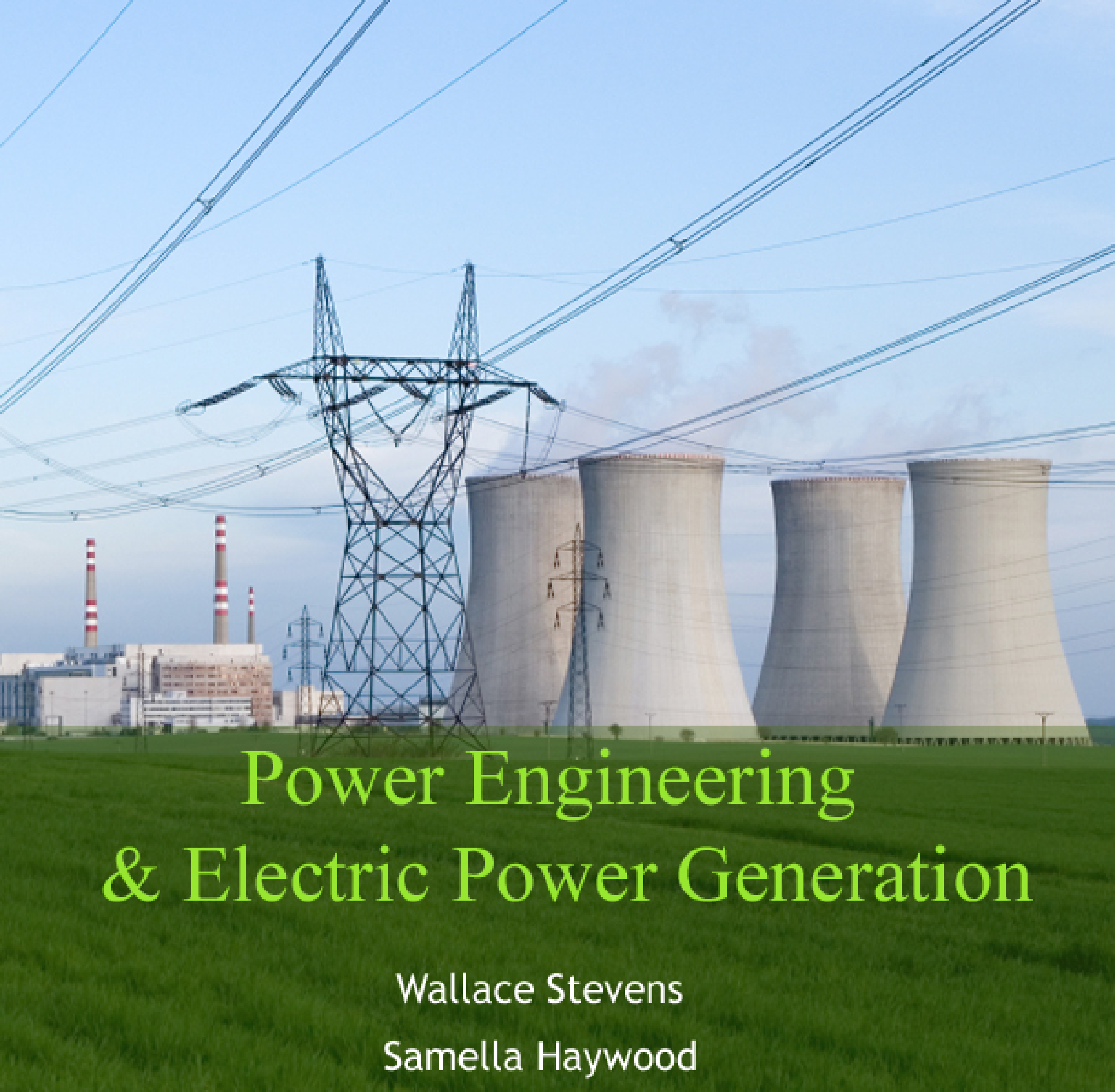

Power Engineering & Electric Power Generation

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Chapter 1

Introduction to 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.

Chapter 2

Electric Power Distribution

Electricity distribution is the final stage in the delivery (before retail) of electricity to end users. A distribution system's network carries electricity from the transmission system and delivers it to consumers. Typically, the network would include medium-voltage (less than 50 kV) power lines, electrical substations and pole-mounted transformers, low-voltage (less than 1 kV) distribution wiring and sometimes electricity meters.

Modern distribution systems

Electric distribution substations transform power from transmission voltage to the lower voltage used for local distribution to homes and businesses

The modern distribution system begins as the primary circuit leaves the sub-station and ends as the secondary service enters the customer's meter socket. A variety of methods, materials, and equipment are used among the various utility companies, but the end result is similar. First, the energy leaves the sub-station in a primary circuit, usually with all three phases.

The actual attachment to a building varies in different parts of the world.

Most areas provide three phase industrial service. There is no substitute for three-phase service to run heavy industrial equipment. A ground is normally provided, connected to conductive cases and other safety equipment, to keep current away from equipment and people. Distribution voltages vary depending on customer need, equipment and availability. Delivered voltage is usually constructed using stock transformers, and either the voltage difference between phase and neutral or the voltage difference from phase to phase.

In many areas, "delta" three phase service is common. Delta service has no distributed neutral wire and is therefore less expensive. The three coils in the generator rotor are in series, in a loop, with the connections made at the three joints between the coils. Ground is provided as a low resistance earth ground, sometimes attached to a synthetic ground made by a transformer in a substation. High frequency noise (like that made by arc furnaces) can sometimes cause transients on a synthetic ground.

In North America and Latin America, three phase service is often a *Y* (*wye*) in which the neutral is directly connected to the center of the generator rotor. Wye service resists transients better than delta, since the distributed neutral provides a low-resistance metallic return to the generator. Wye service is recognizable when a grid has four wires, one of which is lightly insulated.

