considerations, wind turbines mounted on buildings are usually small (with nameplate capacities in the low kilowatts), rather than the megawatt-class wind turbines which are most economical for wind farms. A partial exception is the Bahrain World Trade Centre with three 225 kW wind turbines mounted between twin skyscrapers.

One E-66 wind turbine at Windpark Holtriem, Germany, carries an observation deck, open for visitors. Another turbine of the same type, with an observation deck, is located in Swaffham, England. Airborne wind turbines have been investigated many times but have yet to produce significant energy. Conceptually, wind turbines may also be used in conjunction with a large vertical solar updraft tower to extract the energy due to air heated by the sun.

Wind turbines which utilise the Magnus effect have been developed.

Small wind turbines



Small-scale wind power in rural Indiana.

Small wind turbines are wind turbines which have lower energy output than large commercial wind turbines, such as those found in wind farms. These turbines may be as small as a fifty watt generator for boat, caravan, or miniature refrigeration unit. Small units often have direct drive generators, direct current output, aeroelastic blades, lifetime bearings and use a vane to point into the wind. Larger, more costly turbines generally have geared power trains, alternating current output, flaps and are actively pointed into the wind. Direct drive generators and aeroelastic blades for large wind turbines are being researched.

Market

United States

Small wind turbines added a total of 17.3 MW of generating capacity throughout the United States in 2008, according to the American Wind Energy Association (AWEA). That growth equaled a 78% increase in the domestic market for small wind turbines, which are defined as wind turbines with capacities of 100 kW or less. AWEA's "2009 Small Wind Global Market Study", published in late 2009 May, credited the increase in part to greater manufacturing volumes, as the industry was able to attract enough private investment to finance manufacturing plant expansions. It also credited rising electricity prices and greater public awareness of wind technologies for an increase in residential sale. But a poll of small wind manufacturers found that the growth in 2008 might be only a glimmer of things to come, as the companies projected a 30-fold growth in the U.S. small wind market within as little as five years, despite the global recession. The U.S. small wind industry also benefits from the global market, as it controls about half of the global market share. U.S. manufacturers garnered $77 million of the $156 million that was spent throughout the world on small wind turbine installations. A total of 38.7 MW of small wind power capacity was installed globally in 2008.

Installation

Turbines should be mounted on a suitable tower to raise them above any nearby obstacles. A good rule of thumb is that turbines should be at least 30 feet (9 m) higher than anything within 500 feet (152 m). In general, an effort should be made to make sure that a small wind turbine is as far away as possible from large upwind obstacles. Measurements made in a boundary layer wind tunnel have indicated that significant detrimental effects associated with nearby obstacles can extend up to 80 times the obstacle's height downwind. However, this is an extreme case. Another approach to siting a small turbine is to use a shelter model to predict how nearby obstacles will affect local wind conditions. Models of this type are general and can be applied to any site. They are often developed based on actual wind measurements, and can estimate flow properties such as mean wind speed and turbulence levels at a potential turbine location, taking into account the size, shape, and distance to any nearby obstacles.

A small wind turbine can be installed on a roof. Installation issues then include the strength of the roof, vibration, and the turbulence caused by the roof ledge. Small-scale rooftop turbines suffer from turbulence and rarely generate significant amounts of power, especially in towns and cities.

Types

Smaller scale turbines for residential scale use are available, they are usually approximately 7 to 25 feet (2.1–7.6 m) in diameter and produce electricity at a rate of 300 to 10,000 watts at their tested wind speed. Some units have been designed to be very lightweight in their construction, e.g. 16 kilograms (35 lb), allowing sensitivity to minor wind movements and a rapid response to wind gusts typically found in urban settings and easy mounting much like a television antenna. It is claimed, and a few are certified, as being inaudible even a few feet (about a metre) under the turbine.

Vertical axis wind turbines are a growing type of wind turbine in the small-wind market. These turbines, by being able to take wind from multiple dimensions, are more applicable for use at low heights, on rooftops, and in generally urbanized areas. Their ability to function well at low heights is particularly important when considering the cost of a high tower necessary for traditional turbines. All big companies in this industry, such as WePower, Urban Green Energy, Mariah Power, and Helix Wind, have reported sharply increasing sales over the previous years.

Dynamic braking regulates the speed by dumping excess energy, so that the turbine continues to produce electricity even in high winds. The dynamic braking resistor may be installed inside the building to provide heat (during high winds when more heat is lost by the building, while more heat is also produced by the braking resistor). The location makes low voltage (around 12 volt) distribution practical.

Local use

In the United States, residential wind turbines with outputs of 2–10 kW, typically cost between $12,000 and $55,000 installed ($6 per watt), although there are incentives and rebates available in 19 states that can reduce the purchase price for homeowners by up to 50 percent, to ($3 per watt). The US manufacturer "Southwest Windpower," estimates a turbine to pay for itself in energy savings in 5 to 10 years.

