Energy Technology, Systems and Engineering

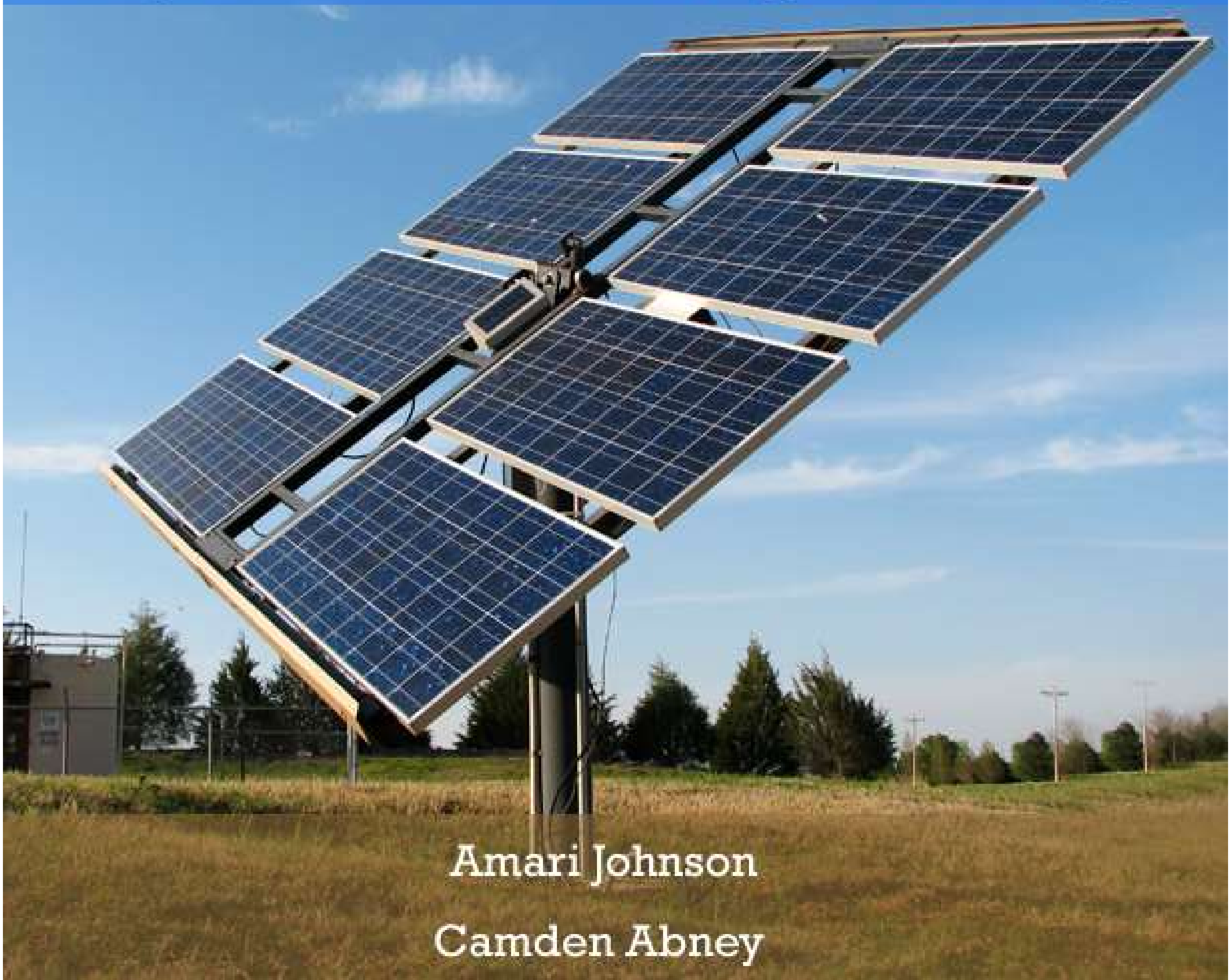

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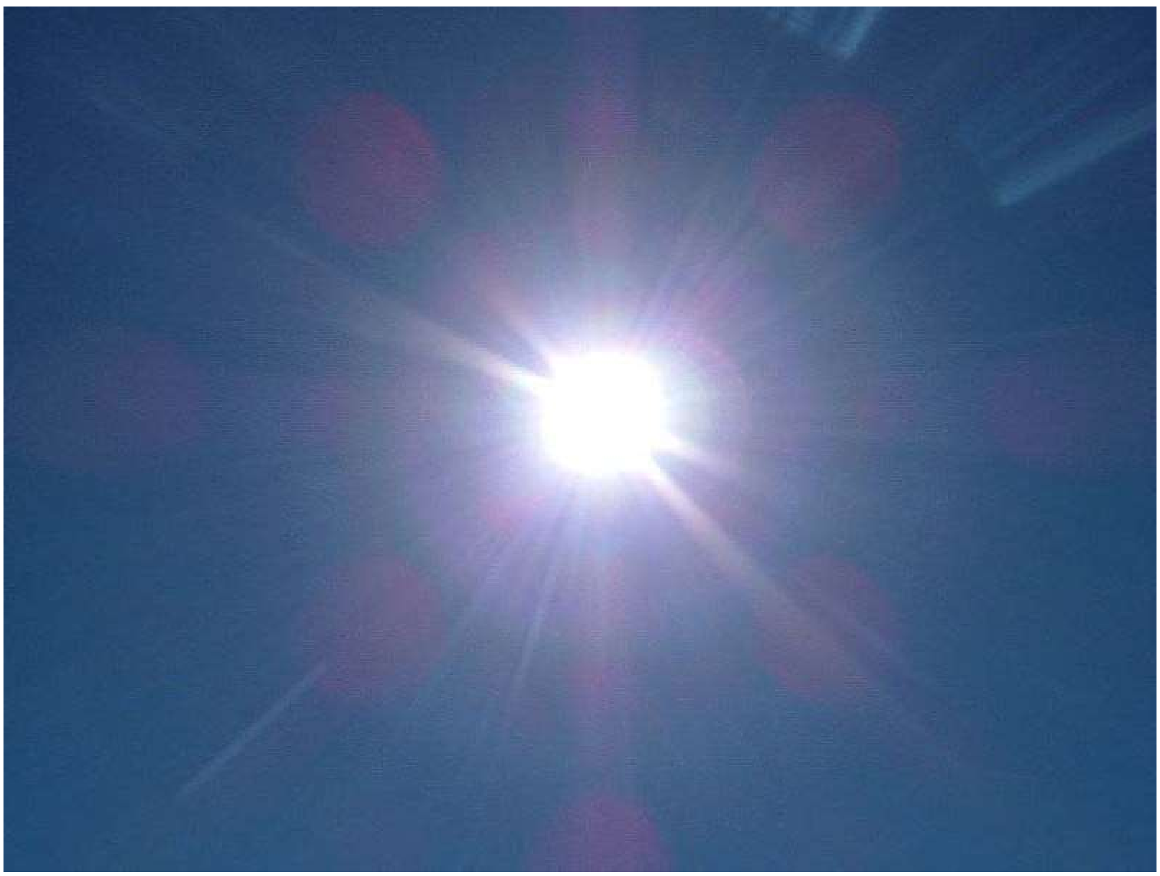
Table of Contents

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

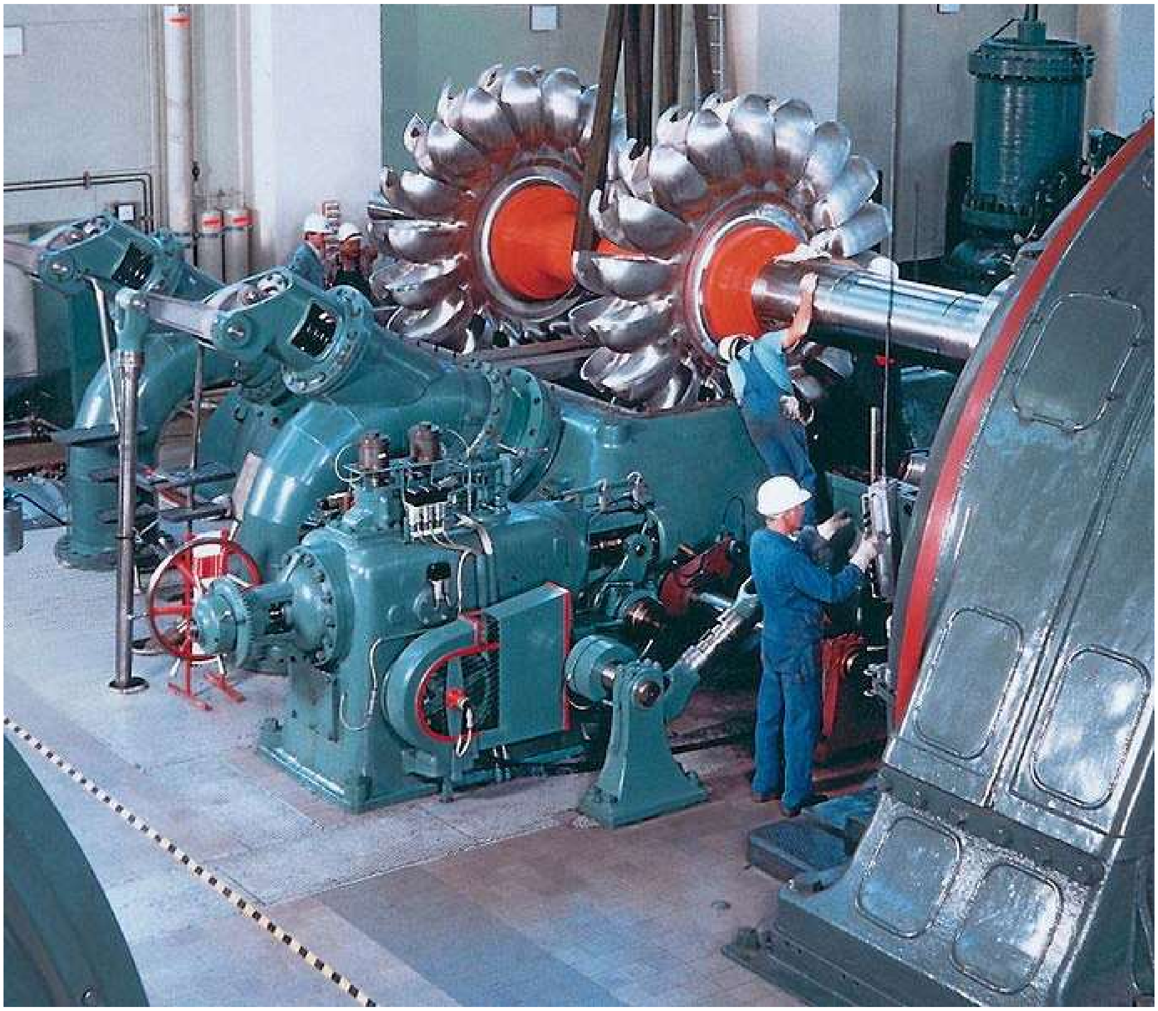
Wind turbines on Inner Mongolian grassland

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.

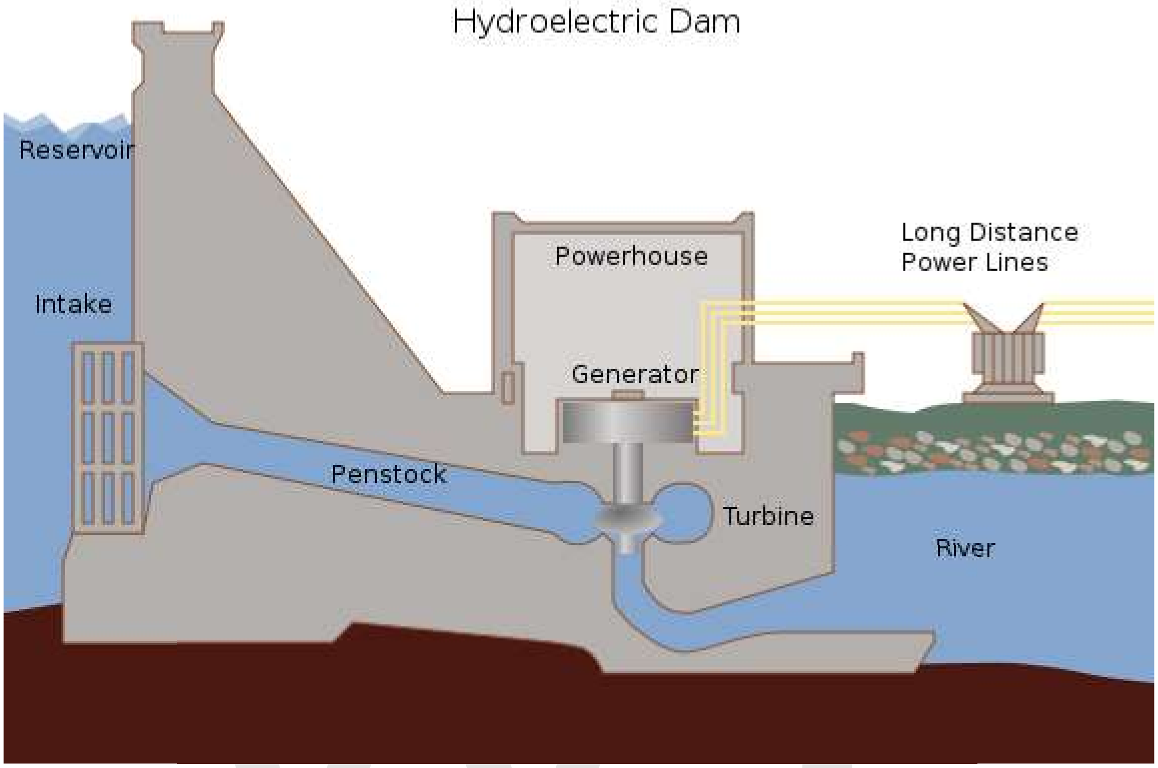
Hydraulic power pipes

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

$$\phi = A v$$

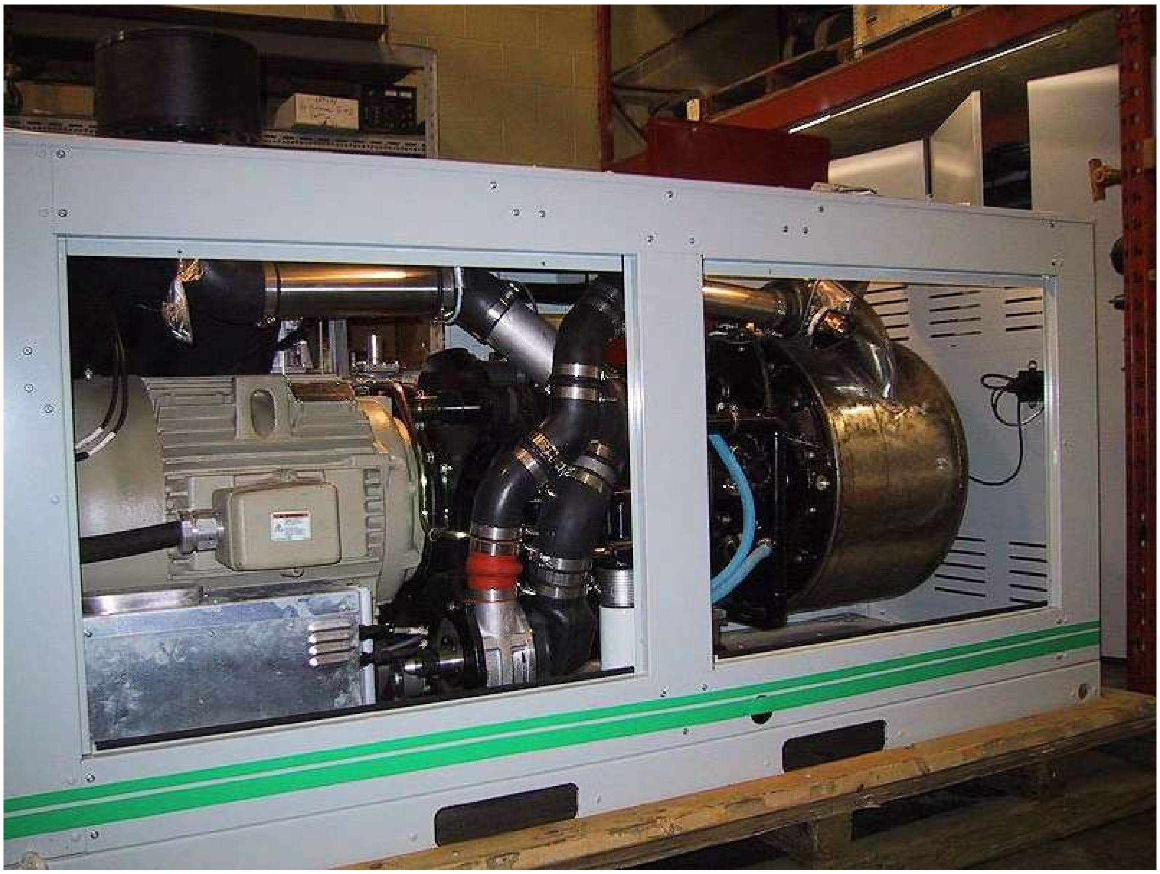
where A is the area through which the water passes, also

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

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.

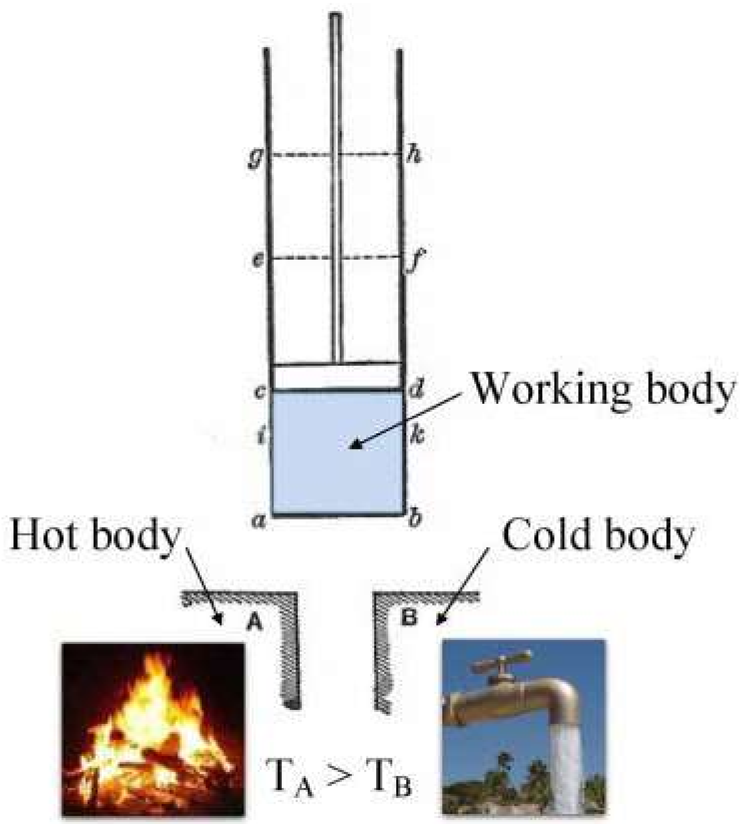
Delhi Technological University has done pioneering research in the sphere of Third Generation Biofuel research. Delhi Technological University(Formerly Delhi College Of Engineering)is also organizing the 1st International Conference On New Frontiers in Bio-fuels.The Conference aims to harbor a platform 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.

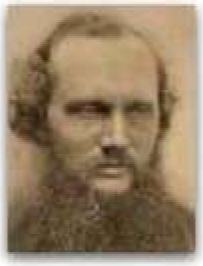
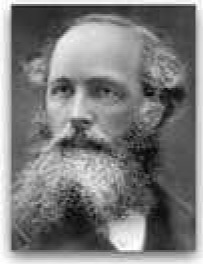
Introduction

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.

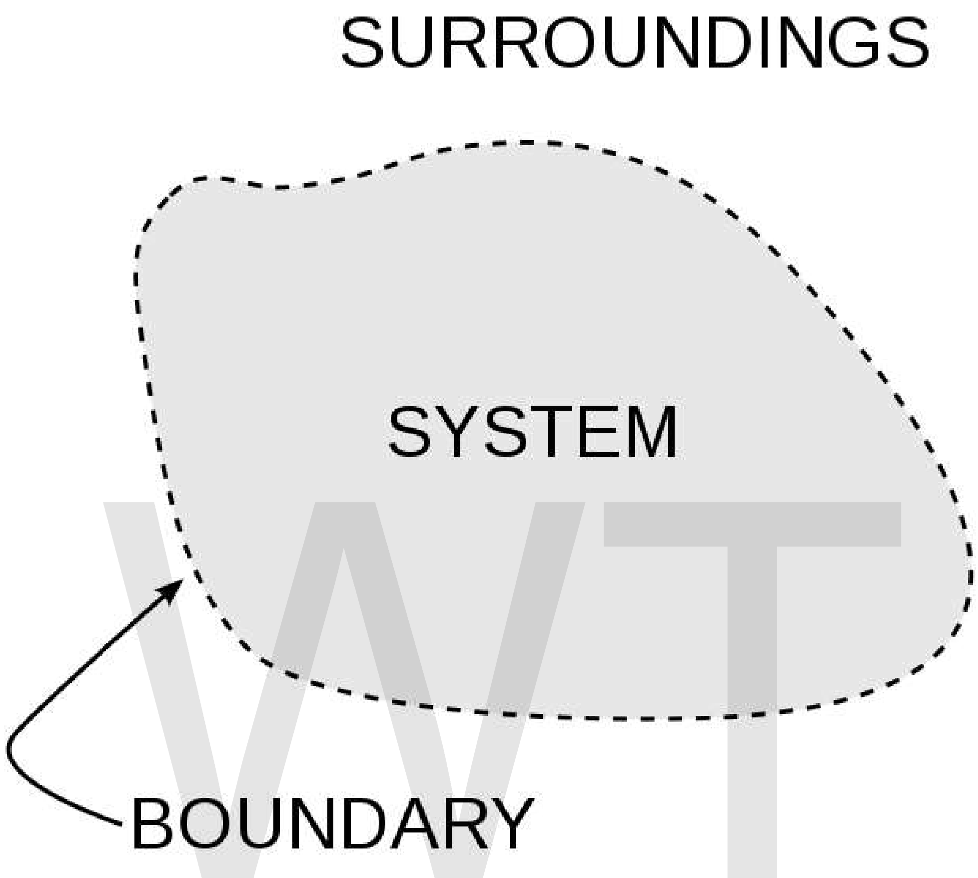
In classical thermodynamics, the second law is a basic postulate applicable to any system involving heat energy transfer; in statistical thermodynamics, the second law is a consequence of the assumed randomness of molecular chaos. There are many versions of the second law, but they all have the same 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	$\int (TdS - pdV + \sum_i \mu_i dN_i)$	$S,V,\{N_i\}$
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

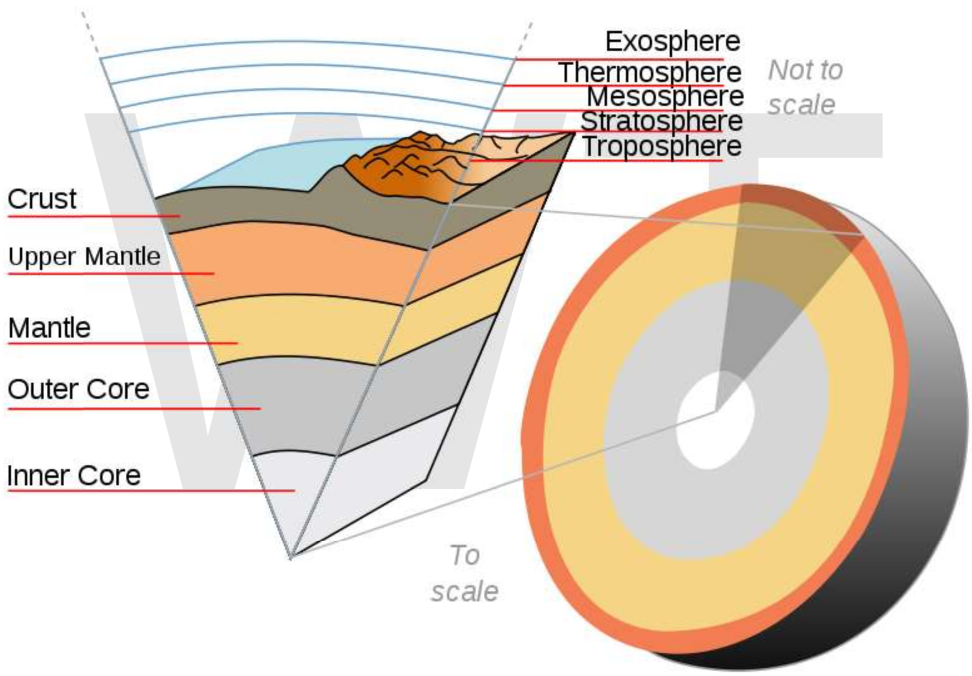
According to the theory, as the Universe cooled after the big bang it eventually became possible for common subatomic particles as we know them (neutrons, protons and electrons) to exist. The most common particles created in the big bang which are still easily observable to us today were protons and 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.