Many areas in the world use single phase 220 V or 230 V residential and light industrial service. In this system, a high voltage distribution network supplies a few substations per city, and the 230V power from each substation is directly distributed. A hot wire and neutral are connected to the building from one phase of three phase service.

In the U.S. and parts of Canada and Latin America, split phase service is the most common. Split phase provides both 120 V and 240 V service with only three wires. Split phase has substations that provide intermediate voltage. The house voltages are provided by neighborhood transformers that lower the voltage of a phase of the distributed three-phase. The neutral is directly connected to the three-phase neutral. Socket voltages are only 120 V, but 240 V is available for heavy appliances because the two two halves of a phase oppose each other.

Japan has a large number of small industrial manufacturers, and therefore supplies standard low voltage three phase service in many suburbs. Also, Japan normally supplies residential service as two phases of a three phase service, with a neutral.

Rural services normally try to minimize the number of poles and wires. Single-wire earth return (SWER) is the least expensive, with one wire. It uses high voltages, which in turn permit use of galvanized steel wire. The strong steel wire permits inexpensive wide pole spacings. Other areas use high voltage split-phase or three phase service at higher cost.

The least expensive network has the fewest transformers, poles and wires. Some experts say that this is three-phase delta for industrial, SWER for rural service, and 230 V single phase for residential and light industrial. The system of three-phase Wye feeding split phase is flexible and somewhat more resistant to geomagnetic faults, but more expensive.

Two frequencies are in wide use. Using 60 Hz permits slightly smaller transformers and is usually associated with 120 V wall sockets. Outside North America 50 Hz is more common and is associated with 230 V wall sockets. Large electrical networks tightly control the line frequencies. The short term accuracy is normally better than 0.1 Hz. The long term accuracy is controlled by making up "lost" cycles so that electric clocks maintain correct time.

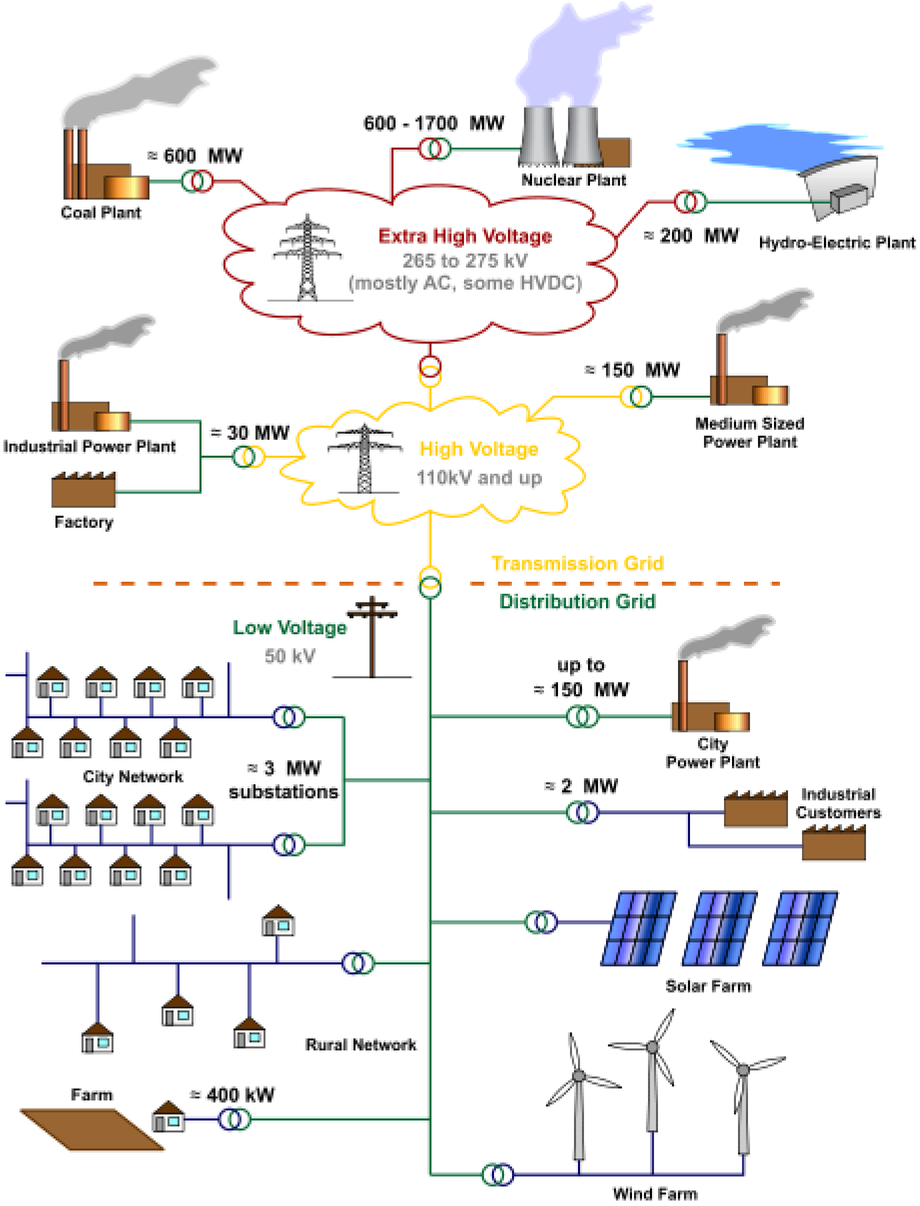
Electricity meters use different equations for each distribution system.

History

In the early days of electricity distribution, direct current (DC) generators were connected to loads at the same voltage. The generation, transmission and loads had to be of the same voltage because there was no way of changing DC voltage levels, other than inefficient motor-generator sets. Low DC voltages were used (on the order of 100 volts) since that was a practical voltage for incandescent lamps, which were the primary electrical load. Low voltage also required less insulation for safe distribution within buildings.