The American Wind Energy Association has released several studies on the small wind turbine market in the U.S. and abroad, showing that the U.S. continues to dominate the Small Wind industry. According to another organization, the World Wind Energy Association, it is difficult to assess the total number or capacity of small-scaled wind turbines, but in China alone, there are roughly 300,000 small-scale wind turbines generating electricity.

The dominant models on the market, especially in the United States, are horizontal-axis wind turbines (HAWT).

Parts

- Blades
- Hub
- DC generator
- Diode
- Mount
- Wires
- Tail

Tower

- Base
- Pole
- Guy-wires

Loopwing

The Loopwing turbine is a low-noise, low-vibration and self-stabilizing device. It is specifically designed for quiet home use. It requires only a 1.6 mph (2.6 km/h) breeze to get started.

DIY and Open Source Wind Turbines

Some hobbyists have built wind turbines from kits, sourced components, or from scratch.

Do it yourself or DIY-wind turbine construction has been made popular by magazines such as OtherPower and Home Power, and websites such as Instructables, and by TV-series as Jericho and The Time Machine.

DIY-made wind turbines are usually smaller (rooftop) turbines of ~ 1 kW or less. These small wind turbines are usually tilt-up or fixed/guyed towers. However, larger (freestanding) and more powerful windtubines are sometimes built as well. The latter can generate power of up to 10 kW. In addition, people are also showing interest in DIY-construction of wind turbines with special designs as the Savonius, Panemone, wind turbine to boost power generation. When compared to similar sized commercial wind turbines, these DIY turbines tend to be cheaper.

Through the internet, the community is now able to obtain plans to construct DIY-wind turbines. and there is a growing trend toward building them for domestic requirements. The DIY-wind turbines are now being used both in developed countries and in developing countries, to help power homes, residences and small businesses. At present, organizations as Practical Action have designed DIY wind turbines that can be easily built by communities in developing nations and are supplying concrete documents on how to do so.

Open source

To assist people in the developing countries, and hobbyists alike, several projects have been open-sourced (e.g. the Jua Kali wind turbine, Hugh Piggot's wind turbine, ForceField Wind Turbine, Chispito Wind Generator.)

A small wind turbine being used at the Riverina Environmental Education Centre near Wagga Wagga, New South Wales, Australia

Small wind turbines may be as small as a fifty-watt generator for boat or caravan use. Small units often have direct drive generators, direct current output, aeroelastic blades, lifetime bearings and use a vane to point into the wind.

Larger, more costly turbines generally have geared power trains, alternating current output, flaps and are actively pointed into the wind. Direct drive generators and aeroelastic blades for large wind turbines are being researched.

Record-holding turbines

Largest capacity

The Enercon E-126 has a rated capacity of 7.58 MW, has an overall height of 198 m (650 ft), a diameter of 126 m (413 ft), and is the world's largest-capacity wind turbine since its introduction in 2007.

At least four companies are working on the development of a 10MW turbine:

- American Superconductor
- Wind Power Ltd are developing a 10 MW VAWT, the Aerogenerator X
- Clipper Windpower are developing the Britannia 10 MW HAWT
- Sway announced the proposed development of a prototype 10 MW wind turbine with a height of 162.5 m (533 ft) and a rotor diameter of 145 m (475 ft).

Largest swept area

The turbine with the largest swept area is a prototype installed by Gamesa at Jaulín, Zaragoza, Spain in 2009. The G10X – 4.5 MW has a rotor diameter of 128m.

Tallest

The tallest wind turbine is Fuhrländer Wind Turbine Laasow. Its axis is 160 meters above ground and its rotor tips can reach a height of 205 meters. It is the only wind turbine taller than 200 meters in the world.

Largest vertical-axis

Le Nordais wind farm in Cap-Chat, Quebec has a vertical axis wind turbine (VAWT) named Éole, which is the world's largest at 110 m. It has a nameplate capacity of 3.8MW.

Most southerly

The turbines currently operating closest to the South Pole are three *Enercon E-33* in Antarctica, powering New Zealand's Scott Base and the United States' McMurdo Station since December 2009 although a modified HR3 turbine from Northern Power Systems operated at the Amundsen-Scott South Pole Station in 1997 and 1998. In March 2010 CITEDEF designed, built and installed a wind turbine in Argentine Marambio Base.

Most productive

Four turbines at Rønland wind farm in Denmark share the record for the most productive wind turbines, with each having generated 63.2 GWh by June 2010

Highest-situated

The world's highest-situated wind turbine is made by DeWind and located in the Andes, Argentina around 4,100 metres (13,500 ft) above sea level. The site uses a type D8.2 - 2000 kW / 50 Hz turbine. This turbine has a new drive train concept with a special torque converter (WinDrive) made by Voith and a synchronous generator. The WKA was put into operation in December 2007 and has supplied the Veladero mine of Barrick Gold with electricity since then.

Gallery of record-holders

Enercon E-126, highest rated capacity

Fuhrländer Wind Turbine Laasow, world's tallest

Éole, the largest vertical axis wind turbine, in Cap-Chat, Quebec

Highest-situated wind turbine, at the Veladero mine in San Juan Province, Argentina