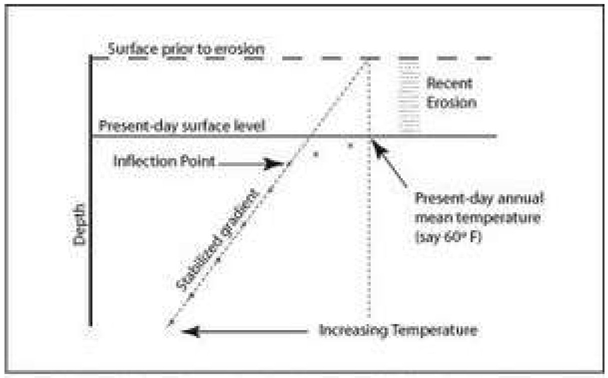


Fig 1. Borehole geothermal gradient in an area of uplift and erosion.

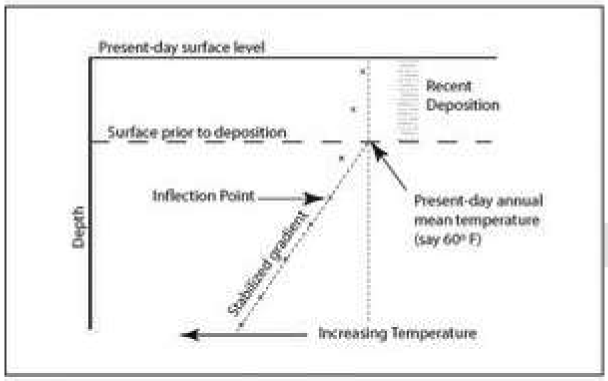


Fig 2. Borehole geothermal gradient in an area of deposition and subsidence.

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.

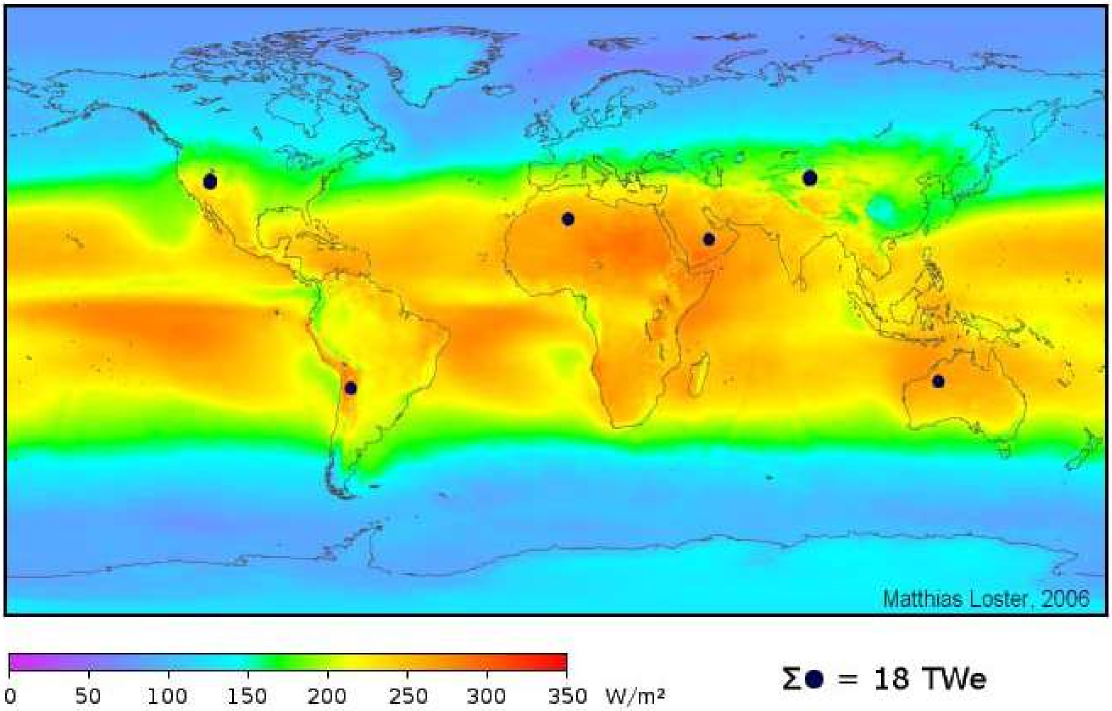
The photovoltaic effect was first observed by Alexandre-Edmond Becquerel in 1839.

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.

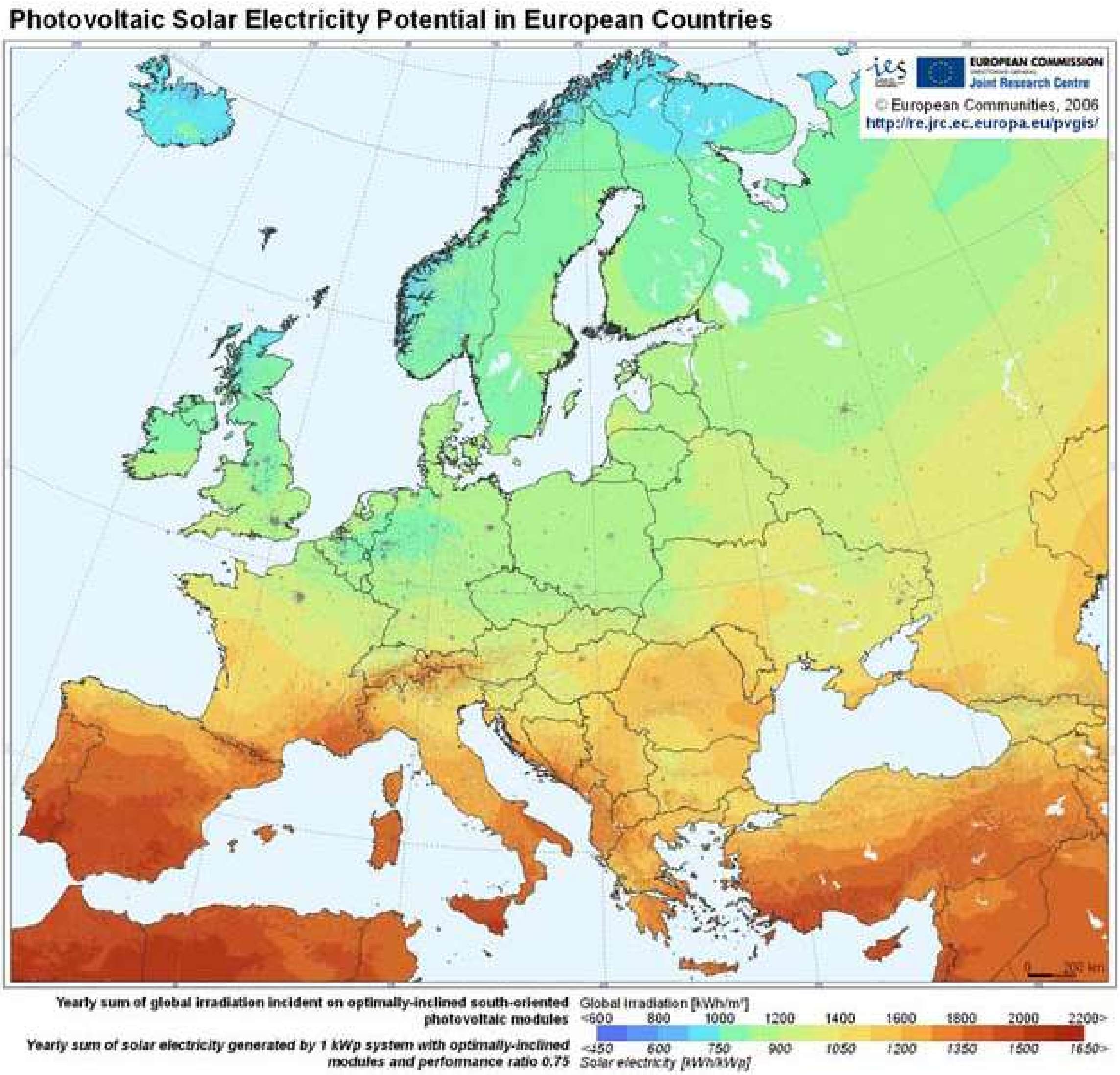
Photovoltaic production has been increasing by an average of more than 20 percent each year since 2002, making it the world's fastest-growing energy technology. At the end of 2009, the cumulative global PV installations surpassed 21,000 megawatts. Germany installed a record 3,800 MW of solar PV in 2009. 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/m² 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.

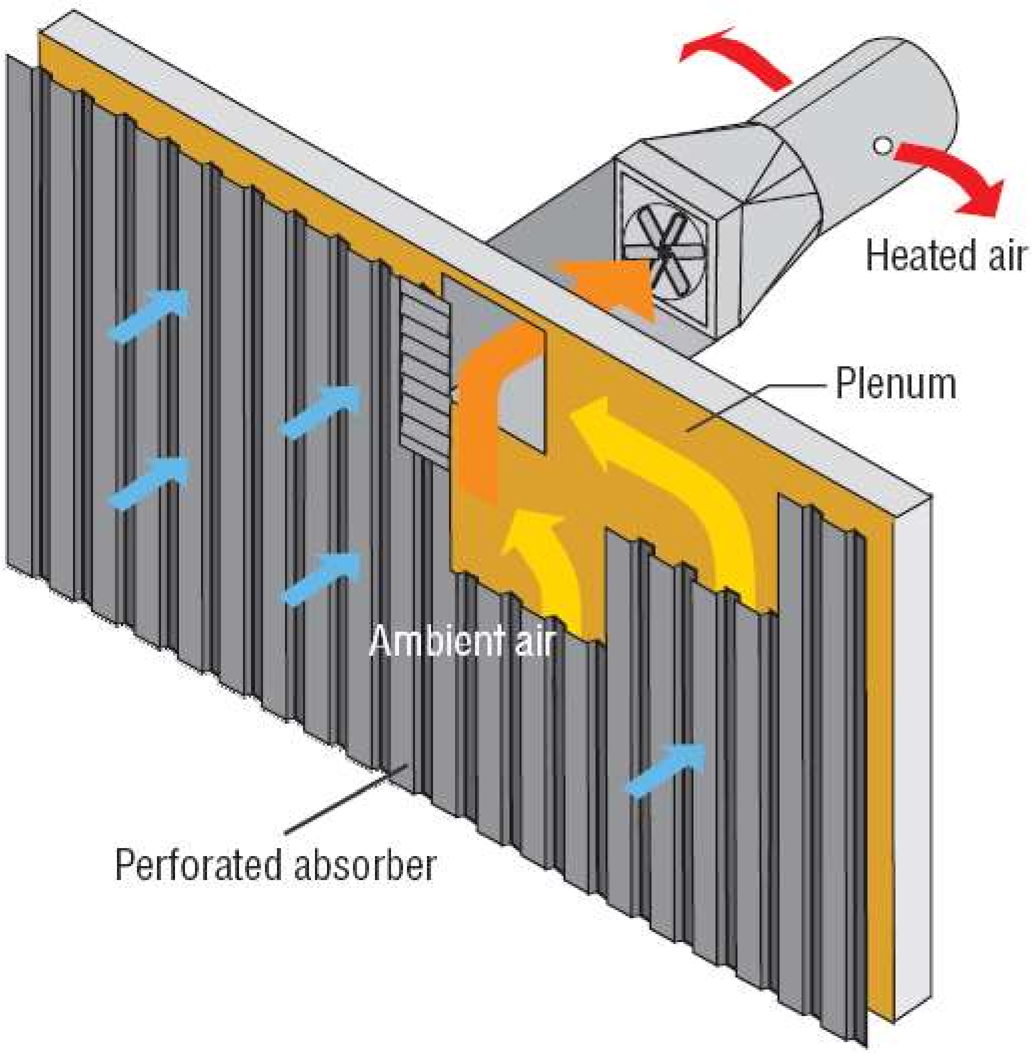
In the United States, heating, ventilation, and air conditioning (HVAC) systems account for over 25 percent (4.75 EJ) of the energy used in commercial buildings and nearly half (10.1 EJ) of the energy used in residential buildings. Solar heating, cooling, and ventilation technologies can be used to offset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

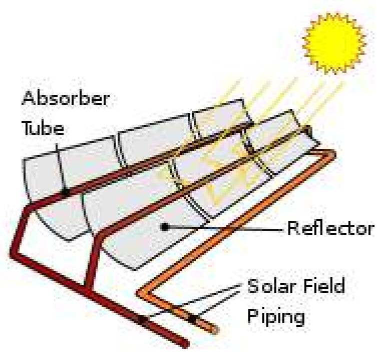
Since the CSP plant generates heat first of all, it can store the heat before conversion to electricity. With current technology, storage of heat is much cheaper and more efficient than storage of electricity. In this way, the CSP plant can produce electricity day and night. If the CSP site has predictable 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



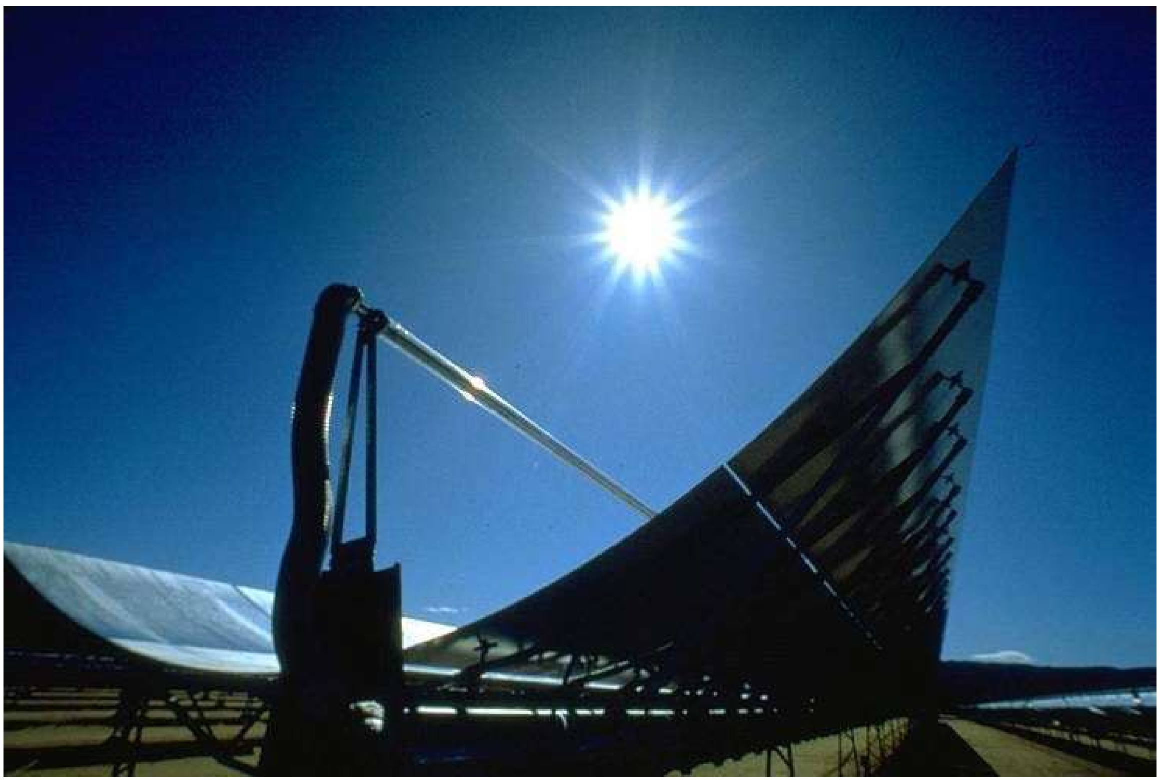
Sketch of a parabolic trough design. A change of position of the sun parallel to the receiver does not require adjustment of the mirrors.

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.



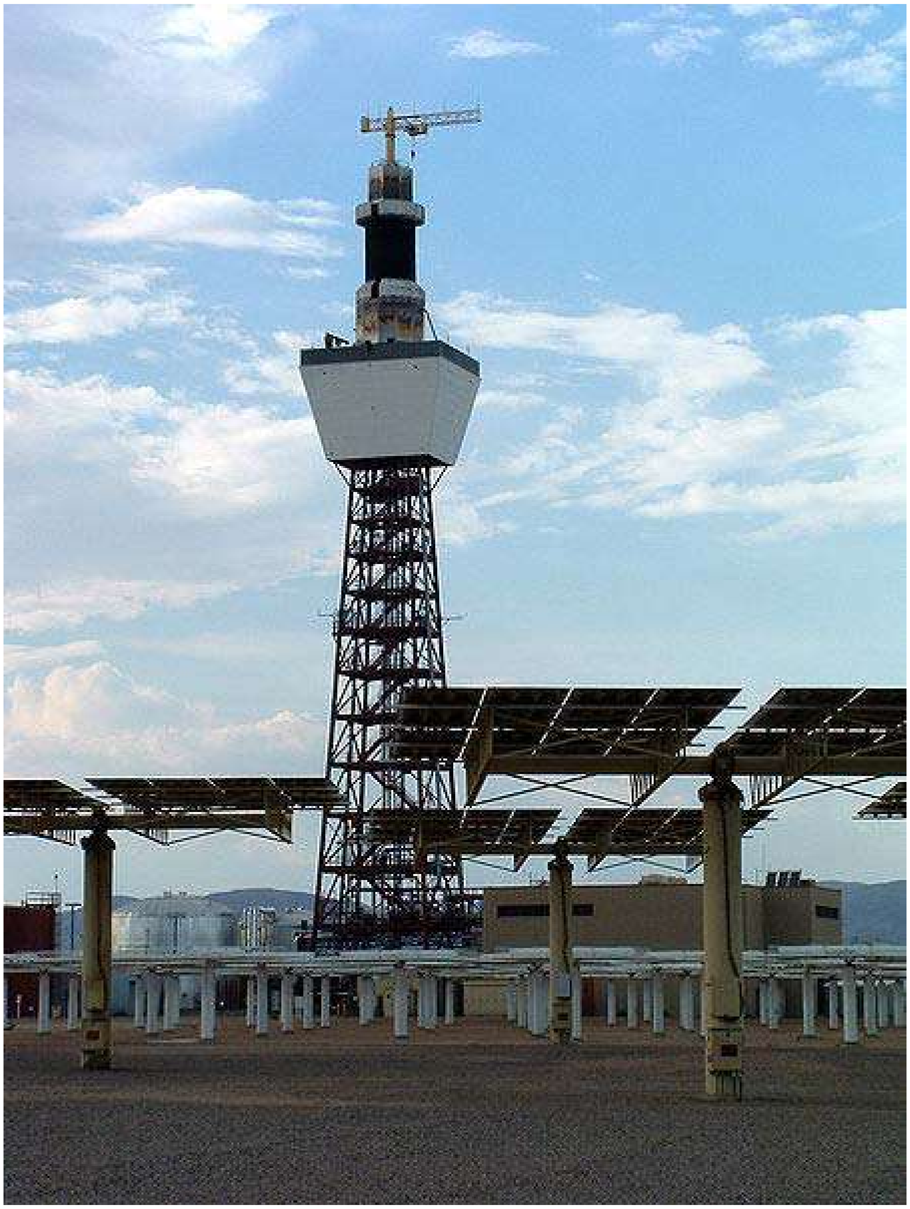
Concentrating solar power systems are a fast growing source of sustainable energy.

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.