The losses in a cable are proportional to the square of the current, the length of the cable, and the resistivity of the material, and are inversely proportional to cross-sectional area. Early transmission networks used copper, which is one of the best economically feasible conductors for this application. To reduce the current and copper required for a given quantity of power transmitted would require a higher transmission voltage, but no efficient method existed to change the voltage of DC power circuits. To keep losses to an economically practical level the Edison DC system needed thick cables and local generators. Early DC generating plants needed to be within about 1.5 miles (2.4 km) of the farthest customer to avoid excessively large and expensive conductors.

Introduction of alternating current



General layout of electricity networks

The adoption of alternating current (AC) for electricity generation following the War of Currents dramatically changed the situation. Power transformers, installed at power stations, could be used to raise the voltage from the generators, and transformers at local substations could reduce voltage to supply loads. Increasing the voltage reduced the current in the transmission and distribution lines and hence the size of conductors and distribution losses. This made it more economical to distribute power over long distances. Generators (such as hydroelectric sites) could be located far from the loads.

In North America, early distribution systems used a voltage of 2.2 kV corner-grounded delta. Over time, this was gradually increased to 2.4 kV. As cities grew, most 2.4 kV systems were upgraded to 2.4/4.16 kV, three-phase systems. In three phase networks that permit connections between phase and neutral, both the phase-to-phase voltage (4160, in this example) and the phase-to-neutral voltage are given; if only one value is shown, the network does not serve single-phase loads connected phase-to-neutral. Some city and suburban distribution systems continue to use this range of voltages, but most have been converted to 7200/12470Y, 7620/13200Y, 14400/24940Y, and 19920/34500Y.

European systems used 3.3 kV to ground, in support of the 220/380Y volt power systems used in those countries. In the UK, urban systems progressed to 6.6 kV and then 11 kV (phase to phase), the most common distribution voltage.

North American and European power distribution systems also differ in that North American systems tend to have a greater number of low-voltage, step-down transformers located close to customers' premises. For example, in the US a pole-mounted transformer in a suburban setting may supply 1-3 houses, whereas in the UK a typical urban or suburban low-voltage substation would normally be rated between 315 kVA and 1 MVA and supply a whole neighbourhood. This is because the higher voltage used in Europe (415 V vs 230 V) may be carried over a greater distance with acceptable power loss. An advantage of the North American setup is that failure or maintenance on a single transformer will only affect a few customers. Advantages of the UK setup are that the transformers may be fewer, larger and more efficient, and due to diversity there need be less spare capacity in the transformers, reducing power wastage. In North American city areas with many customers per unit area, network distribution will be used, with multiple transformers and low-voltage buses interconnected over several city blocks.

Rural Electrification systems, in contrast to urban systems, tend to use higher voltages because of the longer distances covered by those distribution lines. 7.2, 12.47, 25, and 34.5 kV distribution is common in the United States; 11 kV and 33 kV are common in the UK, New Zealand and Australia; 11 kV and 22 kV are common in South Africa. Other voltages are occasionally used.

In New Zealand, Australia, Saskatchewan, Canada, and South Africa, single wire earth return systems (SWER) are used to electrify remote rural areas.

While power electronics now allow for conversion between DC voltage levels, AC is still used in distribution due to the economy, efficiency and reliability of transformers. High-voltage DC is used for transmission of large blocks of power over long distances, or for interconnecting adjacent AC networks, but not for distribution to customers.

Distribution network configurations

Substation near Yellowknife, in the Northwest Territories of Canada

Distribution networks are typically of two types, radial or interconnected. A radial network leaves the station and passes through the network area with no normal connection to any other supply. This is typical of long rural lines with isolated load areas. An interconnected network is generally found in more urban areas and will have multiple connections to other points of supply. These points of connection are normally open but allow various configurations by the operating utility by closing and opening switches. Operation of these switches may be by remote control from a control centre or by a lineman. The benefit of the interconnected model is that in the event of a fault or required maintenance a small area of network can be isolated and the remainder kept on supply.

Within these networks there may be a mix of overhead line construction utilizing traditional utility poles and wires and, increasingly, underground construction with cables and indoor or cabinet substations. However, underground distribution is significantly more expensive than overhead construction. In part to reduce this cost, underground power lines are sometimes co-located with other utility lines in what are called Common utility ducts. Distribution feeders emanating from a substation are generally controlled by a circuit breaker which will open when a fault is detected. Automatic Circuit Reclosers may be installed to further segregate the feeder thus minimizing the impact of faults.

Long feeders experience voltage drop requiring capacitors or voltage regulators to be installed.

Characteristics of the supply given to customers are generally mandated by contract between the supplier and customer. Variables of the supply include:

- AC or DC - Virtually all public electricity supplies are AC today. Users of large amounts of DC power such as some electric railways, telephone exchanges and industrial processes such as aluminium smelting usually either operate their own or have adjacent dedicated generating equipment, or use rectifiers to derive DC from the public AC supply
- Voltage, including tolerance (usually +10 or -15 percentage)
- Frequency, commonly 50 & 60 Hz, 16.6 Hz for some railways and, in a few older industrial and mining locations, 25 Hz.
- Phase configuration (single phase, polyphase including two phase and three phase)
- Maximum demand (usually measured as the largest amount of power delivered within a 15 or 30 minute period during a billing period)
- Load Factor, expressed as a ratio of average load to peak load over a period of time. Load factor indicates the degree of effective utilization of equipment (and capital investment) of distribution line or system.
- Power factor of connected load
- Earthing arrangements - TT, TN-S, TN-C-S or TN-C
- Prospective short circuit current
- Maximum level and frequency of occurrence of transients

Distribution industry

Traditionally the electricity industry has been a publicly owned institution but starting in the 1970s nations began the process of deregulation and privatisation, leading to electricity markets. A major focus of these was the elimination of the former so called *natural monopoly* of generation, transmission, and distribution. As a consequence, electricity has become more of a commodity. The separation has also led to the development of new terminology to describe the business units (e.g., line company, wires business and network company).