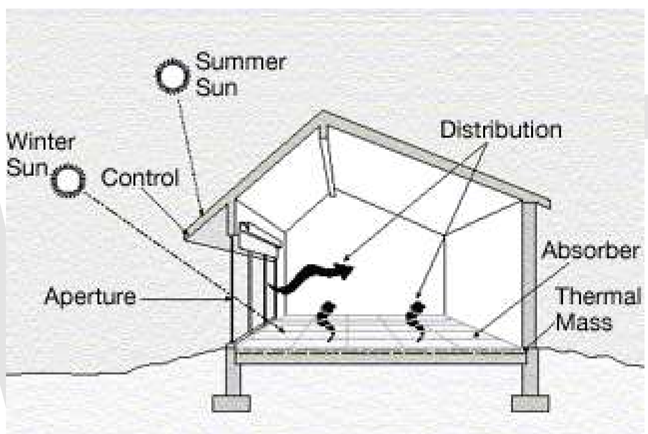
If the cost per kWh may follow the inflation, then the inflation rate can be added to the interest rate. If an investor puts his money on the bank for 7%, then he is not compensated for inflation. However, if the cost per kWh is raised with inflation, then he is compensated and he can add 2% (a normal 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

Passive Solar Building Design



Elements of passive solar design, shown in a direct gain application

Active and passive solar systems are used in the Solar Umbrella house to achieve nearly 100% energy neutrality.

In **passive solar building design**, windows, walls, and floors are made to collect, store, and distribute solar energy in the form of heat in the winter (Passive Solar Heating) and reject solar heat in the summer (Passive Solar Cooling). This is called "passive" solar design (or climatic design) because, unlike "active" (solar heating, photovoltaic, etc.) solar systems, passive solar systems do not involve the use of mechanical or electrical devices, fans, pumps, etc.

The goal to designing a cost-effective passive solar building is to best take advantage of the local climate. Elements to be considered include window placement, orientation, size and glazing type, thermal insulation, thermal mass, and shading on warm days. Passive solar design techniques can be applied most easily to new buildings, but existing buildings can be adapted or "retrofitted". For example, a passive solar sunroom can be added to an existing building with an equator-side exposure.

Solar panels are used in passive and active solar hot water systems

Passive energy gain

Passive solar technologies use sunlight without active mechanical systems (as contrasted to active solar). Such technologies convert sunlight into usable heat (water, air, thermal mass), cause air-movement for ventilating, or future use, with little use of other energy sources. A common example is a solarium on the equator-side of a building. Passive cooling is the use of the same design principles to reduce summer cooling requirements.

Some passive systems use a small amount of conventional energy to control dampers, shutters, night insulation, and other devices that enhance solar energy collection, storage, use, and reduce undesirable heat transfer.

Passive solar technologies include direct and indirect solar gain for space heating, solar water heating systems based on the thermosiphon or geyser pump, use of thermal mass and phase-change materials for slowing indoor air temperature swings, solar cookers, the solar chimney for enhancing natural ventilation, and earth sheltering.

More widely, passive solar technologies include the solar furnace and solar forge, but these typically require some external energy for aligning their concentrating mirrors or receivers, and historically have not proven to be practical or cost effective for widespread use. 'Low-grade' energy needs, such as space and water heating, have proven, over time, to be better applications for passive use of solar energy.

As a science

The scientific basis for **Passive Solar Building Design** has been developed from a combination of climatology, thermodynamics (particularly heat transfer: conduction (heat), convection, and electromagnetic radiation), fluid mechanics / natural convection (passive movement of air and water without the use of electricity, fans or pumps), and human thermal comfort based on heat index, psychrometrics and enthalpy control for buildings to be inhabited by humans or animals, sunrooms, solariums, and greenhouses for raising plants.

Specific attention is divided into: the site, location and solar orientation of the building, local sun path, the prevailing level of insolation (latitude / sunshine / clouds / precipitation (meteorology)), design and construction quality / materials, placement / size / type of windows and walls, and incorporation of solar-energy-storing thermal mass with heat capacity.

While these considerations may be directed toward any building, achieving an ideal optimized cost / performance solution requires careful holistic system integration engineering of these scientific principles. Modern refinements through computer modeling (such as the comprehensive U.S. Department of Energy "Energy Plus" energy simulation software, and application of decades of lessons learned (since the 1970's energy crisis) can achieve significant energy savings and reduction of environmental damage, without sacrificing functionality or aesthetics. In fact, passive-solar design features such as a greenhouse / sunroom / solarium can greatly enhance the livability, daylight, views, and value of a home, at a low-cost per unit of space.

Much has been learned about Passive Solar Building Design since the 1970's energy crisis. Many unscientific intuition-based expensive construction experiments have attempted and failed to achieve zero energy - the total elimination of heating-and-cooling energy bills.

One of the most useful "after-the-fact" quick-evaluation tools has been the use of thermography full-color digital thermal imaging cameras for a formal quantitative scientific energy audit. In an instant, they can irrefutably document areas of bad thermal performance, (such as the negative thermal impact of roof-angled glass or a skylight on a cold winter night or hot summer day). One serious problem of after-the-fact problem documentation is that it can waste a lot of time and capital investment on bad ideas, when passive-solar experiments are based on unscientific intuition (like common misunderstanding of sunrooms and greenhouses with roof-angled glazing, etc.).

The scientific lessons learned over the last three decades have been captured in sophisticated comprehensive energy simulation computer software systems (like U.S. DOE Energy Plus, et.al.), which take time for a scientist or engineer to learn how to use.

Passive Solar Building Construction may not be difficult or expensive (using off-the-shelf existing materials and technology), but the Scientific Passive Solar Building Design Process is a non-trivial advanced engineering effort that requires significant study of previous counter-intuitive lessons learned, and time to enter, evaluate, and iteratively-refine the computer simulation input and output.

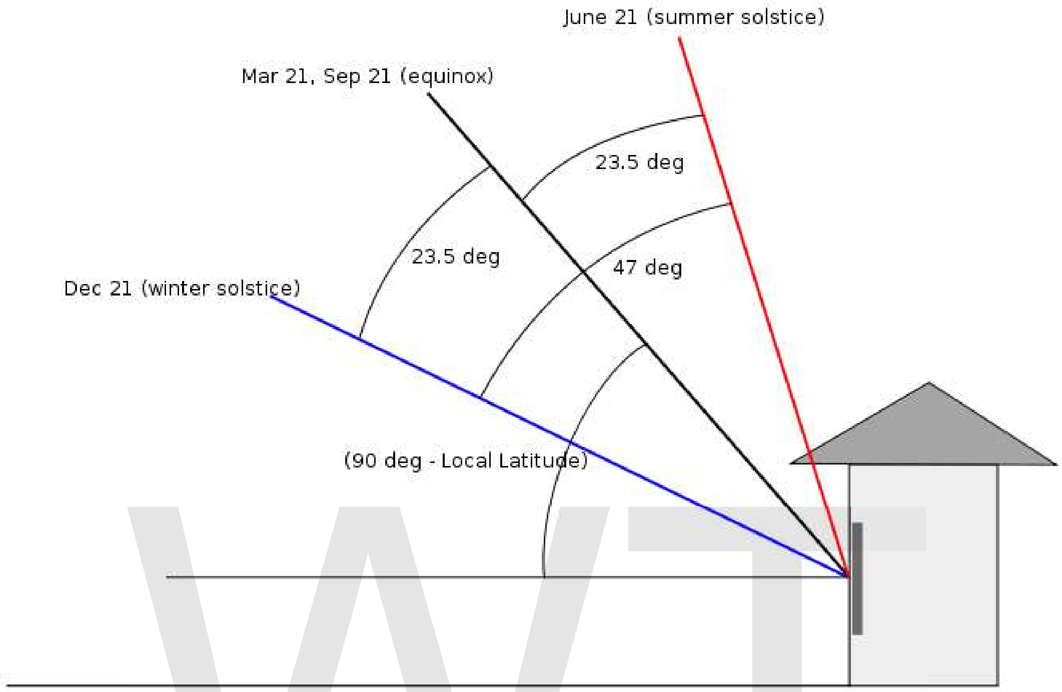
Scientific Passive Solar Building Design with quantitative cost benefit product optimization is not easy for a novice. The level of complexity has resulted in ongoing bad-architecture, and many intuition-based unscientific construction experiments that disappoint their designers and waste a significant portion of their construction budget on inappropriate ideas.

The economic motivation for scientific design and engineering is significant. If it had been applied comprehensively to new building construction beginning in 1980 (based on 1970's lessons learned), America could be be saving over $250,000,000 per year on expensive energy and related pollution today.

Since 1979, Passive Solar Building Design has been a critical element of achieving zero energy by educational institution experimentts, and governments around the world, including the U.S. Department of Energy, and the energy research scientists that they have supported for decades. The cost effective proof of concept was established decades ago, but cultural assimilation into architecture, construction trades, and building-owner decision making has been very slow and difficult to change.

The new terms "Architectural Science" and "Architectural Technology" are being added to some schools of Architecture, with a future goal of teaching the above scientific and energy-engineering principles.

The solar path in passive design



Solar altitude over a year; latitude based on New York, New York

The ability to achieve these goals simultaneously is fundamentally dependent on the seasonal variations in the sun's path throughout the day.

This occurs as a result of the inclination of the Earth's axis of rotation in relation to its orbit. The sun path is unique for any given latitude.

In Northern Hemisphere non-tropical latitudes farther than 23.5 degrees from the equator:

- The sun will reach its highest point toward the South (in the direction of the equator)
- As winter solstice approaches, the angle at which the sun rises and sets progressively moves further toward the South and the daylight hours will become shorter
- The opposite is noted in summer where the sun will rise and set further toward the North and the daylight hours will lengthen

The converse is observed in the Southern Hemisphere, but the sun rises to the east and sets toward the west regardless of which hemisphere you are in.

In equatorial regions at less than 23.5 degrees, the position of the sun at solar noon will oscillate from north to south and back again during the year.

In regions closer than 23.5 degrees from either north-or-south pole, during summer the sun will trace a complete circle in the sky without setting whilst it will never appear above the horizon six months later, during the height of winter.

The 47-degree difference in the altitude of the sun at solar noon between winter and summer forms the basis of passive solar design. This information is combined with local climatic data (degree day) heating and cooling requirements to determine at what time of the year solar gain will be beneficial for thermal comfort, and when it should be blocked with shading. By strategic placement of items such as glazing and shading devices, the percent of solar gain entering a building can be controlled throughout the year.

One passive solar sun path design problem is that although the sun is in the same relative position six weeks before, and six weeks after, the solstice, due to "thermal lag" from the thermal mass of the Earth, the temperature and solar gain requirements are quite different before and after the summer or winter solstice. Movable shutters, shades, shade screens, or window quilts can accommodate day-to-day and hour-to-hour solar gain and insulation requirements.

Careful arrangement of rooms completes the passive solar design. A common recommendation for residential dwellings is to place living areas facing solar noon and sleeping quarters on the opposite side. A heliodon is a traditional movable light device used by architects and designers to help model sun path effects. In modern times, 3D computer graphics can visually simulate this data, and calculate performance predictions.

Passive solar thermodynamic principles

Solar panels are used in passive and active solar hot water systems

Personal thermal comfort is a function of personal health factors (medical, psychological, sociological and situational),ambient air temperature, mean radiant temperature, air movement (wind chill, turbulence) and relative humidity (affecting human evaporative cooling). Heat transfer in buildings occurs through convection, conduction, and thermal radiation through roof, walls, floor and windows.

Convective heat transfer

Convective heat transfer can be beneficial or detrimental. Uncontrolled air infiltration from poor weatherization / weatherstripping / draft-proofing can contribute up to 40% of heat loss during winter, however strategic placement of operable windows or vents can enhance convection, cross-ventilation, and summer cooling when the outside air is of a comfortable temperature and relative humidity. Filtered energy recovery ventilation systems may be useful to eliminate undesirable humidity, dust, pollen, and microorganisms in unfiltered ventilation air.

Natural convection causing rising warm air and falling cooler air can result in an uneven stratification of heat. This may cause uncomfortable variations in temperature in the upper and lower conditioned space, serve as a method of venting hot air, or be designed in as a natural-convection air-flow loop for passive solar heat distribution and temperature equalization. Natural human cooling by perspiration and evaporation may be facilitated through natural or forced convective air movement by fans, but ceiling fans can disturb the stratified insulating air layers at the top of a room, and accelerate heat transfer from a hot attic, or through near by windows. In addition, high relative humidity inhibits evaporative cooling by humans.

Radiative heat transfer

The main source of heat transfer is radiant energy, and the primary source is the sun. Solar radiation occurs predominantly through the roof and windows (but also through walls). Thermal radiation moves from a warmer surface to a cooler one. Roofs receive the majority of the solar radiation delivered to a house. A cool roof, or green roof in addition to a radiant barrier can help prevent your attic from becoming hotter than the peak summer outdoor air temperature.

Windows are a ready and predictable site for thermal radiation. Energy from radiation can move into a window in the day time, and out of the same window at night. Radiation uses photons to transmit electromagnetic waves through a vacuum, or translucent medium. Solar heat gain can be significant even on cold clear days. Solar heat gain through windows can be reduced by insulated glazing, shading, and orientation. Windows are particularly difficult to insulate compared to roof and walls. Convective heat transfer through and around window coverings also degrade its insulation properties. When shading windows, external shading is more effective at reducing heat gain than internal window coverings.

Western and eastern sun can provide warmth and lighting, but are vulnerable to overheating in summer if not shaded. In contrast, the low midday sun readily admits light and warmth during the winter, but can be easily shaded with appropriate length overhangs or angled louvres during summer. The amount of radiant heat received is related to the location latitude, altitude, cloud cover, and seasonal / hourly angle of incidence.

Another passive solar design principle is that thermal energy can be stored in certain building materials and released again when heat gain eases to stabilize diurnal (day/night) temperature variations. The complex interaction of thermodynamic principles can be counterintuitive for first-time designers. Precise computer modeling can help avoid costly construction experiments.

Site specific considerations during design

- Latitude, sun path, and insolation (sunshine)

- Seasonal variations in solar gain e.g. cooling or heating degree days, solar insolation, humidity
- Diurnal variations in temperature
- Micro-climate details related to breezes, humidity, vegetation and land contour
- Obstructions / Over-shadowing - to solar gain or local cross-winds

Design elements for residential buildings in temperate climates

- Placement of room-types, internal doors & walls, & equipment in the house.
- Orienting the building to face the equator (or a few degrees to the East to capture the morning sun)
- Extending the building dimension along the east/west axis
- Adequately sizing windows to face the midday sun in the winter, and be shaded in the summer.
- Minimising windows on other sides, especially western windows
- Erecting correctly sized, latitude-specific roof overhangs, or shading elements (shrubbery, trees, trellises, fences, shutters, etc.)
- Using the appropriate amount and type of insulation including radiant barriers and bulk insulation to minimise seasonal excessive heat gain or loss
- Using thermal mass to store excess solar energy during the winter day (which is then re-radiated during the night)

The precise amount of equator-facing glass and thermal mass should be based on careful consideration of latitude, altitude, climatic conditions, and heating/cooling degree day requirements.

Factors that can degrade thermal performance:

- Deviation from ideal orientation and north/south/east/west aspect ratio
- Excessive glass area ('over-glazing') resulting in overheating (also resulting in glare and fading of soft furnishings) and heat loss when ambient air temperatures fall
- Installing glazing where solar gain during the day and thermal losses during the night cannot be controlled easily e.g. West-facing, angled glazing, skylights
- Thermal losses through non-insulated or unprotected glazing
- Lack of adequate shading during seasonal periods of high solar gain (especially on the West wall)
- Incorrect application of thermal mass to modulate daily temperature variations
- Open staircases leading to unequal distribution of warm air between upper and lower floors as warm air rises
- High building surface area to volume - Too many corners
- Inadequate weatherization leading to high air infiltration
- Lack of, or incorrectly installed, radiant barriers during the hot season.

- Insulation materials that are not matched to the main mode of heat transfer (e.g. undesirable convective/conductive/radiant heat transfer)

Efficiency and economics of passive solar heating

Technically, PSH is highly efficient. Direct-gain systems can utilize (i.e. convert into "useful" heat) 65-70% of the energy of solar radiation that strikes the aperture or collector. To put this in perspective relative to another energy conversion process, the photosynthetic efficiency theoretical limit is around 11%.

Passive solar fraction (PSF) is the percentage of the required heat load met by PSH and hence represents potential reduction in heating costs. RETScreen International has reported a PSF of 20-50%. It must be noted that within the field of sustainability, energy conservation even of the order of 15% is considered substantial.

Other sources report the following PSFs:

- 5-25% for modest systems
- 40% for "highly optimized" systems
- Up to 75% for "very intense" systems

In favorable climates such as the southwest United States, highly optimized systems can exceed 75% PSF.

Key passive solar building design concepts

There are six primary passive solar energy configurations:

- direct solar gain
- indirect solar gain
- isolated solar gain
- heat storage
- insulation and glazing
- passive cooling

Direct solar gain

Direct gain attempts to control the amount of direct solar radiation reaching the living space. This direct solar gain is a critical part of passive solar house designation as it imparts to a direct gain.

The cost effectiveness of these configurations are currently being investigated in great detail and are demonstrating promising results.

Indirect solar gain

Indirect gain attempts to control solar radiation reaching an area adjacent but not part of the living space. Heat enters the building through windows and is captured and stored in thermal mass (e.g. water tank, masonry wall) and slowly transmitted indirectly to the building through conduction and convection. Efficiency can suffer from slow response (thermal lag) and heat losses at night. Other issues include the cost of insulated glazing and developing effective systems to redistribute heat throughout the living area.

Isolated solar gain

Isolated gain involves utilizing solar energy to passively move heat from or to the living space using a fluid, such as water or air by natural convection or forced convection. Heat gain can occur through a sunspace, solarium or solar closet. These areas may also be employed usefully as a greenhouse or drying cabinet. An equator-side sun room may have its exterior windows higher than the windows between the sun room and the interior living space, to allow the low winter sun to penetrate to the cold side of adjacent rooms. Glass placement and overhangs prevent solar gain during the summer. Earth cooling tubes or other passive cooling techniques can keep a solarium cool in the summer.

Measures should be taken to reduce heat loss at night e.g. window coverings or movable window insulation

Examples:

- Thermosiphon
- Barra system
- Double envelope house
- Thermal buffer zone
- Solar space heating system
- Solar chimney

Heat storage

The sun doesn't shine all the time. Heat storage, or thermal mass keeps the building warm when the sun can't heat it.

In diurnal solar houses, the storage is designed for one or a few days. The usual method is a custom-constructed thermal mass. These include a Trombe wall, a ventilated concrete floor, a cistern, water wall or roof pond.

In subarctic areas, or areas that have long terms without solar gain (e.g. weeks of freezing fog), purpose-built thermal mass is very expensive. Don Stephens pioneered an experimental technique to use the ground as thermal mass large enough for annualized heat storage. His designs run an isolated thermosiphon 3m under a house, and insulate the ground with a 6m waterproof skirt.

Insulation

Thermal insulation or superinsulation (type, placement and amount) reduces unwanted leakage of heat. Some passive buildings are actually constructed of insulation.

Special glazing systems and window coverings

The effectiveness of direct solar gain systems is significantly enhanced by insulative (e.g. double glazing), spectrally selective glazing (low-e), or movable window insulation (window quilts, bifold interior insulation shutters, shades, etc.).

Generally, Equator-facing windows should not employ glazing coatings that inhibit solar gain.

There is extensive use of super-insulated windows in the German Passive House standard. Selection of different spectrally selective window coating depends on the ratio of heating versus cooling degree days for the design location.

Glazing selection

Equator-facing glass

The requirement for vertical equator-facing glass is different from the other three sides of a building. Reflective window coatings and multiple panes of glass can reduce useful solar gain. However, direct-gain systems are more dependent on double or triple glazing to reduce heat loss. Indirect-gain and isolated-gain configurations may still be able to function effectively with only single-pane glazing. Nevertheless, the optimal cost-effective solution is both location and system dependent.

Roof-angle glass / Skylights

Skylights admit harsh direct overhead sunlight and glare either horizontally (a flat roof) or pitched at the same angle as the roof slope. In some cases, horizontal skylights are used with reflectors to increase the intensity of solar radiation (and harsh glare), depending on the roof angle of incidence. When the winter sun is low on the horizon, most solar radiation reflects off of roof angled glass (the angle of incidence is nearly parallel to roof-angled glass morning and afternoon). When the summer sun is high, it is nearly perpendicular to roof-angled glass, which maximizes solar gain at the wrong time of year, and acts like a solar furnace. Skylights should be covered and well-insulated to reduce natural convection (warm air rising) heat loss on cold winter nights, and intense solar heat gain during hot spring/summer/fall days.

The equator-facing side of a building is south in the northern hemisphere, and north in the southern hemisphere. Skylights on roofs that face away from the equator provide mostly-indirect illumination, except for summer days when the sun rises on the non-equator side of the building (depending on latitude). Skylights on east-facing roofs provide maximum direct light and solar heat gain in the summer morning. West-facing skylights provide afternoon sunlight and heat gain during the hottest part of the day.

Some skylights have expensive glazing that partially reduces summer solar heat gain, while still allowing some visible light transmission. However, if visible light can pass through it, so can some radiant heat gain (they are both electromagnetic radiation waves.

You can partially reduce some of the unwanted roof-angled-glazing summer solar heat gain by installing a skylight in the shade of deciduous (leaf-shedding) trees, or by adding a movable insulated opaque window covering on the inside or outside of the skylight. This would eliminate the daylight benefit in the summer. If tree limbs hang over a roof, they will increase problems with leaves in rain gutters, possibly cause roof-damaging ice dams, shorten roof life, and provide an easier path for pests to enter your attic. Leaves and twigs on skylights are unappealing, difficult to clean, and can increase the glazing breakage risk in wind storms.

"Sawtooth roof glazing" with vertical-glass-only can bring some of the passive solar building design benefits into the core of a commercial or industrial building, without the need for any roof-angled glass or skylights.

Skylights provide daylight. The only view they provide is essentially straight up in most applications. Well-insulated light tubes can bring daylight into northern rooms, without using a skylight. A passive-solar greenhouse provides abundant daylight for the equator-side of the building.

Infrared thermography color thermal imaging cameras (used in formal energy audits) can quickly document the negative thermal impact of roof-angled glass or a skylight on a cold winter night or hot summer day.

The U.S. Department of Energy states: "vertical glazing is the overall best option for sunspaces." Roof-angled glass and sidewall glass are not recommended for passive solar sunspaces.

The U.S. DOE explains drawbacks to roof-angled glazing: Glass and plastic have little structural strength. When installed vertically, glass (or plastic) bears its own weight because only a small area (the top edge of the glazing) is subject to gravity. As the glass tilts off the vertical axis, however, an increased area (now the sloped cross-section) of the glazing has to bear the force of gravity. Glass is also brittle; it does not flex much before breaking. To counteract this, you usually must increase the thickness of the glazing or increase the number of structural supports to hold the glazing. Both increase overall cost, and the latter will reduce the amount of solar gain into the sunspace.

Another common problem with sloped glazing is its increased exposure to the weather. It is difficult to maintain a good seal on roof-angled glass in intense sunlight. Hail, sleet, snow, and wind may cause material failure. For occupant safety, regulatory agencies usually require sloped glass to be made of safety glass, laminated, or a combination thereof, which reduce solar gain potential. Most of the roof-angled glass on the Crowne Plaza Hotel Orlando Airport sunspace was destroyed in a single windstorm. Roof-angled glass increases construction cost, and can increase insurance premiums. Vertical glass is less susceptible to weather damage than roof-angled glass.

It is difficult to control solar heat gain in a sunspace with sloped glazing during the summer and even during the middle of a mild and sunny winter day. Skylights are the antithesis of zero energy building Passive Solar Cooling in climates with an air conditioning requirement.

Angle of incident radiation

The amount of solar gain transmitted through glass is also affected by the angle of the incident solar radiation. Sunlight striking glass within 20 degrees of perpendicular is mostly transmitted through the glass, whereas sunlight at more than 35 degrees from perpendicular is mostly reflected

All of these factors can be modeled more precisely with a photographic light meter and a heliodon or optical bench, which can quantify the ratio of reflectivity to transmissivity, based on angle of incidence.

Alternatively, passive solar computer software can determine the impact of sun path, and cooling-and-heating degree days on energy performance. Regional climatic conditions are often available from local weather services.

Operable shading and insulation devices

A design with too much equator-facing glass can result in excessive winter, spring, or fall day heating, uncomfortably bright living spaces at certain times of the year, and excessive heat transfer on winter nights and summer days.

Although the sun is at the same altitude 6-weeks before and after the solstice, the heating and cooling requirements before and after the solstice are significantly different. Heat storage on the Earth's surface causes "thermal lag." Variable cloud cover influences solar gain potential. This means that latitude-specific fixed window overhangs, while important, are not a complete seasonal solar gain control solution.

Control mechanisms (such as manual-or-motorized interior insulated drapes, shutters, exterior roll-down shade screens, or retractable awnings) can compensate for differences caused by thermal lag or cloud cover, and help control daily / hourly solar gain requirement variations.

Home automation systems that monitor temperature, sunlight, time of day, and room occupancy can precisely control motorized window-shading-and-insulation devices.

Exterior colors reflecting - absorbing

Materials and colors can be chosen to reflect or absorb solar thermal energy. Using information on a Color for electromagnetic radiation to determine its thermal radiation properties of reflection or absorption can assist the choices.

Landscaping and gardens

Energy-efficient landscaping materials for careful passive solar choices include hardscape building material and "softscape" plants. The use of landscape design principles for selection of trees, hedges, and trellis-pergola features with vines; all can be used to create summer shading. For winter solar gain it is desirable to use deciduous plants that drop their leaves in the autumn gives year round passive solar benefits. Non-deciduous evergreen shrubs and trees can be windbreaks, at variable heights and distances, to create protection and shelter from winter wind chill. Xeriscaping with 'mature size appropriate' native species of-and drought tolerant plants, drip irrigation, mulching, and organic gardening practices reduce or eliminate the need for energy-and-water-intensive irrigation, gas powered garden equipment, and reduces the landfill waste footprint. Solar powered landscape lighting and fountain pumps, and covered swimming pools and plunge pools with solar water heaters can reduce the impact of such amenities.

- Sustainable gardening
- Sustainable landscaping
- Sustainable landscape architecture

Other passive solar principles

Passive solar lighting

Passive solar lighting techniques enhance taking advantage of natural illumination for interiors, and so reduce reliance on artificial lighting systems.

This can be achieved by careful building design, orientation, and placement of window sections to collect light. Other creative solutions involve the use of reflecting surfaces to admit daylight into the interior of a building. Window sections should be adequately sized, and to avoid over-illumination can be shielded with a Brise soleil, awnings, well placed trees, glass coatings, and other passive and active devices.

Another major issue for many window systems is that they can be potentially vulnerable sites of excessive thermal gain or heat loss. Whilst high mounted clerestory window and traditional skylights can introduce daylight in poorly oriented sections of a building, unwanted heat transfer may be hard to control. Thus, energy that is saved by reducing artificial lighting is often more than offset by the energy required for operating HVAC systems to maintain thermal comfort.

Various methods can be employed to address this including but not limited to window coverings, insulated glazing and novel materials such as aerogel semi-transparent insulation, optical fiber embedded in walls or roof, or hybrid solar lighting at Oak Ridge National Laboratory.

Interior reflecting

Reflecting elements, from active and passive daylighting collectors, such as light shelves, lighter wall and floor colors, mirrored wall sections, interior walls with upper glass panels, and clear or translucent glassed hinged doors and sliding glass doors take the captured light and passively reflect it further inside. The light can be from passive windows or skylights and solar light tubes or from active daylighting sources. In traditional Japanese architecture the Shōji sliding panel doors, with translucent Washi screens, are an original precedent. International style, Modernist and Mid-century modern architecture were earlier innovators of this passive penetration and reflection in industrial, commercial, and residential applications.

Passive solar water heating

There are many ways to use solar thermal energy to heat water for domestic use. Different active-and-passive solar hot water technologies have different location-specific economic cost benefit analysis implications.

Fundamental passive solar hot water heating involves no pumps or anything electrical. It is very cost effective in climates that do not have lengthy sub-freezing, or very-cloudy, weather conditions. Other active solar water heating technologies, etc. may be more appropriate for some locations.

It is possible to have active solar hot water which is also capable of being "off grid" and qualifies as sustainable. This is done by the use of a photovoltaic cell which uses energy from the sun to power the pumps.

Comparison to the Passive House standard in Europe

There is growing momentum in Europe for the approach espoused by the Passive House Institute in Germany. Rather than relying solely on traditional passive solar design techniques, this approach seeks to make use of all passive sources of heat, minimises energy usage, and emphasises the need for high levels of insulation reinforced by meticulous attention to detail in order to address thermal bridging and cold air infiltration. Most of the buildings built to the Passive House standard also incorporate an active heat recovery ventilation unit with or without a small (typically 1 kW) incorporated heating component.

The energy design of Passive House buildings is developed using a spreadsheet-based modeling tool called the Passive House Planning Package (PHPP) which is updated periodically. The current version is PHPP2007, where 2007 is the year of issue. A building may be certified as a 'Passive House' when it can be shown that it meets certain criteria, the most important being that the annual specific heat demand for the house should not exceed 15kWh/m^2a.

Design tools

Traditionally a heliodon was used to simulate the altitude and azimuth of the sun shining on a model building at any time of any day of the year. In modern times, computer programs can model this phenomenon and integrate local climate data (including site impacts such as overshadowing and physical obstructions) to predict the solar gain potential for a particular building design over the course of a year. GPS-based smart phone applications can now do this inexpensively on a hand held device. These tools provide the passive solar designer the ability to evaluate local conditions, design elements and orientation prior to construction. Energy performance optimization normally requires an iterative-refinement design-and-evaluate process. There is no such thing as a "one-size-fits-all" universal passive solar building design that would work well in all locations.

Levels of application

Pragmatic

Many detached suburban houses can achieve reductions in heating expense without obvious changes to their appearance, comfort or usability. This is done using good siting and window positioning, small amounts of thermal mass, with good-but-conventional insulation, weatherization, and an occasional supplementary heat source, such as a central radiator connected to a (solar) water heater. Sunrays may fall on a wall during the daytime and raise the temperature of its thermal mass. This will then radiate heat into the building in the evening. This can be a problem in the summer, especially on western walls in areas with high degree day cooling requirements. External shading, or a radiant barrier plus air gap, may be used to reduce undesirable summer solar gain.

Annualised

An extension of the "passive solar" approach to seasonal solar capture and storage of heat and cooling. These designs attempt to capture warm-season solar heat, and convey it to a seasonal thermal store for use months later during the cold season ("annualised passive solar.") Increased storage is achieved by employing large amounts of thermal mass or earth coupling. Anecdotal reports suggest they can be effective but no formal study has been conducted to demonstrate their superiority. The approach also can move cooling into the warm season.

Examples:

- Passive Annual Heat Storage (PAHS) - by John Hait
- Annualized Geothermal Solar (AGS) heating - by Don Stephen

- Earthed-roof

Minimum machinery

A "purely passive" solar-heated house would have no mechanical furnace unit, relying instead on energy captured from sunshine, only supplemented by "incidental" heat energy given off by lights, computers, and other task-specific appliances (such as those for cooking, entertainment, etc.), showering, people and pets. The use of natural convection air currents (rather than mechanical devices such as fans) to circulate air is related, though not strictly solar design.

Passive solar building design sometimes uses limited electrical and mechanical controls to operate dampers, insulating shutters, shades, awnings, or reflectors. Some systems enlist small fans or solar-heated chimneys to improve convective air-flow. A reasonable way to analyse these systems is by measuring their coefficient of performance. A heat pump might use 1 J for every 4 J it delivers giving a COP of 4. A system that only uses a 30 W fan to more-evenly distribute 10 kW of solar heat through an entire house would have a COP of 300.

Zero Energy Building

Passive solar building design is often a foundational element of a cost-effective zero energy building. Although a ZEB uses multiple passive solar building design concepts, a ZEB is usually not purely passive, having active mechanical renewable energy generation systems such as: wind turbine, photovoltaics, micro hydro, geothermal, and other emerging alternative energy sources.

Chapter 7

Power Engineering

A steam turbine used to provide electric power.

Power engineering, also called **power systems engineering**, is a subfield of engineering that deals with the generation, transmission and distribution of electric power as well as the electrical devices connected to such systems including generators, motors and transformers. Although much of the field is concerned with the problems of three-phase AC power - the standard for large-scale power transmission and distribution across the modern world - a significant fraction of the field is concerned with the conversion between AC and DC power as well as the development of specialised power systems such as those used in aircraft or for electric railway networks.

History

A sketch of the Pearl Street Station

Electricity became a subject of scientific interest in the late 17th century with the work of William Gilbert. Over the next two centuries a number of important discoveries were made including the incandescent lightbulb and the voltaic pile. Probably the greatest discovery with respect to power engineering came from Michael Faraday who in 1831 discovered that a change in magnetic flux induces an electromotive force in a loop of wire—a principle known as electromagnetic induction that helps explain how generators and transformers work.

In 1881 two electricians built the world's first power station at Godalming in England. The station employed two waterwheels to produce an alternating current that was used to supply seven Siemens arc lamps at 250 volts and thirty-four incandescent lamps at 40 volts. However supply was intermittent and in 1882 Thomas Edison and his company, The Edison Electric Light Company, developed the first steam-powered electric power station on Pearl Street in New York City. The Pearl Street Station consisted of several generators and initially powered around 3,000 lamps for 59 customers. The power station used direct current and operated at a single voltage. Since the direct current power could not be easily transformed to the higher voltages necessary to minimise power loss during transmission, the possible distance between the generators and load was limited to around half-a-mile (800 m).

That same year in London Lucien Gaulard and John Dixon Gibbs demonstrated the first transformer suitable for use in a real power system. The practical value of Gaulard and Gibbs' transformer was demonstrated in 1884 at Turin where the transformer was used to light up forty kilometres (25 miles) of railway from a single alternating current generator. Despite the success of the system, the pair made some fundamental mistakes. Perhaps the most serious was connecting the primaries of the transformers in series so that switching one lamp on or off would affect other lamps further down the line. Following the demonstration George Westinghouse, an American entrepreneur, imported a number of the transformers along with a Siemens generator and set his engineers to experimenting with them in the hopes of improving them for use in a commercial power system.

One of Westinghouse's engineers, William Stanley, recognised the problem with connecting transformers in series as opposed to parallel and also realised that making the iron core of a transformer a fully enclosed loop would improve the voltage regulation of the secondary winding. Using this knowledge he built a much improved alternating current power system at Great Barrington, Massachusetts in 1886. Then in 1887 and 1888 another engineer called Nikola Tesla filed a range of patents related to power systems including one for a two-phase induction motor. Although Tesla cannot necessarily be attributed with building the first induction motor, his design, unlike others, was practical for industrial use.

By 1890 the power industry had flourished and power companies had built literally thousands of power systems (both direct and alternating current) in the United States and Europe - these networks were effectively dedicated to providing electric lighting. During this time a fierce rivalry known as the "War of Currents" emerged between Edison, Westinghouse and Tesla over which form of transmission (direct or alternating current) was superior. In 1891, Westinghouse installed the first major power system that was designed to drive an electric motor and not just provide electric lighting. The installation powered a 100 horsepower (75 kW) synchronous motor at Telluride, Colorado with the motor being started by a Tesla induction motor. On the other side of the Atlantic, Oskar von Miller built a 20 kV 176 km three-phase transmission line from Lauffen am Neckar to Frankfurt am Main for the Electrical Engineering Exhibition in Frankfurt. In 1895, after a protracted decision-making process, the Adams No. 1 generating station at Niagara Falls began transmitting three-phase alternating current power to Buffalo at 11 kV. Following completion of the Niagara Falls project, new power systems increasingly chose alternating current as opposed to direct current for electrical transmission.

Although the 1880s and 1890s were seminal decades in the field, developments in power engineering continued throughout the 20th and 21st century. In 1936 the first commercial HVDC (high voltage direct current) line using Mercury arc valves was built between Schenectady and Mechanicville, New York. HVDC had previously been achieved by installing direct current generators in series (a system known as the Thury system) although this suffered from serious reliability issues. In 1957 Siemens demonstrated the first solid-state rectifier (solid-state rectifiers are now the standard for HVDC systems) however it was not until the early 1970s that this technology was used in commercial power systems. In 1959 Westinghouse demonstrated the first circuit breaker that used SF_6 as the interrupting medium. SF_6 is a far superior dielectric to air and, in recent times, its use has been extended to produce far more compact switching equipment (known as switchgear) and transformers. Many important developments also came from extending innovations in the information technology and telecommunications field to the power engineering field. For example, the development of computers meant load flow studies could be run more efficiently allowing for much better planning of power systems. Advances in information technology and telecommunication also allowed for much better remote control of the power system's switchgear and generators.

Basics of electric power

An external AC to DC power adapter used for household appliances

Electric power is the mathematical product of two quantities: current and voltage. These two quantities can vary with respect to time (AC power) or can be kept at constant levels (DC power).

Most refrigerators, air conditioners, pumps and industrial machinary use AC power whereas most computers and digital equipment use DC power (the digital devices you plug into the mains typically have an internal or external power adapter to convert from AC to DC power). AC power has the advantage of being easy to transform between voltages and is able to be generated and utilised by brushless machinary. DC power remains the only practical choice in digital systems and can be more economical to transmit over long distances at very high voltages.

The ability to easily transform the voltage of AC power is important for two reasons: Firstly, power can be transmitted over long distances with less loss at higher voltages. So in power networks where generation is distant from the load, it is desirable to step-up the voltage of power at the generation point and then step-down the voltage near the load. Secondly, it is often more economical to install turbines that produce higher voltages than would be used by most appliances, so the ability to easily transform voltages means this mismatch between voltages can be easily managed.

Solid state devices, which are products of the semiconductor revolution, make it possible to transform DC power to different voltages, build brushless DC machines and convert between AC and DC power. Nevertheless devices utilising solid state technology are often more expensive than their traditional counterparts, so AC power remains in widespread use.

Power

Transmission lines transmit power across the grid.

Power Engineering deals with the generation, transmission and distribution of electricity as well as the design of a range of related devices. These include transformers, electric generators, electric motors and power electronics.

The power grid is an electrical network that connects a variety of electric generators to the users of electric power. Users purchase electricity from the grid avoiding the costly exercise of having to generate their own. Power engineers may work on the design and maintenance of the power grid as well as the power systems that connect to it. Such systems are called on-grid power systems and may supply the grid with additional power, draw power from the grid or do both.

Power engineers may also work on systems that do not connect to the grid. These systems are called off-grid power systems and may be used in preference to on-grid systems for a variety of reasons. For example, in remote locations it may be cheaper for a mine to generate its own power rather than pay for connection to the grid and in most mobile applications connection to the grid is simply not practical.

Today, most grids adopt three-phase electric power with alternating current. This choice can be partly attributed to the ease with which this type of power can be generated, transformed and used. Often (especially in the USA), the power is split before it reaches residential customers whose low-power appliances rely upon single-phase electric power. However, many larger industries and organizations still prefer to receive the three-phase power directly because it can be used to drive highly efficient electric motors such as three-phase induction motors.

Transformers play an important role in power transmission because they allow power to be converted to and from higher voltages. This is important because higher voltages suffer less power loss during transmission. This is because higher voltages allow for lower current to deliver the same amount of power, as power is the product of the two. Thus, as the voltage steps up, the current steps down. It is the current flowing through the components that result in both the losses and the subsequent heating. These losses, appearing in the form of heat, are equal to the current squared times the electrical resistance through which the current flows, so as the voltage goes up the losses are dramatically reduced.

For these reasons, electrical substations exist throughout power grids to convert power to higher voltages before transmission and to lower voltages suitable for appliances after transmission.

Components

Power engineering is a network of interconnected components which convert different forms of energy to electrical energy. Modern power engineering consists of three main subsystems: the generation subsystem, the transmission subsystem, and the distribution subsystem. In the generation subsystem, the power plant produces the electricity. The transmission subsystem transmits the electricity to the load centers. The distribution subsystem continues to transmit the power to the customers.

Generation

Generation of electrical power is a process whereby energy is transformed into an electrical form. There are several different transformation processes, among which are chemical, photo-voltaic, and electromechanical. Electromechanical energy conversion is used in converting energy from coal, petroleum, natural gas, uranium into electrical energy. Of these, all except the wind energy conversion process take advantage of the synchronous AC generator coupled to a steam, gas or hydro turbine such that the turbine converts steam, gas, or water flow into rotational energy, and the synchronous generator then converts the rotational energy of the turbine into electrical energy. It is the turbine-generator conversion process that is by far most economical and consequently most common in the industry today.

The AC synchronous machine is the most common technology for generating electrical energy. It is called synchronous because the composite magnetic field produced by the three stator windings rotate at the same speed as the magnetic field produced by the field winding on the rotor. A simplified circuit model is used to analyze steady-state operating conditions for a synchronous machine. The phasor diagram is an effective tool for visualizing the relationships between internal voltage, armature current, and terminal voltage. The excitation control system is used on synchronous machines to regulate terminal voltage, and the turbine-governor system is used to regulate the speed of the machine.

The operating costs of generating electrical energy is determined by the fuel cost and the efficiency of the power station. The efficiency depends on generation level and can be obtained from the heat rate curve. We may also obtain the incremental cost curve from the heat rate curve. Economic dispatch is the process of allocating the required load demand between the available generation units such that the cost of operation is minimized.

Transmission

The electricity is transported to load locations from a power station to a transmission subsystem. Therefore we may think of the transmission system as providing the medium of transportation for electric energy. The transmission system may be subdivided into the bulk transmission system and the sub-transmission system. The functions of the bulk transmission are to interconnect generators, to interconnect various areas of the network, and to transfer electrical energy from the generators to the major load centers. This portion of the system is called "bulk" because it delivers energy only to so-called bulk loads such as the distribution system of a town, city, or large industrial plant. The function of the sub-transmission system is to interconnect the bulk power system with the distribution system.

Transmission circuits may be built either underground or overhead. Underground cables are used predominantly in urban areas where acquisition of overhead rights of way are costly or not possible. They are also used for transmission under rivers, lakes and bays. Overhead transmission is used otherwise because, for a given voltage level, overhead conductors are much less expensive than underground cables.

The transmission system is a highly integrated system. It is referred to the substation equipment and transmission lines. The substation equipment contain the transformers, relays, and circuit breakers. Transformers are important static devices which transfer electrical energy from one circuit with another in the transmission subsystem. Transformers are used to step up the voltage on the transmission line to reduce the power loss which is dissipated on the way. A relay is functionally a level-detector; they perform a switching action when the input voltage (or current) meets or exceeds a specific and adjustable value. A circuit breaker is an automatically operated electrical switch designed to protect an electrical circuit from damage caused by overload or short circuit. A change in the status of any one component can significantly affect the operation of the entire system. There are three possible causes for power flow limitations to a transmission line. These causes are thermal overload, voltage instability, and rotor angle instability. Thermal overload is caused by excessive current flow in a circuit causing overheating. Voltage instability is said to occur when the power required to maintain voltages at or above acceptable levels exceeds the available power. Rotor angle instability is a dynamic problem that may occur following faults, such as short circuit, in the transmission system. It may also occur tens of seconds after a fault due to poorly damped or undamped oscillatory response of the rotor motion.

Distribution

The distribution system transports the power from the transmission system to the customer. The distribution systems are typically radial because networked systems are more expensive. The equipment associated with the distribution system includes the substation transformers connected to the transmission systems, the distribution lines from the transformers to the customers and the protection and control equipment between the transformer and the customer. The protection equipment includes lightning protectors, circuit breakers, disconnectors and fuses. The control equipment includes voltage regulators, capacitors, relays and demand side management equipment.

Chapter 8

Well Logging

Well logging, also known as **borehole logging** is the practice of making a detailed record (a *well log*) of the geologic formations penetrated by a borehole. The log may be based either on visual inspection of samples brought to the surface (*geological* logs) or on physical measurements made by instruments lowered into the hole (*geophysical* logs). Well logging is done during all phases of a well's development; drilling, completing, producing and abandoning. Mostly in the oil and gas, groundwater, minerals, geothermal, and for environmental and geotechnical studies.

Electric or geophysical well logs

The oil and gas industry records rock and fluid properties to find hydrocarbon zones in the geological formations intersected by a borehole. The logging procedure consists of lowering a 'logging tool' on the end of a wireline into an oil well (or hole) to measure the rock and fluid properties of the formation. An interpretation of these measurements is then made to locate and quantify potential depth zones containing oil and gas (hydrocarbons). Logging tools developed over the years measure the electrical, acoustic, radioactive, electromagnetic, nuclear magnetic resonance, and other properties of the rocks and their contained fluids. Logging is usually performed as the logging tools are pulled out of the hole. This data is recorded either at surface (real-time mode), or downhole (memory mode)to electronic data format and then either a printed record or electronic presentation called a "well log" provided to the client. Well logging is performed at various intervals during the drilling of the well and when the total depth is drilled, which could range in depths from 150 m to 10668 m (500 ft to 35,000 ft) or more.

Electric line is the common term for the armored, insulated cable used to conduct current to downhole tools used for well logging. Electric line can be subdivided into open hole operations and cased hole operations. Other conveyance methods for logging are logging while drilling (LWD), tractor, coiled tubing (real-time and memory), drill pipe conveyed, and slickline (memory, and with new development, some slickline telemetry capability).