Chapter 3

Electric Power Transmission

400 kV high-tension transmission lines near Madrid

Electric power transmission or "high voltage electric transmission" is the bulk transfer of electrical energy, from generating power plants to substations located near to population centers. This is distinct from the local wiring between high voltage substations and customers, which is typically referred to as electricity distribution. Transmission lines, when interconnected with each other, become high voltage transmission networks. In the US, these are typically referred to as "power grids" or sometimes simply as "the grid", while in the UK the network is known as the "national grid." North America has three major grids: The Western Interconnection; The Eastern Interconnection and the Electric Reliability Council of Texas (or ERCOT) grid.

Historically, transmission and distribution lines were owned by the same company, but over the last decade or so many countries have introduced market reforms that have led to the separation of the electricity transmission business from the distribution business.

Transmission lines mostly use three phase alternating current (AC), although single phase AC is sometimes used in railway electrification systems. High-voltage direct current (HVDC) technology is used only for very long distances (typically greater than 400 miles, or 600 km); submarine power cables (typically longer than 30 miles, or 50 km); or for connecting two AC networks that are not synchronized.

Electricity is transmitted at high voltages (110 kV or above) to reduce the energy lost in long distance transmission. Power is usually transmitted through overhead power lines. Underground power transmission has a significantly higher cost and greater operational limitations but is sometimes used in urban areas or sensitive locations.

A key limitation in the distribution of electricity is that, with minor exceptions, electrical energy cannot be stored, and therefore it must be generated as it is needed. A sophisticated system of control is therefore required to ensure electric generation very closely matches the demand. If supply and demand are not in balance, generation plants and transmission equipment can shut down which, in the worst cases, can lead to a major regional blackout, such as occurred in California and the US Northwest in 1996 and in the US Northeast in 1965, 1977 and 2003. To reduce the risk of such failures, electric transmission networks are interconnected into regional, national or continental wide networks thereby providing multiple redundant alternate routes for power to flow should (weather or equipment) failures occur. Much analysis is done by transmission companies to determine the maximum reliable capacity of each line which is mostly less than its physical or thermal limit, to ensure spare capacity is available should there be any such failure in another part of the network.

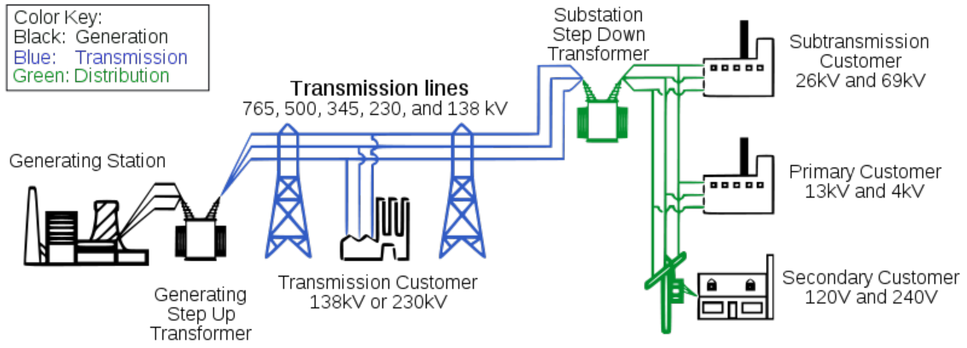
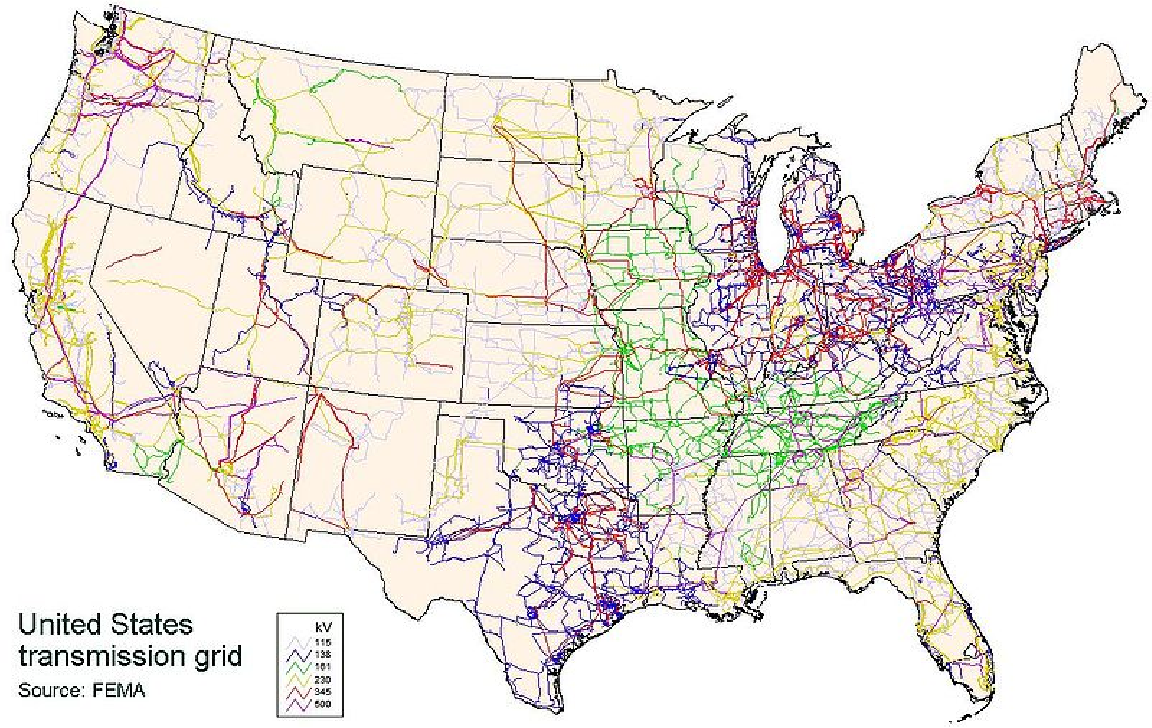


Diagram of an electrical system.