Open hole operations, or reservoir evaluation, involves the deployment of tools into a freshly drilled well. As the toolstring traverses the wellbore, the individual tools gather information about the surrounding formations. A typical open hole log will have information about the density, porosity, permeability, lithology, presence of hydrocarbons, and oil and water saturation.

Cased hole operations, or production optimization, focuses of the optimization of the completed oil well through mechanical services and logging technologies. At this point in the well's life, the well is encased in steel pipe, cemented into the well bore and may or may not be producing. A typical cased hole log may show cement quality, production information, formation data. Mechanical services uses jet perforating guns, setting tools, and dump bailors to optimize the flow of hydrocarbons.

Wireline tool types

Typically the wireline tools are cylindrical in shape, usually from 1.5 to 5 inches in diameter. "Open hole" tool combinations can extend to over 100 feet long; "cased hole" tool combinations are often limited in length by the height restrictions imposed by constraints of "lubricator" pipe section required to contain the well pressure while deploying cased hole tools. There are many types of logging tools, ranging from common measurements (pressure and temperature) to advanced rock properties and fracture analysis, fluid properties in the wellbore, or formation properties extending several meters into the rock formation.

1. With sensors without excitation

There are units to measure spontaneous potential (SP), which is a voltage difference between a surface electrode and another electrode located in the downhole instrument, other instruments that measure the natural radiation from natural isotopes of potassium, thorium, etc., to measure pressure and temperature, etc.

2. With sources of excitation and sensors

There are sensor systems consistent with a source of excitation and a sensor. In this type we find acoustic (also called sonic), electric, inductive, magnetic resonance, sensing systems, just to name a few.

3. Instruments that produce some mechanical work, or retrieve a sample of fluid or rock to the surface.

Devices to collect samples of rock, samples of fluid extracted from the rock, and some other mechanical devices.

Types of electric/electronic logs

There are many types of electric/electronic logs and they can be categorized either by their function or by the technology that they use. "Open hole logs" are run before the oil or gas well is lined with pipe or cased. "Cased hole logs" are run after the well is lined with casing or production pipe.

Electric/electronic logs can also be divided into two general types based on what physical properties they measure. Resistivity logs measure some aspect of the specific resistance of the geologic formation. There are about 17 types of resistivity logs.

Porosity logs measure the fraction or percentage of pore volume in a volume of rock. Most porosity logs use either acoustic or nuclear technology. Acoustic logs measure characteristics of sound waves propagated through the well-bore environment. Nuclear logs utilize nuclear reactions that take place in the downhole logging instrument or in the formation. Nuclear logs include density logs and neutron logs, as well as gamma ray logs which are used for correlation. The basic principle behind the use of nuclear technology is that a neutron source placed near the formation of which the porosity is required to be measured will result in neutrons being scattered by the hydrogen atoms, largely those present in the formation fluid. Since there is little difference in the neutrons scattered by hydrocarbons or water, the porosity measured gives a figure close to the true physical porosity whereas the figure obtained from electrical resistivity measurements is that due to the conductive formation fluid. The difference between neutron porosity and electrical porosity measurements therefore indicates the presence of hydrocarbons in the formation fluid.

History

Conrad and Marcel Schlumberger, who founded Schlumberger Limited in 1926, are considered the inventors of electric well logging. Conrad developed the Schlumberger array, which was a technique for prospecting for metal ore deposits, and the brothers adopted that surface technique to subsurface applications. On September 5, 1927, a crew working for Schlumberger lowered an electric sonde or tool down a well in Pechelbronn, Alsace, France creating the first well log. In modern terms, the first log was a resistivity log that could be described as 3.5-meter upside-down lateral log.

In 1931, Henri George Doll and G. Dechatre, working for Schlumberger, discovered that the galvanometer wiggled even when no current was being passed through the logging cables down in the well. This led to the discovery of the spontaneous potential (SP) which was as important as the ability to measure resistivity. The SP effect was produced naturally by the borehole mud at the boundaries of permeable beds. By simultaneously recording SP and resistivity, loggers could distinguish between permeable oil-bearing beds and impermeable nonproducing beds.

In 1940, Schlumberger invented the spontaneous potential dipmeter; this instrument allowed the calculation of the dip and direction of the dip of a layer. The basic dipmeter was later enhanced by the resistivity dipmeter (1947) and the continuous resistivity dipmeter (1952).

Oil-based mud (OBM) was first used in Rangely Field, Colorado in 1948. Normal electric logs require a conductive or water-based mud, but OBMs are nonconductive. The solution to this problem was the induction log, developed in the late 1940s.

The introduction of the transistor and integrated circuits in the 1960s made electric logs vastly more reliable. Computerization allowed much faster log processing, and dramatically expanded log data-gathering capacity. The 1970s brought more logs and computers. These included combo type logs where resistivity logs and porosity logs were recorded in one pass in the borehole.

The two types of porosity logs (acoustic logs and nuclear logs) date originally from the 1940s. Sonic logs grew out of technology developed during World War II. Nuclear logging has supplemented acoustic logging, but acoustic or sonic logs are still run on some combination logging tools.

Nuclear logging was initially developed to measure the natural gamma radiation emitted by underground formations. However, the industry quickly moved to logs that actively bombard rocks with nuclear particles. The gamma ray log, measuring the natural radioactivity, was introduced by Well Surveys Inc. in 1939, and the WSI neutron log came in 1941. The gamma ray log is particularly useful as shale beds which often provide a relatively low permeability cap over hydrocarbon reservoirs usually display a higher level of gamma radiation. These logs were important because they can be used in cased wells (wells with production casing). WSI quickly became part of Lane-Wells. During World War II, the US Government gave a near wartime monopoly on open-hole logging to Schlumberger, and a monopoly on cased-hole logging to Lane-Wells. Nuclear logs continued to evolve after the war.

The nuclear magnetic resonance log was developed in 1958 by Borg Warner. Initially the NMR log was a scientific success but an engineering failure. However, the development of a continuous NMR logging tool by Numar (now a subsidiary of Halliburton) is a promising new technology.

Many modern oil and gas wells are drilled directionally. At first, loggers had to run their tools somehow attached to the drill pipe if the well was not vertical. Modern techniques now permit continuous information at the surface. This is known as logging while drilling (LWD) or measurement-while-drilling (MWD). MWD logs use mud pulse technology to transmit data from the tools on the bottom of the drillstring to the processors at the surface.

Logging while drilling

In the 1980s, a new technique, logging while drilling (LWD), was introduced which provided similar information about the well. Instead of sensors being lowered into the well at the end of wireline cable, the sensors are integrated into the drill string and the measurements are made while the well is being drilled. While wireline well logging occurs after the drill string is removed from the well, LWD measures geological parameters while the well is being drilled. However, because there are no wires to the surface, data are recorded downhole and retrieved when the drill string is removed from the hole. A small subset of the measured data can also be transmitted to the surface in real time via pressure pulses in the well's mud fluid column. This mud telemetry method provides a bandwidth of much less than 100 bits per second, although, as drilling through rock is a fairly slow process, data compression techniques mean that this is an ample bandwidth for real-time delivery of information.

Logging measurement types

Logging measurements are quite sophisticated. The prime target is the measurement of various geophysical properties of the subsurface rock formations. Of particular interest are porosity, permeability, and fluid content. Porosity is the proportion of fluid-filled space found within the rock. It is this space that contains the oil and gas. Permeability is the ability of fluids to flow through the rock. The higher the porosity, the higher the possible oil and gas content of a rock reservoir. The higher the permeability, the easier for the oil and gas to flow toward the wellbore. Logging tools provide measurements that allow for the mathematical interpretation of these quantities.

Beyond just the porosity and permeability, various logging measurements allow the interpretation of what kinds of fluids are in the pores—oil, gas, brine. In addition, the logging measurements are used to determine mechanical properties of the formations. These mechanical properties determine what kind of enhanced recovery methods may be used (tertiary recovery) and what damage to the formation (such as erosion) is to be expected during oil and gas production.

The types of instruments used in well logging are quite broad. The first logging measurements consisted of basic electrical resistivity logs and spontaneous potential (SP) logs, introduced by the Schlumberger brothers in the 1920s. Tools later became available to estimate porosity via sonic velocity and nuclear measurements. Tools are now more specialized and better able to resolve fine details in the formation. Radiofrequency transmission and coupling techniques are used to determine electrical conductivity of fluid (brine is more conductive than oil or gas). Sonic transmission characteristics (pressure waves) determine mechanical integrity. Nuclear magnetic resonance (NMR) can determine the properties of the hydrogen atoms in the pores (surface tension, etc.). Nuclear scattering (radiation scattering), spectrometry and absorption measurements can determine density and elemental analysis or composition. High resolution electrical or acoustical imaging logs are used to visualize the formation, compute formation dip, and analyze thinly-bedded and fractured reservoirs.

In addition to sensor-based measurements above, robotic equipment can sample formation fluids which may then be brought to the surface for laboratory examination. Also, controlled flow measurements can be used to determine in situ viscosity, water and gas cut (percentage), and other fluid and production parameters.

Geological logs

Geological logs use data collected at the surface, rather than by downhole instruments. The geological logs include *drilling time logs*, *core logs*, *sample logs*, and *mud logs*. Mud logs have become the oil industry standard.

Drilling time logs record the time required to drill a given thickness of rock formation. A change in the drilling rate or penetration rate usually means a change in the type of rock penetrated by the bit. The drilling time is expressed as minutes per foot, while the rate of penetration is usually expressed as feet per hour. Therefore, drilling time is the inverse of penetration rate.

Sample logs are made by examining cuttings, which are bits of rock circulated to the surface by the drilling mud in rotary drilling. The cuttings have traveled up the wellbore suspended in the drilling fluid or mud which was pumped into the wellbore via the drill string/pipe and they return to the surface via the annulus, then to the shale shakers via the flow line. Cuttings are then separated from the drilling fluid as they move across the shale shakers and are sampled at regular depth intervals. These rock samples are analyzed and described by the wellsite geologist or mudlogger.

Mud logs are prepared by a mud logging company contracted by the operating company. One parameter a typical mud log displays is the formation gas (gas units or ppm). "The gas recorder usually is scaled in terms of arbitrary gas units, which are defined differently by the various gas-detector manufactures. In practice, significance is placed only on relative changes in the gas concentrations detected." The current industry standard mud log normally includes real-time drilling parameters such as rate of penetration (ROP), lithology, gas hydrocarbons, flow line temperature (temperature of the drilling fluid) and chlorides but may also include mud weight, estimated pore pressure and corrected d-exponent (corrected drilling exponent) for a pressure pack log. Other information that is normally notated on a mud log include lithology descriptions, directional data (deviation surveys), weight on bit, rotary speed, pump pressure, pump rate, viscosity, drill bit info, casing shoe depths, formation tops, mud pump info, to name just a few.

Wireline log

A continuous measurement of formation properties w ith electrically powered instruments to infer properties and make decisions about drilling and production operations. The record of the measurements, typically a long strip of paper, is also called a log. Measurements include electrical properties (resistivity at various frequencies), sonic properties, active and passive nuclear measurements, dimensional measurements of the wellbore, formation fluid sampling, formation pressure measurement, wireline-conveyed sidewall coring tools, and others. In wireline measurements, the logging tool (or probe) is lowered into the open wellbore on a multiple conductor, contra-helically armored wireline. Once lowered to the bottom of the interval of interest, the measurements are taken on the way out of the wellbore. This is done in an attempt to maintain tension on the cable (which stretches) as constant as possible for depth correlation purposes. (The exception to this practice is in certain hostile environments in which the tool electronics might not survive the temperatures on bottom for the amount of time it takes to lower the tool and then record measurements while pulling the tool up the hole. In this case, "down log" measurements might actually be conducted on the way into the well, and repeated on the way out if possible.) Most wireline measurements are recorded continuously even though the probe is moving. Certain fluid sampling and pressure-measuring tools require that the probe be stopped, increasing the chance that the probe or the cable might become stuck. LWD tools take measurements in much the same way as wireline-logging tools, except that the measurements are taken by a self-contained tool near the bottom of the bottomhole assembly and are recorded downward (as the well is deepened) rather than upward from the bottom of the hole (as wireline logs are recorded).

Memory log

This method of data acquisition involves recording the sensor data into a down hole memory, rather than transmitting "Real Time" to surface. There are some advantages and disadvantages to this memory option.

- The tools can be conveyed into wells where the trajectory is deviated or extended beyond the reach of conventional Electric Wireline cables. This can involve a combination of weight to strength ratio of the electric cable over this extended reach. In such cases the memory tools can be conveyed on Pipe or Coil Tubing.
- The type of sensors are limited in comparison to those used on Electric Line, and tend to be focussed on the cased hole,production stage of the well. Although there are now developed some memory "Open Hole" compact formation evaluation tool combinations. These tools can be deployed and carried downhole concealed internally in drill pipe to protect them from damage while running in the hole, and then "Pumped" out the end at depth to initate logging. Other basic open hole formation evaluation memory tools are available for use in "Commodity" markets on slickline to reduce costs and operating time.
- In cased hole operation there is normally a "Slick Line" intervention unit. This uses a solid mechanical wire (.82 - .125 inches in OD), to manipulate or otherwise carry out operations in the well bore completion system. Memory operations are often carried out on this Slickline conveyance in preference to mobilizing a full service Electric Wireline unit.
- Since the results are not known until returned to surface, any realtime well dynamic changes cannot be monitored real time. This limits the ability to modify or change the well down hole production conditions accuratly during the memory

logging by changing the surface production rates. Something that is often done in Eletric Line operations.

- Failure during recording is not known until the memory tools are retrieved. This loss of data can be a major issue on large offshore (expensive) locations. On land locations (e.g. South Texas, US) where there is what is called a "Commodity" Oil service sector, where logging often is without the rig infrastructure. this is less problematic, and logs are often run again without issue.

Information use

In the oil industry, the well and mud logs are usually transferred in 'real time' to the operating company, which uses these logs to make operational decisions about the well, to correlate formation depths with surrounding wells, and to make interpretations about the quantity and quality of hydrocarbons present. Specialists involved in well log interpretation are called log analysts.

Well logging images

Wireline attached to top of Christmas Tree

Oil Well Top of Wireline

Wireline Truck with drum (inside)

Wax being removed off a wireline wax knife

BO shifting tool

Chapter 9

Pigging

Pigging in the maintenance of pipelines refers to the practice of using pipeline inspection gauges or 'pigs' to perform various operations on a pipeline without stopping the flow of the product in the pipeline.

These operations include but are not limited to cleaning and inspecting of the pipeline. This is accomplished by inserting the pig into a 'pig launcher' (or 'launching station') - a funnel shaped Y section in the pipeline. The launcher / launching station is then closed and the pressure of the product in the pipeline is used to push it along down the pipe until it reaches the receiving trap - the 'pig catcher' (or receiving station).

If the pipeline contains butterfly valves, the pipeline cannot be pigged. Ball valves cause no problems because the inside diameter of the ball can be specified to be the same as that of the pipe (assuming they are full bore valves).

Pigging has been used for many years to clean larger diameter pipelines in the oil industry. Today, however, the use of smaller diameter pigging systems is now increasing in many continuous and batch process plants as plant operators search for increased efficiencies and reduced costs.

Pigging can be used for almost any section of the transfer process between, for example, blending, storage or filling systems. Pigging systems are already installed in industries handling products as diverse as lubricating oils, paints, chemicals, toiletries, cosmetics and foodstuffs.

Pigs are used in lube oil or painting blending: they are used to clean the pipes to avoid cross-contamination, and to empty the pipes into the product tanks (or sometimes to send a component back to its tank). Usually pigging is done at the beginning and at the end of each batch, but sometimes it is done in the midst of a batch, e.g. when producing a premix that will be used as an intermediate component.

Pigs are also used in oil and gas pipelines: they are used to clean the pipes but also there are "smart pigs" used to measure things like pipe thickness and corrosion along the pipeline. They usually do not interrupt production, though some product can be lost when the pig is extracted. They can also be used to separate different products in a multiproduct pipeline.

Etymology

Pigs get their name from the squealing sound they make while travelling through a pipeline. (Disputed: 'PIG' is an acronym or backronym derived from the initial letters of the term 'Pipeline Inspection Gauge' or possibly 'Pipeline Inspection Gizmo' or 'Pipeline Internal Geometry' or 'Pipeline Inspection Gadget').

Pigging in production environments

Product and time saving

A major advantage of piggable systems is the potential resulting product savings. At the end of each product transfer, it is possible to clear out the entire line contents with the pig, either forwards towards the receipt point, or backwards to the source tank. There is no requirement for extensive line flushing.

Without the need for line flushing, pigging offers the additional advantage of a much more rapid and reliable product changeover. Product sampling at the receipt point becomes faster because the interface between products is very clear, and the old method of checking at intervals, until the product is on-specification, is considerably shortened.

Pigging systems can also be operated totally by a programmable logic controller (PLC).

Environmental issues

Pigging has a significant role to play in reducing the environmental impact of batch operations. Traditionally, the only way that an operator of a batch process could ensure a product was completely cleared from a line was to flush the line with a cleaning agent such as water or a solvent or even the next product. This cleaning agent then had to be subjected to effluent treatment or solvent recovery. If product was used to clear the line, the contaminated finished product was downgraded or dumped. In some cases, the finished product could contain polychlorinated biphenyl (PCB), which has been found to be carcinogenic. All of these problems can now be eliminated due to the very precise interface produced by modern pigging systems.

Safety considerations

Pigging systems are designed so that the pig is loaded into the launcher, which is pressured up to launch the pig into the pipeline through a kicker line. In some cases, the pig is removed from the pipeline via the receiver at the end of each run. All systems must allow for the receipt of pigs at the launcher, as blockages in the pipeline may require the pigs to be pushed back to the launcher. Most of the time, systems are designed to pig the pipeline in either direction.

The pig is pushed either with an inert gas or a liquid; if pushed by gas, some systems can be adapted in the gas inlet in order to ensure pig's constant speed, whatever the pressure drop is. The pigs must be removed, as many pigs are rented, pigs wear and must be replaced, and cleaning pigs push contaminants from the pipeline such as wax, foreign objects, hydrates, etc, which must be removed from the pipeline. There are inherent risks in opening the barrel to atmosphere and care must be taken to ensure that the barrel is depressured prior to opening. If the barrel is not completely depressured, the pig can be ejected from the barrel and operators have been severely injured when standing in front of an open pig door. When the product is sour, the barrel should be evacuated to a flare system where the sour gas is burnt. Operators should be wearing a self-contained breathing apparatus when working on sour systems.

A few pigging systems utilize a "captive pig", and the pipeline is only opened up very occasionally to check the condition of the pig. At all other times, the pig is shuttled up and down the pipeline at the end of each transfer, and the pipeline itself is never opened up during process operation. These systems are not common.

Intelligent pigging

Inserting a pig into a natural gas pipeline

Modern intelligent pigs are highly sophisticated instruments that vary in technology and complexity by the intended use and by manufacturer. An intelligent pig, or smart pig, is basically a computer that collects various forms of data during the trip through the pipeline.

The computer part, consisting mostly of electronics, must be sealed to prevent leakage of the pipeline product into the electronics. Sealing is a very important aspect as the products in the pipeline can range from highly basic to highly acidic and can be of extremely high temperature. Many pigs use specific materials according to the product in the pipeline. Power for the electronics is provided by onboard batteries which also must be sealed from the product environment. Recording of data may be by various means ranging from analog tape in a reel-to-reel format, digital tape or solid state memory in more modern digital units.

This technology is used to accomplish the service vary by the service required and the design of the pig, each pigging service provider may have unique and proprietary technologies to accomplish the service. Surface pitting and corrosion, as well as cracks and weld defects in steel/ferrous pipelines are often detected using magnetic flux leakage (MFL) pigs. Other "smart" pigs use electromagnetic acoustic transducers to detect pipe defects. Caliper pigs can measure the "roundness" of the pipeline to determine areas of crushing or other deformations. Some smart pigs can combine technologies such as MFL and Caliper into a single tool. Recent trials of pigs using Acoustic Resonance Technology have been reported.

During the pigging run the pig is unable to directly communicate with the outside world due to the distance underground or underwater and/or materials that the pipe is made of. For example, steel pipelines effectively prevent any reliable radio communications outside the pipe. It is therefore necessary that the pig use internal means to record its own movement during the trip. This may be done by gyroscope-assisted tilt gauges, odometers and other technologies. The pig will record this positional data so that the distance it moves along with any bends can be interpreted later to determine the exact path taken.

Location verification is often accomplished by surface instruments that record the pig's passage by either audible or gravinometric (or other) means. The sensors will record when they detect passage of the pig; this is then compared to the internal record for verification or adjustment. The external sensors may have GPS capability to assist in their location or even to transmit the pig's passage, but the pig itself usually cannot use GPS as it requires being able to "see" (in satellite terminology) the satellites.

After the pigging run has been completed, the positional data is combined with the pipeline evaluation data (corrosion, cracks, etc) to provide a location-specific defect map and characterization. In other words, the combined data will tell the operator the location and type and size of each pipe defect. This is used to judge the severity of the defect and help repair crews locate and repair the defect quickly without having to dig up excessive amounts of pipeline. By evaluating the rate of change of a particular defect over several years, proactive plans can be made to repair the pipeline before any leakage or environmental damage occurs.

Pipeline Inspection Gauge

A pig on display in a section of cutaway pipe, from the Alaska Pipeline

A "Pig" launcher/receiver, belonging to the natural gas pipeline in Switzerland.

A pipeline inspection gauge or "PIG" in the pipeline industry is a tool that is sent down a pipeline and propelled by the pressure of the product in the pipeline itself. There are four main uses for pigs:

1. physical separation between different liquids being transported in pipelines;
2. internal cleaning of pipelines;
3. inspection of the condition of pipeline walls (also known as an Inline Inspection (ILI) tool);
4. capturing and recording geometric information relating to pipelines (e.g. size, position).

The original pigs were made from straw wrapped in wire used for cleaning. They made a squealing noise while traveling through the pipe, sounding to some like a pig squealing. The term "pipeline inspection gauge" was later created as a backronym.

One kind of pig is a soft, bullet shaped polyurethane foam plug that is forced through pipelines to separate products to reduce mixing. There are several types of pigs for cleaning. Some have tungsten studs or abrasive wire mesh on the outside to cut rust, scale, or paraffin deposits off the inside of the pipe. Others are plain plastic covered polyurethane.

Inline inspection pigs use various methods for inspecting a pipeline. A sizing pig uses one (or more) notched round metal plates that are used as gauges. The notches allow different parts of the plate to bend when a bore restriction is encountered. More complex systems exist for inspecting various aspects of the pipeline. Intelligent pigs, also called smart pigs, are used to inspect the pipeline with sensors and record the data for later analysis. These pigs use technologies such as MFL and ultrasonics to inspect the pipeline. Intelligent pigs may also use calipers to measure the inside geometry of the pipeline.