Overhead transmission

High-voltage overhead conductors are not covered by insulation. The conductor material is nearly always an aluminium alloy, made into several strands and possibly reinforced with steel strands. Copper was sometimes used for overhead transmission but aluminium is lower in weight for equivalent performance, and much lower in cost. Overhead conductors are a commodity supplied by several companies worldwide. Improved conductor material and shapes are regularly used to allow increased capacity and modernize transmission circuits. Conductor sizes range from 12 mm^2 (#6 American wire gauge) to 750 mm^2 (1,590,000 circular mils area), with varying resistance and current-carrying capacity. Thicker wires would lead to a relatively small increase in capacity due to the skin effect, that causes most of the current to flow close to the surface of the wire.



Contiguous United States power transmission grid consists of 300,000 km of lines operated by 500 companies.

Today, transmission-level voltages are usually considered to be 110 kV and above. Lower voltages such as 66 kV and 33 kV are usually considered sub-transmission voltages but are occasionally used on long lines with light loads. Voltages less than 33 kV are usually used for distribution. Voltages above 230 kV are considered extra high voltage and require different designs compared to equipment used at lower voltages.

Since overhead transmission lines are uninsulated, design of these lines requires minimum clearances to be observed to maintain safety. Adverse weather conditions of high wind and low temperatures can lead to power outages: wind speeds as low as 23 knots (43 km/h) can permit conductors to encroach operating clearances, resulting in a flashover and loss of supply. Oscillatory motion of the physical line can be termed gallop or flutter depending on the frequency and amplitude of oscillation.

Underground transmission

Electric power can also be transmitted by underground power cables instead of overhead power lines. They can assist the transmission of power across:

- Densely populated urban areas
- Areas where land is unavailable or planning consent is difficult
- Rivers and other natural obstacles
- Land with outstanding natural or environmental heritage
- Areas of significant or prestigious infrastructural development
- Land whose value must be maintained for future urban expansion and rural development

Some other advantages of underground power cables:

- Less subject to damage from severe weather conditions (mainly lightning, wind and freezing)
- Greatly reduced emission, into the surrounding area, of electromagnetic fields (EMF). All electric currents generate EMF, but the shielding provided by the earth surrounding underground cables restricts their range and power.
- Underground cables need a narrower surrounding strip of about 1–10 meters to install, whereas an overhead line requires a surrounding strip of about 20–200 meters wide to be kept permanently clear for safety, maintenance and repair.
- Underground cables pose no hazard to low flying aircraft or to wildlife, and are significantly safer as they pose no shock hazard (except to the unwary digger).
- Much less subject to conductor theft, illegal connections, sabotage, and damage from armed conflict.

Some disadvantages of underground power cables:

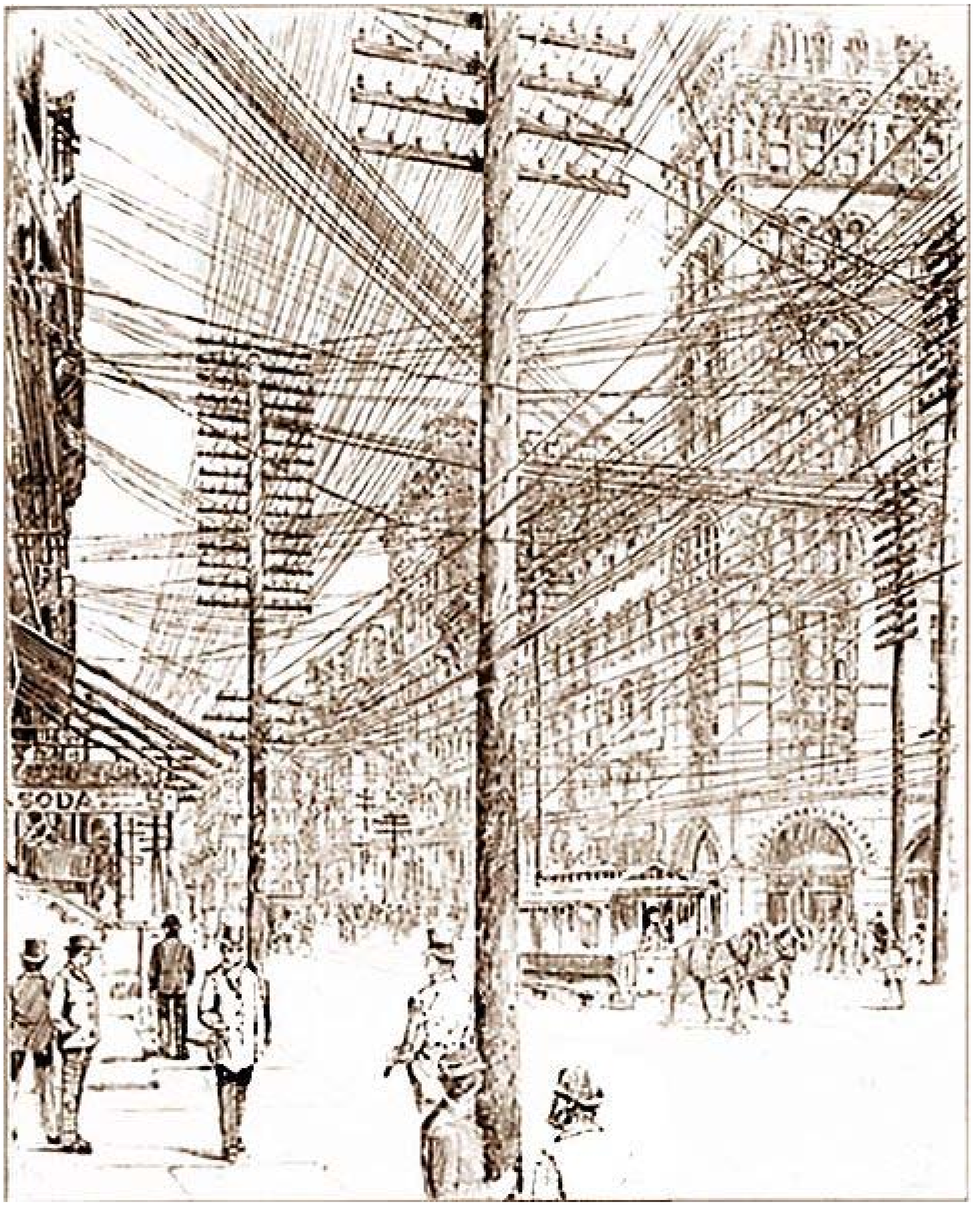
- Undergrounding is more expensive, since the cost of burying cables at transmission voltages is several times greater than overhead power lines, and the life-cycle cost of an underground power cable is two to four times the cost of an overhead power line. Above ground lines cost around $10 per foot and underground lines cost in the range of $20 to $40 per foot.
- Whereas finding and repairing overhead wire breaks can be accomplished in hours, underground repairs can take days or weeks, and for this reason redundant lines are run.

- Underground power cables, due to their proximity to earth, cannot be maintained live, whereas overhead power cables can be.
- Operations are more difficult since the high reactive power of underground cables produces large charging currents and so makes voltage control more difficult.

The advantages can in some cases outweigh the disadvantages of the higher investment cost, and more expensive maintenance and management.

Most high voltage cables for power transmission that are currently sold on the market are insulated by a sheath of cross-linked polyethylene (XLPE). Some cables may have a lead or aluminium jacket in conjunction with XLPE insulation to allow for fiber optics to be seamlessly integrated within the cable. Before 1960, underground power cables were insulated with oil and paper and ran in a rigid steel pipe, or a semi-rigid aluminium or lead jacket or sheath. The oil was kept under pressure to prevent formation of voids that would allow partial discharges within the cable insulation. There are still many of these oil-and-paper insulated cables in use worldwide. Between 1960 and 1990, polymers became more widely used at distribution voltages, mostly EPDM (ethylene propylene diene M-class); however, their relative unreliability, particularly early XLPE, resulted in a slow uptake at transmission voltages. While cables of 330 kV are commonly constructed using XLPE, this has occurred only in recent decades.

History

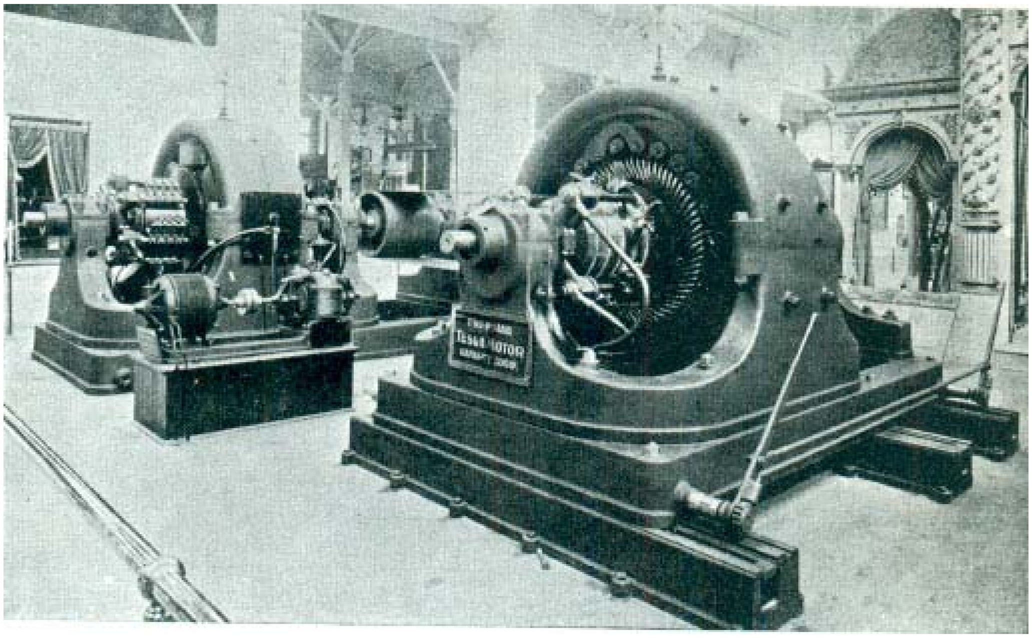


New York City streets in 1890. Besides telegraph lines, multiple electric lines were required for each class of device requiring different voltages.

In the early days of commercial electric power, transmission of electric power at the same voltage as used by lighting and mechanical loads restricted the distance between generating plant and consumers. In 1882, generation was with direct current, which could not easily be increased in voltage for long-distance transmission. Different classes of loads (for example, lighting, fixed motors, and traction/railway systems) required different voltages, and so used different generators and circuits.

Due to this specialization of lines and because transmission was so inefficient that generators needed to be near their loads, it seemed at the time that the industry would develop into what is now known as a distributed generation system with large numbers of small generators located nearby their loads.