In 1961, the first intelligent pig was run by Shell Development. It demonstrated that a self contained electronic instrument could traverse a pipe line while measuring and recording wall thickness. The instrument used electromagnetic fields to sense wall integrity. In 1964 Tuboscope ran the first commercial instrument. It used MFL technology to inspect the bottom portion of the pipeline. The system used a black box similar to those used on aircraft to record the information.

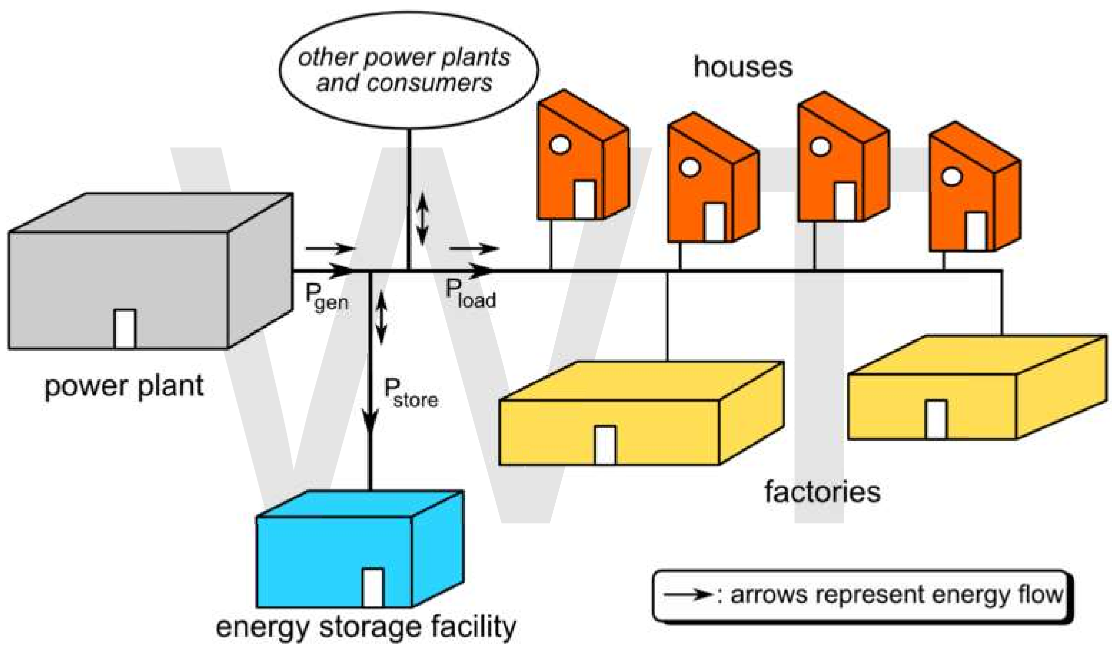
A pig has been used as a plot device in three James Bond films: *Diamonds Are Forever*, where Bond disabled a pig to escape from a pipeline, *The Living Daylights*, where a pig was modified to secretly transport a person through the Iron Curtain, and *The World Is Not Enough*, where a pig was used to move a nuclear weapon through a pipeline.

A pig was also used as a plot device in the *Tony Hillerman* book *The Sinister Pig* where an abandoned pipeline from Mexico to the United States was to use a pig to transport illegal drugs.

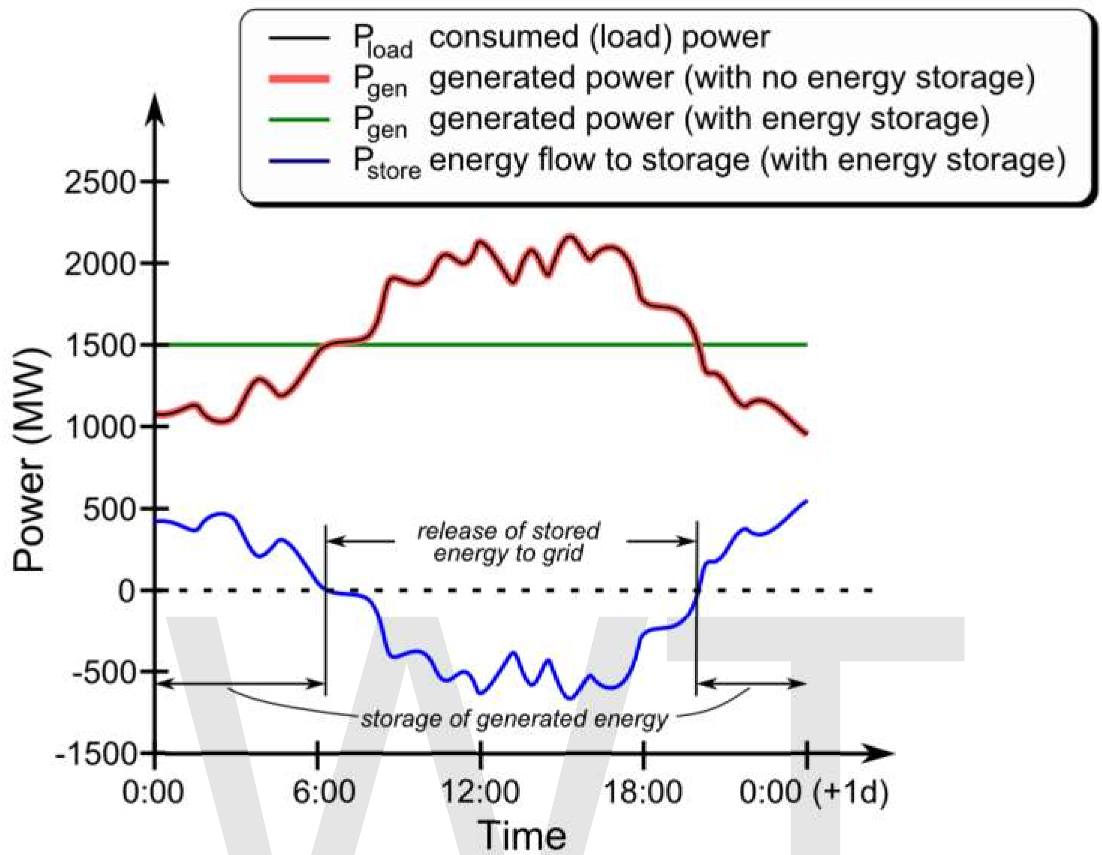
Capacitive sensor probes are used in the process of detecting defects in polyethylene pipe gas pipeline. These probes are attached to the pig in which the pig is sent through the polyethylene pipe that will detect any defects in the outside of the pipe wall. This is done by using a triple plate capacitive sensor in which the electrostatic waves are propogated outware through the pipes all. Any change in dielectric material will result in a change in capacitance. Testing was conducted by NETL DOE research lab at the Battelle West Jefferson's Pipeline Simulation Facility (PSF) near Columbus, Ohio.

Chapter 10

Grid Energy Storage



Simplified electrical grid with energy storage.



Simplified grid energy flow with and without idealized energy storage for the course of one day.

Grid energy storage (also called **large-scale energy storage**) refers to the methods used to large-scale store electricity within an electrical power grid. Electrical energy is stored during times when production (from power plants) exceeds consumption and the stores are used at times when consumption exceeds production. In this way, electricity production need not be drastically scaled up and down to meet momentary consumption – instead, production is maintained at a more constant level. This has the advantage that fuel-based power plants (i.e. coal, oil, gas) can be more efficiently and easily operated at constant production levels.

In particular, the use of grid-connected intermittent energy sources such as photovoltaics and wind turbines can benefit from grid energy storage. Intermittent energy sources are by nature unpredictable – the amount of electrical energy they produce varies over time and depends heavily on random factors such as the weather. In an electrical power grid without energy storage, energy sources that rely on energy stored within fuels (coal, oil, gas) must be scaled up and down to match the rise and fall of energy production from intermittent energy sources.

Thus, grid energy storage is one method that the operator of an electrical power grid can use to adapt energy production to energy consumption, both of which can vary randomly over time. This is done to increase efficiency and lower the cost of energy production, and/or to facilitate the use of intermittent energy sources.

An alternate approach to grid energy storage is the smart grid. The current power grid is designed to have generation sources respond on-demand to user needs, while a smart grid can be designed so that usage varies on-demand with production availability from intermittent power sources such as wind and solar. End-user loads can be actively shed by the utility during peak usage periods, or the cost per kilowatt can dynamically vary between peak and non-peak periods to incentivize turning off non-essential high power loads.

Forms

Batteries

Battery storage was used in the early days of direct-current electric power networks, and is appearing again. Battery systems connected to large solid-state converters have been used to stabilize power distribution networks. For example in Puerto Rico a system with a capacity of 20 megawatts for 15 minutes is used to stabilize the frequency of electric power produced on the island. A 27 megawatt 15 minute nickel-cadmium battery bank was installed at Fairbanks Alaska in 2003 to stabilize voltage at the end of a long transmission line. Many "off-the-grid" domestic systems rely on battery storage, but storing large amounts of electricity in batteries or by other electrical means has not yet been put to general use.

Batteries are generally expensive, have high maintenance, and have limited lifespans, mainly due to pure chemical crystals that form inside the cells during the charge and discharge cycles. These crystals usually can not be re-dissolved back into the electrolyte. They can grow large enough to apply significant mechanical pressure to interior structures inside the battery to bend plates, bulge battery casings, and short out individual cells.

One possible technology for large-scale storage are large-scale flow batteries and liquid metal batteries. Sodium-sulfur batteries could also be inexpensive to implement on a large scale and have been used for grid storage in Japan and in the United States . Vanadium redox batteries and other types of flow batteries are also beginning to be used for energy storage including the averaging of generation from wind turbines. Battery storage has relatively high efficiency, as high as 90% or better. The world's largest battery is in Fairbanks, Alaska, composed of Ni-Cd cells.

Rechargeable flow batteries can be used as a rapid-response storage medium. Vanadium redox flow batteries are currently installed at Huxley Hill wind farm (Australia), Tomari Wind Hills at Hokkaidō (Japan), as well as in other non-wind farm applications. A further 12 MW·h flow battery is to be installed at the Sorne Hill wind farm (Ireland). These storage systems are designed to smooth out transient fluctuations in wind energy supply. The redox flow battery mentioned in the first article cited above has a capacity of 6 MW·h, which represents under an hour of electrical flow from this particular wind farm (at 20% capacity factor on its 30 MW rated capacity).

Electric Vehicles

Companies are researching the possible use of Electric Vehicles for meeting peak demand. A parked and plugged-in EV could sell the electricity from the battery during peak loads and charge either during night (at home) or during off-peak.

When plug-in hybrid and/or electric cars are mass-produced these mobile energy sinks could be used for their energy storage capabilities. Vehicle-to-grid technology can be employed, turning each vehicle with its 20 to 50 kW·h battery pack into a distributed load-balancing device or emergency power source. This represents 2 to 5 days per vehicle of average household requirements of 10 kW·h per day, assuming annual consumption of 3650 kW·h. This quantity of energy is equivalent to between 40 and 300 miles (64 and 480 km) of range in such vehicles consuming 0.5 to 0.16 kW·h per mile. These figures can be achieved even in home-made electric vehicle conversions. Some electric utilities plan to use old plug-in vehicle batteries (sometimes resulting in a giant battery) to store electricity However, a large disadvantage of using vehicle to grid energy storage is the fact that each storage cycle stresses the battery with one complete charge-discharge cycle. Current lithium ion batteries break down with the number of cycles.

Compressed air

Another grid energy storage method is to use off-peak or renewably generated electricity to compress air, which is usually stored in an old mine or some other kind of geological feature. When electricity demand is high, the compressed air is heated with a small amount of natural gas and then goes through turboexpanders to generate electricity.

Flywheel

Mechanical inertia is the basis of this storage method. A heavy rotating disc is accelerated by an electric motor, which acts as a generator on reversal, slowing down the disc and producing electricity. Electricity is stored as the kinetic energy of the disc. Friction must be kept to a minimum to prolong the storage time. This is often achieved by placing the flywheel in a vacuum and using magnetic bearings, tending to make the method expensive. Larger flywheel speeds allow greater storage capacity but require strong materials such as steel or composite materials to resist the centrifugal forces (or rather, to provide centripetal forces). The ranges of power and energy storage technically and economically achievable, however, tend to make flywheels unsuitable for general power system application; they are probably best suited to load-leveling applications on railway power systems and for improving power quality in renewable energy systems. Applications that use flywheel storage are those that require very high bursts of power for very short durations such as tokamak and laser experiments where a motor generator is spun up to operating speed and is partially slowed down during discharge. Flywheel storage is also currently used to provide uninterruptible power supply systems (such as those in large datacenters) for ride-through power necessary during transfer – that is, the relatively brief amount of time between a loss of power to the mains and the warm-up of an alternate source, such as a diesel generator.

This potential solution has been implemented by EDA in the Azores on the islands of Graciosa and Flores. This system uses a 18 MWs flywheel to improve power quality and thus allow increased renewable energy usage. As the description suggests, these systems are again designed to smooth out transient fluctuations in supply, and could never be used to cope with an outage of couple of days or more. The most powerful flywheel energy storage systems currently for sale on the market can hold up to 133 kW·h of energy.

Powercorp in Australia have been developing applications using wind turbines, flywheels and low load diesel (LLD) technology to maximise the wind input to small grids. A system installed in Coral Bay, Western Australia, uses wind turbines coupled with a flywheel based control system and LLDs to achieve better than 60% wind contribution to the town grid.

The Gerald R. Ford class aircraft carrier will use flywheels to accumulate energy from the ship's power supply, for rapid release into the Electromagnetic Aircraft Launch System. The shipboard power system cannot on its own supply the high power transients necessary to launch aircraft.

Hydrogen

Hydrogen is also being developed as an electrical energy storage medium. Hydrogen is produced (presumably using electrical energy and/or heat), then perhaps compressed or liquefied, stored, and then converted back to electrical energy and/or heat. Hydrogen can be used as a fuel for portable (vehicles) or stationary energy generation. Compared to pumped water storage and batteries, hydrogen has the advantage that it is a high energy density, amassable fuel.

Hydrogen can be produced either by reforming natural gas with steam or by the electrolysis of water into hydrogen and oxygen. Reforming natural gas produces carbon dioxide as a by-product. High temperature electrolysis and high pressure electrolysis are two techniques by which the efficiency of hydrogen production may able to be increased. Hydrogen is then be converted back to electricity in an internal combustion engine, or a fuel cell which convert chemical energy into electricity without combustion, similar to the way the human body burns fuel.

The overall efficiency of hydrogen storage depends greatly on the technique used and the scale of the operation, but is typically 50 to 60%, which is lower than for pumped storage systems or batteries. About 50 kW·h (180 MJ) of energy is required to produce a kilogram of hydrogen by electrolysis, so the cost of the electricity clearly is crucial, even for hydrogen uses other than storage for electrical generation. At $0.03/kW·h, common off-peak high-voltage line rate in the U.S., this means hydrogen costs $1.50 a kilogram for the electricity, equivalent to $1.50 a US gallon (40¢/L) for gasoline if used in a fuel cell vehicle. The equipment necessary for hydrogen energy storage includes an electrolysis plant, hydrogen compressors or liquifiers, and storage tanks.

Biohydrogen is a process being investigated for producing hydrogen using biomass.

Micro combined heat and power (microCHP) can use hydrogen as a fuel.

Some nuclear power plants may be able to benefit from a symbiosis with hydrogen production. High temperature (950 to 1,000 °C) gas cooled nuclear generation IV reactors have the potential to electrolyze hydrogen from water by thermochemical means using nuclear heat as in the sulfur-iodine cycle.

A community based pilot program using wind turbines and hydrogen generators was started in 2007 in the remote community of Ramea, Newfoundland and Labrador. A similar project has been going on since 2004 on Utsira, a small Norwegian island municipality.

Underground hydrogen storage is the practice of hydrogen storage in underground caverns, salt domes and depleted oil and gas fields. Large quantities of gaseous hydrogen have been stored in underground caverns by ICI for many years without any difficulties.

Pumped water

In many places, pumped storage hydroelectricity is used to even out the daily generating load, by pumping water to a high storage reservoir during off-peak hours and weekends, using the excess base-load capacity from coal or nuclear sources. During peak hours, this water can be used for hydroelectric generation, often as a high value rapid-response reserve to cover transient peaks in demand. Pumped storage recovers about 75% of the energy consumed, and is currently the most cost effective form of mass power storage. The chief problem with pumped storage is that it usually requires two nearby reservoirs at considerably different heights, and often requires considerable capital expenditure.

Pumped water systems have high dispatchability, meaning they can come on-line very quickly, typically within 15 seconds, which makes these systems very efficient at soaking up variability in electrical *demand* from consumers. There is over 90 GW of pumped storage in operation around the world, which is about 3% of *instantaneous* global generation capacity. Pumped water storage systems, such as the Dinorwig storage system, hold five or six hours of generating capacity, and are used to smooth out demand variations.

Another example is the Tianhuangping Pumped-Storage Hydro Plant in China, which has a reservoir capacity of eight million cubic meters (2.1 billion U.S. gallons or the volume of water over Niagara Falls in 25 minutes) with a vertical distance of 600 m (1970 feet). The reservoir can provide about 13 GW·h of stored gravitational potential energy (convertible to electricity at about 80% efficiency), or about 2% of China's daily electricity consumption.

A new concept in pumped-storage is utilizing wind energy or solar power to pump water. Wind turbines or solar cells that direct drive water pumps for an energy storing wind or solar dam can make this a more efficient process but are limited. Such systems can only increase kinetic water volume during windy and daylight periods.

Hydroelectric dam uprating

Hydroelectric dams with large reservoirs can also be operated to provide peak generation at times of peak demand. Water is stored in the reservoir during periods of low demand and released through the plant when demand is higher. The net effect is the same as pumped storage, but without the pumping loss. Depending on the reservoir capacity the plant can provide daily, weekly, or seasonal load following.

Many existing hydroelectric dams are fairly old (for example, the Hoover Dam was built in the 1930s), and their original design predated the newer intermittent power sources such as wind and solar by decades. A hydroelectric dam originally built to provide baseload power will have its generators sized according to the average flow of water into the reservoir. Uprating such a dam with additional generators increases its peak power output capacity, thereby increasing its capacity to operate as a virtual grid energy storage unit. The United States Bureau of Reclamation reports an investment cost of $69 per kilowatt capacity to uprate an existing dam, compared to more than $400 per kilowatt for oil-fired peaking generators. While an uprated hydroelectric dam does not directly store excess energy from other generating units, it behaves equivalently by accumulating its own fuel - incoming river water - during periods of high output from other generating units. Functioning as a virtual grid storage unit in this way, the uprated dam is one of the most efficient forms of energy storage, because it has no pumping losses to fill its reservoir. A dam which impounds a large reservoir can store and release a correspondingly large amount of energy, by raising and lowering its reservoir level a few meters.

Superconducting magnetic energy

Superconducting magnetic energy storage (SMES) systems store energy in the magnetic field created by the flow of direct current in a superconducting coil which has been cryogenically cooled to a temperature below its superconducting critical temperature. A typical SMES system includes three parts: superconducting coil, power conditioning system and cryogenically cooled refrigerator. Once the superconducting coil is charged, the current will not decay and the magnetic energy can be stored indefinitely. The stored energy can be released back to the network by discharging the coil. The power conditioning system uses an inverter/rectifier to transform alternating current (AC) power to direct current or convert DC back to AC power. The inverter/rectifier accounts for about 2–3% energy loss in each direction. SMES loses the least amount of electricity in the energy storage process compared to other methods of storing energy. SMES systems are highly efficient; the round-trip efficiency is greater than 95%. The high cost of superconductors is the primary limitation for commercial use of this energy storage method.

Due to the energy requirements of refrigeration, and the limits in the total energy able to be stored, SMES is currently used for short duration energy storage. Therefore, SMES is most commonly devoted to improving power quality. If SMES were to be used for utilities it would be a diurnal storage device, charged from base load power at night and meeting peak loads during the day.

For superconducting magnetic energy to become practical the technical challenges have to be solved.

Thermal

Design proposals have been made for the use of molten salt as a heat store to store heat collected by a solar power tower so that it can be used to generate electricity in bad weather or at night. Thermal efficiencies over one year of 99% have been predicted.

Off-peak electricity can be used to make ice from water, and the ice can be stored until the next day, when it is used to cool either the air in a large building, thereby shifting that demand off-peak, or the intake air of a gas turbine generator, thus increasing the on-peak generation capacity.

The second prototype of Isentropic Pumped Heat Electricity Storage System was a success proving the electricity-in to electricity-out (round trip efficiency) in the range of 72 to 85%. The isentropic PHES system utilises a highly reversible heat engine/heat pump to pump heat between two storage vessels.

Economics

Generally speaking, energy storage is economical when the marginal cost of electricity varies more than the costs of storing and retrieving the energy plus the price of energy lost in the process. For instance, assume a pumped-storage reservoir can pump to its upper reservoir water equivalent to 1,200 MW·h during the night, for $15 per MW·h, at a total cost of $18,000. The next day, all of the stored energy can be sold at the peak hours for $40 per MW·h, but from the 1,200 MW·h pumped 50 were lost due to evaporation and seeping in the reservoir. 1,150 MW·h are sold for $46,000, for a final profit of $28,000.

However, the marginal cost of electricity varies because of the varying operational and fuel costs of different classes of generators. At one extreme, base load power plants such as coal-fired power plants and nuclear power plants are low marginal cost generators, as they have high capital and maintenance costs but low fuel costs. At the other extreme, peaking power plants such as gas turbine natural gas plants burn expensive fuel but are cheaper to build, operate and maintain. To minimize the total operational cost of generating power, base load generators are dispatched most of the time, while peak power generators are dispatched only when necessary, generally when energy demand peaks. This is called "economic dispatch".

Demand for electricity from the world's various grids varies over the course of the day and from season to season. For the most part, variation in electric demand is met by varying the amount of electrical energy supplied from primary sources. Increasingly, however, operators are storing lower-cost energy produced at night, then releasing it to the grid during the peak periods of the day when it is more valuable. In areas where hydroelectric dams exist, release can be delayed until demand is greater; this form of storage is common and can make use of existing reservoirs. This is not storing "surplus" energy produced elsewhere, but the net effect is the same - although without the efficiency losses. Renewable supplies with variable production, like wind and solar power, tend to increase the net variation in electric load, increasing the opportunity for grid energy storage.

Load leveling

The demand for electricity from consumers and industry is constantly changing, broadly within the following categories:

- Seasonal (during dark winters more electric lighting and heating is required, while in other climates hot weather boosts the requirement for air conditioning)
- Weekly (most industry closes at the weekend, lowering demand)
- Daily (such as the peak as everyone arrives home and switches the television on)
- Hourly (one method for estimating television viewing figures in the United Kingdom is to measure the power spikes during advertisement breaks or after programmes when viewers go to switch the kettle on)
- Transient (fluctuations due to individual's actions, differences in power transmission efficiency and other small factors that need to be accounted for)

There are currently three main methods for dealing with changing demand:

- Electrical devices generally having a working voltage range that they require, commonly 110–120 V or 220–240 V. Minor variations in load are automatically smoothed by slight variations in the voltage available across the system.
- Power plants can be run below their normal output, with the facility to increase the amount they generate almost instantaneously. This is termed 'spinning reserve'.
- Additional power plants can be brought online to provide a larger generating capacity. Typically, these would be combustion gas turbines, which can be started in a matter of minutes.

The problem with relying on these last two methods in particular is that they are expensive, because they leave expensive generating equipment unused much of the time, and because plants running below maximum output usually produce at less than their best efficiency. Grid energy storage is used to shift load from peak to off-peak hours. Power plants are able to run closer to their peak efficiency for much of the year.

Energy demand management

The only way to deal with varying electrical loads is to decrease the difference between generation and demand. If this is done by changing loads it is referred to as demand side management (DSM). For decades, utilities have sold off-peak power to large consumers at lower rates, to encourage these users to shift their loads to off-peak hours, in the same way that telephone companies do with individual customers. Usually, these time-dependent prices are negotiated ahead of time. In an attempt to save more money, some utilities are experimenting with selling electricity at minute-by-minute spot prices, which allow those users with monitoring equipment to detect demand peaks as they happen, and shift demand to save both the user and the utility money. Demand side management can be manual or automatic and is not limited to large industrial customers. In residential and small business applications, for example, appliance control modules can reduce energy usage of water heaters, air conditioning units, refrigerators, and other devices during these periods by turning them off for some portion of the peak demand time or by reducing the power that they draw. Energy demand management includes more than reducing overall energy use or shifting loads to off-peak hours. A particularly effective method of energy demand management involves encouraging electric consumers to install more energy efficient equipment. For example, many utilities give rebates for the purchase of insulation, weatherstripping, and appliances and light bulbs that are energy efficient. Some utilities subsidize the purchase of geothermal heat pumps by their customers, to reduce electricity demand during the summer months by making air conditioning up to 70% more efficient, as well as to reduce the winter electricity demand compared to conventional air-sourced heat pumps or resistive heating. Companies with factories and large buildings can also install such products, but they can also buy energy efficient industrial equipment, like boilers, or use more efficient processes to produce products. Companies may get incentives like rebates or low interest loans from utilities or the government for the installation of energy efficient industrial equipment.

Portability

This is the area of greatest success for current energy storage technologies. Single-use and rechargeable batteries are ubiquitous, and provide power for devices with demands as varied as digital watches and cars. Advances in battery technology have generally been slow, however, with much of the advance in battery life that consumers see being attributable to efficient power management rather than increased storage capacity. Portable consumer electronics have benefited greatly from size and power reductions associated with Moore's law. Unfortunately, Moore's law does not apply to hauling people and freight; the underlying energy requirements for transportation remain much higher than for information and entertainment applications. Battery capacity has become an issue as pressure grows for alternatives to internal combustion engines in cars, trucks, buses, trains, ships, and airplanes. These uses require far more energy density (the amount of energy stored in a given volume or weight) than current battery technology can deliver. Liquid hydrocarbon fuel (such as gasoline/petrol and diesel), as well as alcohols (methanol, ethanol, and butanol) and lipids (straight vegetable oil, biodiesel) have much higher energy densities.

There are synthetic pathways for using electricity to reduce carbon dioxide and water to liquid hydrocarbon or alcohol fuels. These pathways begin with electrolysis of water to generate hydrogen, and then reducing carbon dioxide with excess hydrogen in variations of the reverse water gas shift reaction. Non-fossil sources of carbon dioxide include fermentation plants and wastewater treatment plants. Converting electrical energy to carbon-based liquid fuel has potential to provide portable energy storage usable by the large existing stock of motor vehicles and other engine-driven equipment, without the difficulties of dealing with hydrogen or another exotic energy carrier. These synthetic pathways may attract attention in connection with attempts to improve energy security in nations that rely on imported petroleum, but have or can develop large sources of renewable or nuclear electricity, as well as to deal with possible future declines in the amount of petroleum available to import.

Because the transport sector uses so much energy from petroleum, replacing petroleum with electricity for mobile energy will require very large investments over many years, regardless of which energy carriers become popular.

Reliability

Virtually all devices that operate on electricity are adversely affected by the sudden removal of their power supply. Solutions such as UPS (uninterruptible power supplies) or backup generators are available, but these are expensive. Efficient methods of power storage would allow for devices to have a built-in backup for power cuts, and also reduce the impact of a failure in a generating station. Examples of this are currently available using fuel cells and flywheels.

Chapter 11

Electric Power System

An **electric power system** is a network of electrical components used to supply, transmit and use electric power. An example of an electric power system is the network that supplies a region's homes and industry with power - for sizable regions, this power system is known as *the grid* and can be broadly divided into the generators that supply the power, the transmission system that carries the power from the generating centres to the load centres and the distribution system that feeds the power to nearby homes and industries. Smaller power systems are also found in industry, hospitals, commercial buildings and homes. The majority of these systems rely upon three-phase AC power - the standard for large-scale power transmission and distribution across the modern world. Specialised power systems that do not always rely upon three-phase AC power are found in aircraft, electric rail systems, ocean liners and automobiles.

History

A sketch of the Pearl Street Station

In 1881 two electricians built the world's first power system at Godalming in England. It was powered by a power station consisting of two waterwheels that produced an alternating current that in turn supplied seven Siemans arc lamps at 250 volts and 34 incandescent lamps at 40 volts. However supply to the lamps was intermittent and in 1882 Thomas Edison and his company, The Edison Electric Light Company, developed the first steam powered electric power station on Pearl Street in New York City. The Pearl Street Station initially powered around 3,000 lamps for 59 customers. The power station used direct current and operated at a single voltage. Since direct current power could not be easily transformed to the higher voltages necessary to minimise power loss during long-distance transmission, the possible distance between the generators and load was limited to around one-half mile (800 m).

That same year in London Lucien Gaulard and John Dixon Gibbs demonstrated the first transformer suitable for use in a real power system. The practical value of Gaulard and Gibbs' transformer was demonstrated in 1884 at Turin where the transformer was used to light up forty kilometres (25 miles) of railway from a single alternating current generator. Despite the success of the system, the pair made some fundamental mistakes. Perhaps the most serious was connecting the primaries of the transformers in series so that active lamps would affect the brightness of other lamps further down the line. Following the demonstration George Westinghouse, an American entrepreneur, imported a number of the transformers along with a Siemens generator and set his engineers to experimenting with them in the hopes of improving them for use in a commercial power system.

One of Westinghouse's engineers, William Stanley, recognised the problem with connecting transformers in series as opposed to parallel and also realised that making the iron core of a transformer a fully-enclosed loop would improve the voltage regulation of the secondary winding. Using this knowledge he built a much improved alternating current power system at Great Barrington, Massachusetts in 1886.

By 1890 the power industry had flourished and power companies had built literally thousands of power systems (both direct and alternating current) in the United States and Europe - these networks were effectively dedicated to providing electric lighting. During this time a fierce rivalry known as the "War of Currents" emerged between Edison and Nicola Tesla who was employed by Westinghouse over which form of transmission (direct or alternating current) was superior. In 1891, Westinghouse installed the first major power system that was designed by Tesla to drive an electric motor and not just provide electric lighting. The installation powered a 100 horsepower (75 kW) synchronous motor at Telluride, Colorado. On the other side of the Atlantic, Oskar von Miller built a 20 kV 176 km three-phase transmission line from Lauffen am Neckar to Frankfurt am Main for the Electrical Engineering Exhibition in Frankfurt. In 1895, after a protracted decision-making process, the Adams No. 1 generating station at Niagara Falls began transferring three-phase alternating current power to Buffalo at 11 kV. Following completion of the Niagara Falls project, new power systems increasingly chose alternating current as opposed to direct current for electrical transmission.

Although the 1880s and 1890s were seminal decades for the development of power systems, developments continued throughout the 20th and 21st century. In 1936 the first commercial HVDC (high voltage direct current) line using Mercury arc valves was built between Schenectady and Mechanicville, New York. HVDC had previously been achieved by installing direct current generators in series (a system known as the Thury system) although this suffered from serious reliability issues. In 1957 Siemens demonstrated the first solid-state rectifier (solid-state rectifiers are now the standard for HVDC systems) however it was not until the early 1970s that this technology was used in commercial power systems. In recent times, many important developments have come from extending innovations in the information technology and telecommunications field to the power engineering field. For example, the development of computers meant load flow studies could be run more efficiently allowing for much better planning of power systems. Advances in information technology and telecommunication also allowed for remote control of a power system's switchgear and generators.

Basics of electric power

An external AC to DC power adapter used for household appliances

Electric power is the mathematical product of two quantities: current and voltage. These two quantities can vary with respect to time (AC power) or can be kept at constant levels (DC power).

Most refrigerators, air conditioners, pumps and industrial machinery use AC power where as most computers and digital equipment use DC power (the digital devices you plug into the mains typically have an internal or external power adapter to convert from AC to DC power). AC power has the advantage of being easy to transform between voltages and is able to be generated and utilised by brushless machinery. DC power remains the only practical choice in digital systems and can be more economical to transmit over long distances at very high voltages.

The ability to easily transform the voltage of AC power is important for two reasons: Firstly, power can be transmitted over long distances with less loss at higher voltages. So in power systems where generation is distant from the load, it is desirable to step-up (increase) the voltage of power at the generation point and then step-down (decrease) the voltage near the load. Secondly, it is often more economical to install turbines that produce higher voltages than would be used by most appliances, so the ability to easily transform voltages means this mismatch between voltages can be easily managed.

Solid state devices, which are products of the semiconductor revolution, make it possible to transform DC power to different voltages, build brushless DC machines and convert between AC and DC power. Nevertheless devices utilising solid state technology are often more expensive than their traditional counterparts, so AC power remains in widespread use.

Components of power systems

Supplies

The majority of the world's power still comes from coal-fired power stations like this.

All power systems have one or more sources of power. For some power systems, the source of power is external to the system but for others it is part of the system itself - it is these internal power sources that are discussed here. Direct current power can be supplied by batteries, fuel cells or photovoltaic cells. Alternating current power is typically supplied by a rotor that spins in a magnetic field in a device known as a turbo generator in a power station. There have been a wide range of techniques used to spin a turbine's rotor, from superheated steam heated using fossil fuel (including coal, gas and oil) to water itself (hydroelectric power) and wind (wind power). Even nuclear power typically depends on water heated to steam using a nuclear reaction.

The speed at which the rotor spins in combination with the number of generator poles determines the frequency of the alternating current produced by the generator. All generators on a single system, for example the National Grid (UK) rotate synchronously (i.e. at an identical speed) and will target a set frequency, in European countries 50 Hz. If the load on the system increases, the generators will require more torque to spin at that speed and, in a typical power station, more steam must be supplied to the turbines driving them. Thus the steam used and the fuel expended are directly dependent on the quantity of electrical energy supplied.

Depending on how the poles are fed, alternating current generators can produce a variable number of phases of power. A higher number of phases leads to more efficient power system operation but also increases the infrastructure requirements of the system.

In national electricity grid systems the frequency and number of phases are usually specified, the commonest being three-phase at 50 or 60 Hz. However there are other considerations. These range from the obvious: How much power should the generator be able to supply? What is an acceptable length of time for starting the generator (some generators can take hours to start)? Is the availability of the power source acceptable (some renewables are only available when the sun is shining or the wind is blowing)? To the more technical: How should the generator start (some turbines act like a motor to bring themselves up to speed in which case they need an appropriate starting circuit)? What is the mechanical speed of operation for the turbine and consequently what are the number of poles required? What type of generator is suitable (synchronous or asynchronous) and what type of rotor (squirrel-cage rotor, wound rotor, salient pole rotor or cylindrical rotor)?

Loads

A toaster is great example of a single-phase load that might appear in a residence. Toasters typically draw 2 to 10 amps at 110 to 260 volts consuming around 600 to 1200 watts of power

In addition to sources of power, all power systems have loads that use the electrical energy to perform a function. These loads range from household appliances to industrial machinery. Most loads expect a certain voltage and, for alternating current devices, a certain frequency and number of phases. The appliances found in your home, for example, will typically be single-phase operating at 50 or 60 Hz with a voltage between 110 and 260 volts (depending on national standards). An exception exists for centralized air conditioning systems as these are now typically three-phase because this allows them to operate more efficiently. All devices in your house will also have a wattage, this specifies the amount of power the device consumes. At any one time, the net amount of power consumed by the loads on a power system must equal the net amount of power produced by the supplies less the power lost in transmission.

Making sure that the voltage, frequency and amount of power supplied to the loads is in line with expectations is one of the great challenges of power system engineering. However it is not the only challenge, in addition to the power used by a load to do useful work (termed real power) many alternating current devices also use an additional amount of power because they cause the alternating voltage and alternating current to become slightly out-of-sync (termed reactive power). The reactive power like the real power must balance (that is the reactive power produced on a system must equal the reactive power consumed) and can be supplied from the generators, however it is often more economical to supply such power from capacitors.

A final consideration with loads is to do with power quality. In addition to sustained overvoltages and undervoltages (voltage regulation issues) as well as sustained deviations from the system frequency (frequency regulation issues), power system loads can be adversely affected by a range temporal issues. These include voltage sags, dips and swells, transient overvoltages, flicker, high frequency noise, phase imbalance and poor power factor. Power quality issues occur when the power supply to a load deviates from the ideal: For an AC supply, the ideal is the current and voltage in-sync fluctuating as a perfect sine wave at a prescribed frequency with the voltage at a prescribed amplitude. For DC supply, the ideal is the voltage not varying from a prescribed level. Power quality issues can be especially important when it comes to specialist industrial machinary or hospital equipment.

Conductors

Conductors carry power from the generators to the load. In a grid, conductors may be classified as belonging to the transmission system, which carries large amounts of power at high voltages (typically more than 50 kV) from the generating centres to the load centres, or the distribution system, which feeds smaller amounts of power at lower voltages (typically less than 50 kV) from the load centres to nearby homes and industry.

Choice of conductors is based upon considerations such as cost, transmission losses and other desirable characteristics of the metal like tensile strength. Copper, with lower resistivity than aluminium, was the conductor of choice for most power systems. However, aluminum has lower cost for the same current carrying capacity and is the primary metal used for transmission line conductors. Overhead line conductors may be reinforced with steel or aluminum alloys.

Conductors in exterior power systems may be placed overhead or underground. Overhead conductors are usually air insulated and supported on porcelain, glass or polymer insulators. Cables used for underround transmission or building wiring are insulated with cross-linked polyethylene or other flexible insulation. Large conductors are stranded for ease of handling; small conductors used for building wiring are often solid, especially in light commercial or residential construction.

Conductors are typically rated for the maximum current that they can carry at a given temperature rise over ambient conditions. As current flow increases through a conductor it heats up. For insulated conductors, the rating is determined by the insulation. . For overhead conductors, the rating is determined by the point at which the sag of the conductors would become unacceptable.

Capacitors and reactors

The majority of the load in a typical AC power system, is inductive; the current lags behind the voltage. Since the voltage and current are out-of-sync, this leads to the emergence of a "useless" form of power known as reactive power. Reactive power does no measurable work but is transmitted back and forth between the reactive power source and load every cycle. This reactive power can be provided by the generators themselves but it is often cheaper to provide it through capacitors, hence capacitors are often placed near inductive loads to reduce current demand on the power system. Power factor correction may be applied at a central substation or adjacent to large loads.

Reactors consume reactive power and are used to regulate voltage on long transmission lines. In light load conditions, where the loading on transmission lines is well below the surge impedance loading, the efficiency of the power system may actually be improved by switching in reactors. Reactors installed in series in a power system also limit rushes of current flow, small reactors are therefore almost always installed in series with capacitors to limit the current rush associated with switching in a capacitor. Series reactors can also be used to limit fault currents.

Capacitors and reactors are switched by circuit breakers, which results in moderately large steps in reactive power. A solution comes in the form of static VAR compensators and static synchronous compensators. Briefly, static VAR compensators work by switching in capacitors using thyristors as opposed to circuit breakers allowing capacitors to be switched-in and switched-out within a single cycle. This provides a far more refined response than circuit breaker switched capacitors. Static synchronous compensators take it a step further by achieving reactive power adjustments using only power electronics.

Power electronics

Power electronics are semi-conductor based devices that are able to switch quantities of power ranging from a few hundred watts to several hundred megawatts. Despite their relatively simple function, their speed of operation (typically in the order of nanoseconds) means they are capable of a wide range of tasks that would be difficult or impossible with conventional technology. The classic function of power electronics is rectification, or the conversion of AC-to-DC power, power electronics are therefore found in almost every digital device that is supplied from an AC source either as an adapter that plugs into the wall or as component internal to the device. High-powered power electronics can also be used to convert AC power to DC power for long distance transmission in a system known as HVDC. HVDC is used because it proves to be more economical than similar high voltage AC systems for very long distances (hundreds to thousands of kilometres). HVDC is also desirable for interconnects because it allows frequency independence thus improving system stability. Power electronics are also essential for any power source that is required to produce an AC output but that by its nature produces a DC output. They are therefore used by many photovoltaic installations both industrial and residential.

Power electronics also feature in a wide range of more exotic uses. They are at the heart of all modern electric and hybrid vehicles - where they are used for both motor control and as part of the brushless DC motor. Power electronics are also found in practically all modern petrol-powered vehicles, this is because the power provided by the car's batteries alone is insufficient to provide ignition, air-conditioning, internal lighting, radio and dashboard displays for the life of the car. So the batteries must be recharged while driving using DC power from the engine - a feat that is typically accomplished using power electronics. Where as conventional technology would be unsuitable for a modern electric car, commutators can and have been used in petrol-powered cars, the switch to alternators in combination with power electronics has occurred because of the improved durability of brushless machinery.

Some electric railway systems also use DC power and thus make use of power electronics to feed grid power to the locomotives and often for speed control of the locomotive's motor. In the middle twentieth century, rectifier locomotives were popular, these used power electronics to convert AC power from the railway network for use by a DC motor. Today most electric locomotives are supplied with AC power and run using AC motors, but still use power electronics to provide suitable motor control. The use of power electronics to assist with motor control and with starter circuits cannot be underestimated and, in addition to rectification, is responsible for power electronics appearing in a wide range of industrial machinery. Power electronics even appear in modern residential air conditioners.

Power electronics are also at the heart of the variable-speed wind turbine. Put simply, conventional wind turbines require significant engineering to ensure they operate at some ratio of the system frequency (the ratio being accounted for using gears), however by using power electronics this requirement can be eliminated as can the gears leading to quieter, more flexible and (at the moment) more costly wind turbines. A final example of one of the more exotic uses of power electronics comes from the previous section where the fast-switching times of power electronics were used to provide more refined reactive compensation to the power system.

Protective devices

All practical power systems contain protective devices that serve two purposes: firstly, to minimise harm to people and animals that may come in contact with the power system and secondly, to isolate faults and protect the power system and its various elements from damage. The quintessential protective device is the fuse. When the current through a fuse exceeds a certain threshold, the fuse element melts producing an arc across the resulting gap that is then extinguished. Given that fuses can be built as the weak point of a system, fuses are ideal for protecting circuitry from damage. Fuses however have two problems: First, after they have functioned, fuses must be replaced as they cannot be reset. This can prove inconvenient if the fuse is at a remote site or a spare fuse is not on hand. And second, fuses are typically inadequate as the sole safety device in most power systems as they allow current flows well in excess of that that would prove lethal to a human or animal.

The first problem is resolved by the use of circuit breakers - devices that can be reset after they have broken current flow. In modern systems that use less than about 10 kW, miniature circuit breakers are typically used. These devices combine the mechanism that initiates the trip (by sensing excess current) as well as the mechanism that breaks the current flow in a single unit. Some miniature circuit breakers operate solely on the basis of electromagnetism. In these miniature circuit breakers, the current is run through a solenoid, and, in the event of excess current flow, the magnetic pull of the solenoid is sufficient to force open the circuit breaker's contacts (often indirectly through a tripping mechanism). A better design however arises by inserting a bimetallic strip before the solenoid - this means that instead of always producing a magnetic force, the solenoid only produces a magnetic force when the current is strong enough to deform the bimetallic strip and complete the solenoid's circuit.

In higher powered applications, the protective relays that detect a fault and initiate a trip are separate from the circuit breaker. Early relays worked based upon electromagnetic principles similar to those mentioned in the previous paragraph, modern relays are application-specific computers that determine whether to trip based upon readings from the power system. Different relays will initiate trips depending upon different protection schemes. For example, an overcurrent relay might initiate a trip if the current on any phase exceeds a certain threshold where as a set of differential relays might initiate a trip if the sum of currents between them indicates there may be current leaking to earth. The circuit breakers in higher powered applications are different too. Air is typically no longer sufficient to quell the arc that forms when the contacts are forced open so a variety of techniques are used. The most popular technique at the moment is to keep the chamber enclosing the contacts flooded with sulfur hexafluoride (SF_6) - a non-toxic gas that has superb arc-quelling properties. Other techniques are discussed in the reference.

The second problem, the inadequacy of fuses to act as the sole safety device in most power systems, is probably best resolved by the use of residual current devices (RCDs). In any properly functioning electrical appliance the current flowing into the appliance on the active line should equal the current flowing out of the appliance on the neutral line. A residual current device works by monitoring the active and neutral lines and tripping the active line if it notices a difference. Residual current devices require a separate neutral line for each phase and to be able to trip within a time frame before harm occurs. This is typically not a problem in most residential applications where standard wiring provides an active and neutral line for each appliance (that's why your power plugs always have at least two tongs) and the voltages are relatively low however these issues do limit the effectiveness of RCDs in other applications such as industry. Even with the installation of an RCD, exposure to electricity can still prove lethal.