In 1886 in Great Barrington, Massachusetts, a 1 kV AC distribution system was installed. That same year, AC power at 2 kV, transmitted 30 km, was installed at Cerchi, Italy. At an AIEE meeting on May 16, 1888, Nikola Tesla delivered a lecture entitled *A New System of Alternating Current Motors and Transformers*, describing the equipment which allowed efficient generation and use of polyphase alternating currents. The transformer, and Tesla's polyphase and single-phase induction motors, were essential for a combined AC distribution system for both lighting and machinery. Ownership of the rights to the Tesla patents was a key advantage to the Westinghouse Company in offering a complete alternating current power system for both lighting and power.



Nikola Tesla's Alternating current polyphase generators on display at the 1893 World's Fair in Chicago. Tesla's polyphase innovations revolutionized transmission.

Regarded as one of the most influential electrical innovations, the *universal system* used transformers to step-up voltage from generators to high-voltage transmission lines, and then to step-down voltage to local distribution circuits or industrial customers. By a suitable choice of utility frequency, both lighting and motor loads could be served. Rotary converters and later mercury-arc valves and other rectifier equipment allowed DC to be provided where needed. Generating stations and loads using different frequencies could be interconnected using rotary converters. By using common generating plants for every type of load, important economies of scale were achieved, lower overall capital investment was required, load factor on each plant was increased allowing for higher efficiency, a lower cost for the consumer and increased overall use of electric power.

By allowing multiple generating plants to be interconnected over a wide area, electricity production cost was reduced. The most efficient available plants could be used to supply the varying loads during the day. Reliability was improved and capital investment cost was reduced, since stand-by generating capacity could be shared over many more customers and a wider geographic area. Remote and low-cost sources of energy, such as hydroelectric power or mine-mouth coal, could be exploited to lower energy production cost.

The first transmission of three-phase alternating current using high voltage took place in 1891 during the international electricity exhibition in Frankfurt. A 25 kV transmission line, approximately 175 km long, connected Lauffen on the Neckar and Frankfurt.

Voltages used for electric power transmission increased throughout the 20th century. By 1914, fifty-five transmission systems each operating at more than 70 kV were in service. The highest voltage then used was 150 kV.

The rapid industrialization in the 20th century made electrical transmission lines and grids a critical part of the infrastructure in most industrialized nations. Interconnection of local generation plants and small distribution networks was greatly spurred by the requirements of World War I, where large electrical generating plants were built by governments to provide power to munitions factories. Later these plants were connected to supply civil loads through long-distance transmission.

Bulk power transmission

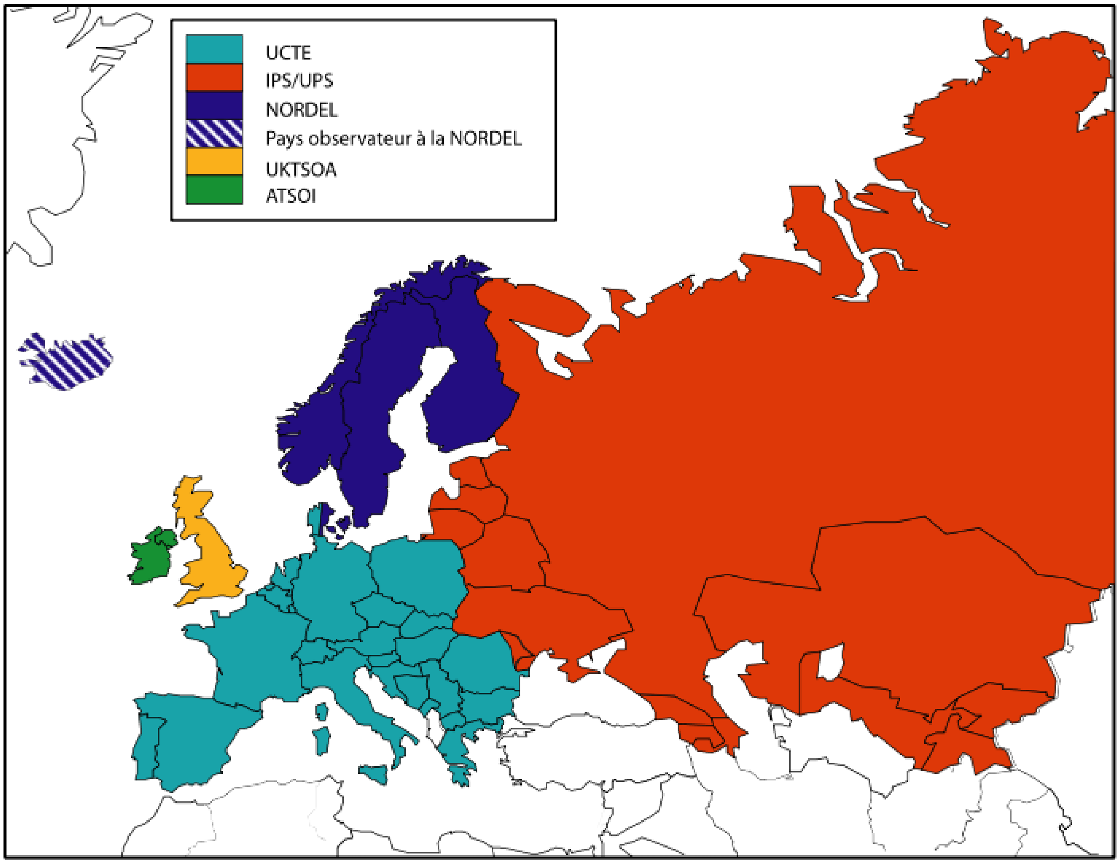
A transmission substation decreases the voltage of incoming electricity, allowing it to connect from long distance high voltage transmission, to local lower voltage distribution. It also reroutes power to other transmission lines that serve local markets. A transmission substation may include phase-shifting or voltage regulating transformers. This is the PacifiCorp Hale Substation, Orem, Utah, USA.