SCADA systems

In large electric power systems, Supervisory Control And Data Acquisition (SCADA) is used for tasks such as switching on generators, controlling generator output and switching in or out system elements for maintenance. The first supervisory control systems implemented consisted of a panel of lamps and switches at a central console near the controlled plant. The lamps provided feedback on the state of plant (the data acquisition function) and the switches allowed adjustments to the plant to be made (the supervisory control function). Today, SCADA systems are much more sophisticated and, due to advances in communication systems, the consoles controlling the plant no longer need to be near the plant itself. Instead in today's power systems, it is increasingly common for plant to be controlled from a central remote site with equipment similar to (if not identical to) a desktop computer. The ability to control such plant through computers has increased the need for security and already there have been reports of cyber-attacks on such systems causing significant disruptions to power systems.

Power systems in practice

Despite their common components, power systems vary widely both with respect to their design and how they operate.

Residential power systems

Residential dwellings almost always take supply from the low voltage distribution lines or cables that run past the dwelling. These operate at voltages of between 110 and 260 volts (phase-to-earth) depending upon national standards. A few decades ago small dwellings would be fed a single phase using a dedicated two-core service cable (one core for the active phase and one core for the neutral return). The active line would then be run through a main isolating switch in the fuse box and then split into one or more circuits to feed lighting and appliances inside the house. By convention, the lighting and appliance circuits would be kept separate so the failure of an appliance would not leave the dwelling's occupants in the dark. All circuits would be fused with an appropriate fuse based upon the wire size used for that circuit. Circuits would have both a active and neutral wire with both the lighting and power sockets being connected in parallel. Sockets would also be provided with a protective earth. This would be made available to appliances to connect to any metallic casing. If this casing were to become live, the theory is the connection to earth would cause an RCD or fuse to trip - thus preventing the future electrocution of an occupant handling the appliance. Earthing systems vary between regions, but in countries such as the United Kingdom and Australia both the protective earth and neutral line would be earthed together near the fuse box before the main isolating switch and the neutral earthed once again back at the distribution transformer.

There have been a number of minor changes over the year to practice of residential wiring. Some of the most significant ways modern residential power systems tend to vary from older ones include:

- For convenience, MCBs are now almost always used in the fuse box instead of fuses as these can easily be reset by occupants.
- For safety reasons, RCDs are now installed on appliance circuits and, increasingly, even on lighting circuits.
- Dwellings are typically connected to all three-phases of the distribution system with the phases being arbitrarily allocated to the house's single-phase circuits.
- Where as air conditioners of the past might have been fed from a dedicated circuit attached to a single phase, centralised air conditioners that require three-phase power are now becoming common.
- Protective earths are now run with lighting circuits to allow for metallic lamp holders to be earthed.
- Increasingly residential power systems are incorporating microgenerators, most notably, photovoltaic cells.

Commercial power systems

Commercial power systems are in many ways similar to residential systems but are often much grander in scale. One of the main consequences of this is that, unlike residential systems, electrical designs for larger commercial systems (e.g. shopping centres, office buildings, etc.) are rarely done without simulation. The key focus in simulating commercial power systems is typically to ensure the supplied voltages are within reasonable limits and the wire sizes are appropriate for the expected load however some consideration may also be given to system transients. Many larger commercial installations will also have an orderly system of sub-panels, (i.e. distribution boards separate from the main distribution board) so as to allow for better system protection and more efficient electrical installation.

One of the largest appliances connected to a commercial power system is typically the HVAC unit and ensuring this unit is adequately supplied is an important consideration in commercial power systems. There are also typically other requirements jurisdictions place on commercial systems that are not placed on residential systems: In Australia, commercial systems must comply with AS 2293, the standard for emergency lighting, which requires emergency lighting be maintained for at least 90 minutes in the event of loss of mains supply. In the United States, the National Electrical Code requires commercial systems to be built with at least one 20A sign outlet in order to light outdoor signage.

Chapter 12

Fault (Power Engineering)

In an electric power system, a **fault** is any abnormal flow of electric current. For example a short circuit is a fault in which current flow bypasses the normal load. An open circuit fault occurs if a circuit is interrupted by some failure. In three phase systems, a fault may involve one or more phases and ground, or may occur only between phases. In a "ground fault" or "earth fault", current flows into the earth. The prospective short circuit current of a fault can be calculated for power systems. In power systems, protective devices detect fault conditions and operate circuit breakers and other devices to limit the loss of service due to a failure.

In a polyphase system, a fault may affect all phases equally which is a "symmetrical fault". If only some phases are affected, the "asymmetrical fault" requires use of methods such as symmetrical components for analysis, since the simplifying assumption of equal current magnitude in all phases is no longer applicable.

Transient fault

A **transient fault** is a fault that is no longer present if power is disconnected for a short time.

Many faults in overhead powerlines are transient in nature. At the occurrence of a fault power system protection operates to isolate area of the fault. A transient fault will then clear and the powerline can be returned to service. Typical examples of transient faults include:

- momentary tree contact
- bird or other animal contact
- lightning strike
- conductor clash

In electricity transmission and distribution systems an automatic reclose function is commonly used on overhead lines to attempt to restore power in the event of a transient fault. This functionality is not as common on underground systems as faults there are typically of a persistent nature. Transient faults may still cause damage both at the site of the original fault or elsewhere in the network as fault current is generated.

Persistent fault

A **persistent fault** does not disappear when power is disconnected. Faults in underground power cables are often persistent. Underground power lines are not affected by trees or lightning, so faults, when they occur, are probably due to damage. In such cases, if the line is reconnected, it is likely to be only damaged further.

Symmetric fault

A **symmetric**, **symmetrical** or **balanced fault** affects each of the three-phases equally. In transmission line faults, roughly 5% are symmetric. This is in contrast to an asymmetric fault, where the three phases are not affected equally. In practice, most faults in power systems are unbalanced. With this in mind, symmetric faults can be viewed as somewhat of an abstraction; however, as asymmetric faults are difficult to analyze, analysis of asymmetric faults is built up from a thorough understanding of symmetric faults.

Asymetric fault

An **asymmetric** or **unbalanced fault** does not affect each of the three phases equally.

Common types of asymmetric faults, and their causes:

- *line-to-line* - a short circuit between lines, caused by ionization of air, or when lines come into physical contact, for example due to a broken insulator.
- *line-to-ground* - a short circuit between one line and ground, very often caused by physical contact, for example due to lightning or other storm damage
- *double line-to-ground* - two lines come into contact with the ground (and each other), also commonly due to storm damage

Analysis

Symmetric faults can be analyzed via the same methods as any other phenomena in power systems, and in fact many software tools exist to accomplish this type of analysis automatically. However, there is another method which is as accurate and is usually more instructive.

First, some simplifying assumptions are made. It is assumed that all electrical generators in the system are in phase, and operating at the nominal voltage of the system. Electric motors can also be considered to be generators, because when a fault occurs, they usually supply rather than draw power. The voltages and currents are then calculated for this *base case*.

Next, the location of the fault is considered to be supplied with a negative voltage source, equal to the voltage at that location in the base case, while all other sources are set to zero. This method makes use of the principle of superposition.

To obtain a more accurate result, these calculations should be performed separately for three separate time ranges:

- *subtransient* is first, and is associated with the largest currents
- *transient* comes between subtransient and steady-state
- *steady-state* occurs after all the transients have had time to settle

An asymmetric fault breaks the underlying assumptions used in three phase power, namely that the load is balanced on all three phases. Consequently, it is impossible to *directly* use tools such as the one-line diagram, where only one phase is considered. However, due to the linearity of power systems, it is usual to consider the resulting voltages and currents as a superposition of symmetrical components, to which three phase analysis can be applied.

In the method of symmetric components, the power system is seen as a superposition of three components:

- a *positive-sequence* component, in which the phases are in the same order as the original system, i.e., *a-b-c*
- a *negative-sequence* component, in which the phases are in the opposite order as the original system, i.e., *a-c-b*
- a *zero-sequence* component, which is not truly a three phase system, but instead all three phases are in phase with each other.

To determine the currents resulting from an asymmetrical fault, one must first know the per-unit zero-, positive-, and negative-sequence impedances of the transmission lines, generators, and transformers involved. Three separate circuits are then constructed using these impedances. The individual circuits are then connected together in a particular arrangement that depends upon the type of fault being studied (this can be found in most power systems textbooks). Once the sequence circuits are properly connected, the network can then be analyzed using classical circuit analysis techniques. The solution results in voltages and currents that exist as symmetrical components; these must be transformed back into phase values by using the **A** matrix.

Analysis of the prospective short-circuit current is required for selection of protective devices such as fuses and circuit breakers. If a circuit is to be properly protected, the fault current must be high enough to operate the protective device within as short a time as possible; also the protective device must be able to withstand the fault current and extinguish any resulting arcs without itself being destroyed or sustaining the arc for any significant length of time.

The magnitude of fault currents differ widely depending on the type of earthing system used, the installation's supply type and earthing system, and its proximity to the supply. For example, for a domestic UK 230 V, 60 A TN-S or USA 120 V/240 V supply, fault currents may be a few thousand amperes. Large low-voltage networks with multiple sources may have fault levels of 300,000 amperes. A high-resistance-grounded system may restrict line to ground fault current to only 5 amperes. Prior to selecting protective devices, prospective fault current must be measured reliably at the origin of the installation and at the furthest point of each circuit, and this information applied properly to the application of the circuits.

Detecting and locating faults

Locating faults in a cable system can be done either with the circuit de-energized, or in some cases, with the circuit under power. Fault location techniques can be broadly divided into terminal methods, which use voltages and currents measured at the ends of the cable, and tracer methods, which require inspection along the length of the cable. Terminal methods can be used to locate the general area of the fault, to expedite tracing on a long or buried cable.

In very simple wiring systems, the fault location is often found through visual inspection of the wires. In complex wiring systems (e.g. aircraft wiring) where the electrical wires may be hidden behind cabinets and extended for miles, wiring faults are located with a Time-domain reflectometer. The time domain reflectometer sends a pulse down the wire and then analyzes the returning reflected pulse to identify faults within the electrical wire.

In historic submarine telegraph cables, sensitive galvanometers were used to measure fault currents; by testing at both ends of a faulted cable, the fault location could be isolated to within a few miles, which allowed the cable to be grappled up and repaired. The *Murray loop* and the *Varley loop* were two types of connections for locating faults in cables

Sometimes an insulation fault in a power cable will not show up at lower voltages. A "thumper" test set applies a high-energy, high-voltage pulse to the cable. Fault location is done by listening for the sound of the discharge at the fault. While this test contributes to damage at the cable site, it is practical because the faulted location would have to be re-insulated when found in any case.

In a high resistance grounded distribution system, a feeder may develop a fault to ground but the system continues in operation. The faulted, but energized, feeder can be found with a ring-type current transformer collecting all the phase wires of the circuit; only the circuit containing a fault to ground will show a net unbalanced current. To make the ground fault current easier to detect, the grounding resistor of the system may be switched between two values so that the fault current pulses.

Batteries

The prospective fault current of larger batteries, such as deep-cycle batteries used in stand-alone power systems, is often given by the manufacturer.

In Australia, when this information is not given, the prospective fault current in amperes "should be considered to be 6 times the nominal battery capacity at the C_{120} A·h rate," according to AS 4086 part 2 (Appendix H).

Chapter 13

Thermal Depolymerization

Thermal depolymerization (TDP) is a depolymerization process using hydrous pyrolysis for the reduction of complex organic materials (usually waste products of various sorts, often biomass and plastic) into light crude oil. It mimics the natural geological processes thought to be involved in the production of fossil fuels. Under pressure and heat, long chain polymers of hydrogen, oxygen, and carbon decompose into short-chain petroleum hydrocarbons with a maximum length of around 18 carbons.

Similar Processes

Thermal depolymerisation is similar to other processes which use superheated water as a major step to produce fuels, such as direct Hydrothermal Liquefaction . These are distinct from processes using dry materials to depolymerize, such as pyrolysis. The term Thermochemical Conversion (TCC) has also been used for conversion of biomass to oils using superheated water, although it is more usually applied to fuel production via pyrolysis. Other commercial scale processes include the "SlurryCarb" process operated by EnerTech, which uses similar technology to decarboxylate wet solid biowaste, which can then be physically dewatered and used as a solid fuel called E-Fuel. The plant at Rialto is said to be able to process 683 tons of waste per day. The Hydro Thermal Upgrading (HTU) process uses superheated water to produce oil from domestic waste. A demonstration plant is due to start up in The Netherlands said to be capable of processing 64 tons of biomass (dry basis) per day into oil. Thermal depolymerisation differs in that it contains a hydrous process followed by an anhydrous cracking / distillation process.

History

Thermal depolymerization is similar to the geological processes that produced the fossil fuels used today, except that the technological process occurs in a timeframe measured in hours. Until recently, the human-designed processes were not efficient enough to serve as a practical source of fuel—more energy was required than was produced.

In U. S. patent 2,177,557, issued in 1939, Bergstrom and Cederquist discuss a method for obtaining oil from wood in which the wood is heated under pressure in water with a significant amount of calcium hydroxide added to the mixture. In the early 1970s Herbert R. Appell and coworkers worked with hydrous pyrolysis methods, as exemplified by U. S. patent 3,733,255 (issued in 1973), which discusses the production of oil from sewer sludge and municipal refuse by heating the material in water, under pressure, and in the presence of carbon monoxide.

An approach that exceeded break-even was developed by Illinois microbiologist Paul Baskis in the 1980s and refined over the next 15 years. The technology was finally developed for commercial use in 1996 by Changing World Technologies (CWT). Brian S. Appel (CEO of CWT) took the technology in 2001 and expanded and changed it into what is now referred to as TCP (Thermal Conversion Process), and has applied for several patents (see, for example, published patent application US 2004/0192980). A Thermal Depolymerization demonstration plant was completed in 1999 in Philadelphia by Thermal Depolymerization, LLC, and the first full-scale commercial plant was constructed in Carthage, Missouri, about 100 yards (91m) from ConAgra Foods' massive Butterball turkey plant, where it is expected to process about 200 tons of turkey waste into 500 barrels (21,000 US gallons or 80 m^3) of oil per day.

Theory and process

In the method used by CWT, the water improves the heating process and contributes hydrogen to the reactions.

In the Changing World Technologies (CWT) process, the feedstock material is first ground into small chunks, and mixed with water if it is especially dry. It is then fed into a pressure vessel reaction chamber where it is heated at constant volume to around 250 °C. Similar to a pressure cooker (except at much higher pressure), steam naturally raises the pressure to 600 psi (4 MPa) (near the point of saturated water). These conditions are held for approximately 15 minutes to fully heat the mixture, after which the pressure is rapidly released to boil off most of the water (see: Flash evaporation). The result is a mix of crude hydrocarbons and solid minerals. The minerals are removed, and the hydrocarbons are sent to a second-stage reactor where they are heated to 500 °C, further breaking down the longer hydrocarbon chains. The hydrocarbons are then sorted by fractional distillation, in a process similar to conventional oil refining.

The CWT company claims that 15 to 20% of feedstock energy is used to provide energy for the plant. The remaining energy is available in the converted product. Working with turkey offal as the feedstock, the process proved to have yield efficiencies of approximately 85%; in other words, the energy contained in the end products of the process is 85% of the energy contained in the inputs to the process (most notably the energy content of the feedstock, but also including electricity for pumps and natural gas or woodgas for heating). If one considers the energy content of the feedstock to be free (i.e., waste material from some other process), then 85 units of energy are made available for every 15 units of energy consumed in process heat and electricity. This means the "Energy Returned on Energy Invested" (EROEI) is (6.67), which is comparable to other energy harvesting processes. Higher efficiencies may be possible with drier and more carbon-rich feedstocks, such as waste plastic.

By comparison, the current processes used to produce ethanol and biodiesel from agricultural sources have EROEI in the 4.2 range, when the energy used to produce the feedstocks is accounted for (in this case, usually sugar cane, corn, soybeans and the like). These EROEI values are not directly comparable, because these EROEI calculations include the energy cost to produce the feedstock, whereas the above EROEI calculation for thermal depolymerization process (TDP) does not.

The process breaks down almost all materials that are fed into it. TDP even efficiently breaks down many types of hazardous materials, such as poisons and difficult-to-destroy biological agents such as prions.

Feedstocks and outputs with thermal depolymerization

Average TDP Feedstock Outputs

Feedstock	**Oils**	**Gases**	**Solids (mostly carbon based)**	**Water (Steam)**
Plastic bottles	70%	16%	6%	8%
Medical waste	65%	10%	5%	20%
Tires	44%	10%	42%	4%
Turkey offal	39%	6%	5%	50%
Sewage sludge	26%	9%	8%	57%
Paper (cellulose)	8%	48%	24%	20%

(Note: Paper/cellulose contains at least 1% minerals, which was probably grouped under carbon solids.)

Carthage plant products

As reported on 04/02/2006 by Discover Magazine, the Carthage plant was producing 500 barrels per day (79 m^3/d) of oil made from 270 tons of turkey entrails and 20 tons of hog lard. This represents an oil yield of 22.3 percent. The Carthage, Missouri plant produces API 40+, a high value crude oil. It contains light and heavy naphthas, a kerosene, and a gas oil fraction, with essentially no heavy fuel oils, tars, asphaltenes or waxes. It can be further refined to produce No. 2 and No. 4 fuel oils.

TDP-40 Oil Classification by D-5443 PONA method

Output Material	% by Weight
Paraffins	22%
Olefins	14%
Naphthenes	3%
Aromatics	6%
C14/C14+	55%
	100%

The fixed carbon solids produced by the TDP process have multiple uses as a filter, a fuel source and a fertilizer. It can be used as activated carbon in wastewater treatment, as a fertilizer, or as a fuel similar to coal.

Advantages

The process can break down organic poisons, due to breaking chemical bonds and destroying the molecular shape needed for the poison's activity. It is likely to be highly effective at killing pathogens, including prions. It can also safely remove heavy metals from the samples by converting them from their ionized or organometallic forms to their stable oxides which can be safely separated from the other products.

Along with similar processes, it is a method of recycling the energy content of organic materials without first removing the water. It can produce liquid fuel, which separates from the water physically without need for drying. Other methods to recover energy often require pre-drying (e.g. burning, pyrolysis) or produce gaseous products (e.g. anaerobic digestion).

Potential sources of waste inputs

The United States Environmental Protection Agency estimates that in 2006 there were 251 million tons of municipal solid waste, or 4.6 pounds generated per day per person in the USA. Much of this mass is considered unsuitable for oil conversion.

Limitations

The process only breaks long molecular chains into shorter ones, so small molecules such as carbon dioxide or methane cannot be converted to oil through this process. However, the methane in the feedstock is recovered and burned to heat the water that is an essential part of the process. In addition, the gas can be burned in a combined heat and power plant, consisting of a gas turbine which drives a generator to create electricity, and a heat exchanger to heat the process input water from the exhaust gas. The electricity can be sold to the power grid, for example under a Feed-in Tariff scheme. This also increases the overall efficiency of the process (already said to be over 85% of feedstock energy content).

Another option is to sell the methane product as biogas. For example, biogas can be compressed, much like natural gas, and used to power motor vehicles.

Many agricultural and animal wastes could be processed, but many of these are already used as fertilizer, animal feed, and, in some cases, as feedstocks for paper mills or as boiler fuel. Energy crops constitute another potentially large feedstock for thermal depolymerization.

Current status

Reports in 2004 claimed that the facility was selling products at 10% below the price of equivalent oil, but its production costs were low enough that the plant produced a profit. At the time it was paying for turkey waste.

The plant then consumed 270 tons of turkey offal (the full output of the turkey processing plant) and 20 tons of egg production waste daily. In February 2005, the Carthage plant was producing about 400 barrels per day (64 m^3/d) of crude oil.

In April 2005 the plant was reported to be running at a loss. Further 2005 reports summarized some economic setbacks which the Carthage plant encountered since its planning stages. It was thought that concern over mad cow disease would prevent the use of turkey waste and other animal products as cattle feed, and thus this waste would be free. As it turned out, turkey waste may still be used as feed in the United States, so that the facility must purchase that feed stock at a cost of $30 to $40 per ton, adding $15 to $20 per barrel to the cost of the oil. Final cost, as of January 2005, was $80/barrel ($1.90/gal).

The above cost of production also excludes the operating cost of the thermal oxidizer and scrubber added in May 2005 in response to odor complaints (see below).

A biofuel tax credit of roughly $1 per US gallon (26 ¢/L) on production costs was not available because the oil produced did not meet the definition of "biodiesel" according to the relevant American tax legislation. The Energy Policy Act of 2005 specifically added thermal depolymerization to a $1 renewable diesel credit, which became effective at the end of 2005, allowing a profit of $4/barrel of output oil.

Company expansion

The company has explored expansion in California, Pennsylvania, and Virginia, and is presently examining projects in Europe, where animal products cannot be used as cattle feed. TDP is also being considered as an alternative means for sewage treatment in the United States.

Smell complaints

The pilot plant in Carthage was temporarily shut down due to smell complaints. It was soon restarted when it was discovered that few of the odors were generated by the plant. Furthermore, the plant agreed to install an enhanced thermal oxidizer and to upgrade its air scrubber system under a court order. Since the plant is located only four blocks from the tourist-attracting town center, this has strained relations with the mayor and citizens of Carthage.

According to a company spokeswoman, the plant has received complaints even on days when it is not operating. She also contended that the odors may not have been produced by their facility, which is located near several other agricultural processing plants.

On December 29, 2005, the plant was ordered by the state governor to shut down once again over allegations of foul odors as reported by MSNBC.

As of March 7, 2006, the plant has begun limited test runs to validate it has resolved the odor issue.

As of August 24, 2006, the last lawsuit connected with the odor issue has been dismissed and the problem is acknowledged as fixed. In late November, however, another complaint was filed over bad smells. This complaint was closed on January 11 of 2007 with no fines assessed.

Status as of February 2009

A May 2003 article in Discover magazine stated, "Appel has lined up federal grant money to help build demonstration plants to process chicken offal and manure in Alabama and crop residuals and grease in Nevada. Also in the works are plants to process turkey waste and manure in Colorado and pork and cheese waste in Italy. He says the first generation of depolymerization centers will be up and running in 2005. By then it should be clear whether the technology is as miraculous as its backers claim."

However, as of August 2008, the only operational plant listed at the company's website is the initial one in Carthage, Missouri.

Changing World Technology applied for an IPO on August 12; 2008, hoping to raise $100 million.

The unusual Dutch Auction type IPO failed possibly because CWT has lost nearly $20 million with very little revenue.

CWT, the parent company of Renewable Energy Solutions, filed for Chapter 11 bankruptcy. No details on plans for the Carthage plant have been released.

Similar technologies

- Plasma Converters use powerful electric arcs to reduce and extract energy from waste.