Engineers design transmission networks to transport the energy as efficiently as feasible, while at the same time taking into account economic factors, network safety and redundancy. These networks use components such as power lines, cables, circuit breakers, switches and transformers. The transmission network is usually administered on a regional basis by an entity such as a regional transmission organization or transmission system operator.

Transmission efficiency is hugely improved by devices that increase the voltage, and proportionately reduce the current in the conductors, thus keeping the power transmitted nearly equal to the power input. The reduced current flowing through the line reduces the losses in the conductors. According to Joule's Law, energy losses are directly proportional to the square of the current. Thus, reducing the current (amperage) by a factor of 2 will lower the energy lost to conductor resistance by a factor of 4.

This change in voltage is usually achieved in AC circuits using a *step-up transformer*. DC systems require relatively costly conversion equipment which may be economically justified for particular projects, but are less common currently.

A transmission grid is a network of power stations, transmission circuits, and substations. Energy is usually transmitted within a grid with three-phase AC. Single phase AC is used only for distribution to end users since it is not usable for large polyphase induction motors. In the 19th century, two-phase transmission was used but required either three wires with unequal currents or four wires. Higher order phase systems require more than three wires, but deliver marginal benefits.



The synchronous grids of Eurasia.

The capital cost of electric power stations is so high, and electric demand is so variable, that it is often cheaper to import some portion of the needed power than to generate it locally. Because nearby loads are often correlated (hot weather in the Southwest portion of the US might cause many people to use air conditioners), electricity often comes from distant sources. Because of the economics of load balancing, wide area transmission grids now span across countries and even large portions of continents. The web of interconnections between power producers and consumers ensures that power can flow, even if a few links are inoperative.

The unvarying (or slowly varying over many hours) portion of the electric demand is known as the *base load* and is generally served best by large facilities (which are therefore efficient due to economies of scale) with low variable costs for fuel and operations. Such facilities might be nuclear or coal-fired power stations, or hydroelectric, while other renewable energy sources such as concentrated solar thermal and geothermal power have the potential to provide base load power. Renewable energy sources such as solar photovoltaics, wind, wave, and tidal are, due to their intermittency, not considered "base load" but can still add power to the grid. The remaining power demand, if any, is supplied by peaking power plants, which are typically smaller, faster-responding, and higher cost sources, such as combined cycle or combustion turbine plants fueled by natural gas.

A high-power electrical transmission tower.

Long-distance transmission of electricity (thousands of kilometers) is cheap and efficient, with costs of US$0.005–0.02/kWh (compared to annual averaged large producer costs of US$0.01–0.025/kWh, retail rates upwards of US$0.10/kWh, and multiples of retail for instantaneous suppliers at unpredicted highest demand moments). Thus distant suppliers can be cheaper than local sources (e.g., New York City buys a lot of electricity from Canada). Multiple **local sources** (even if more expensive and infrequently used) can make the transmission grid more fault tolerant to weather and other disasters that can disconnect distant suppliers.

Long distance transmission allows remote renewable energy resources to be used to displace fossil fuel consumption. Hydro and wind sources can't be moved closer to populous cities, and solar costs are lowest in remote areas where local power needs are minimal. Connection costs alone can determine whether any particular renewable alternative is economically sensible. Costs can be prohibitive for transmission lines, but various proposals for massive infrastructure investment in high capacity, very long distance super grid transmission networks could be recovered with modest usage fees.

Grid input

At the generating plants the energy is produced at a relatively low voltage between about 2.3 kV and 30 kV, depending on the size of the unit. The generator terminal voltage is then stepped up by the power station transformer to a higher voltage (115 kV to 765 kV AC, varying by country) for transmission over long distances.

Losses

Transmitting electricity at high voltage reduces the fraction of energy lost to resistance. For a given amount of power, a higher voltage reduces the current and thus the resistive losses in the conductor. For example, raising the voltage by a factor of 10 reduces the current by a corresponding factor of 10 and therefore the I^2Rlosses by a factor of 100, provided the same sized conductors are used in both cases. Even if the conductor size (cross-sectional area) is reduced 10-fold to match the lower current the I^2Rlosses are still reduced 10-fold. Long distance transmission is typically done with overhead lines at voltages of 115 to 1,200 kV. At extremely high voltages, more than 2 MV between conductor and ground, corona discharge losses are so large that they can offset the lower resistance loss in the line conductors.

Transmission and distribution losses in the USA were estimated at 6.6% in 1997 and 6.5% in 2007. In general, losses are estimated from the discrepancy between energy produced (as reported by power plants) and energy sold to end customers; the difference between what is produced and what is consumed constitute transmission and distribution losses.

As of 1980, the longest cost-effective distance for electricity was 7,000 km (4,300 mi), although all present transmission lines are considerably shorter.

In an alternating current circuit, the inductance and capacitance of the phase conductors can be significant. The currents that flow in these components of the circuit impedance constitute reactive power, which transmits no energy to the load. Reactive current causes extra losses in the transmission circuit. The ratio of real power (transmitted to the load) to apparent power is the power factor. As reactive current increases, the reactive power increases and the power factor decreases. For systems with low power factors, losses are higher than for systems with high power factors. Utilities add capacitor banks and other components (such as phase-shifting transformers; static VAR compensators; physical transposition of the phase conductors; and flexible AC transmission systems, FACTS) throughout the system to control reactive power flow for reduction of losses and stabilization of system voltage.

Transmission grid exit

At the substations, transformers reduce the voltage to a lower level for distribution to commercial and residential users. This distribution is accomplished with a combination of sub-transmission (33 kV to 132 kV) and distribution (3.3 to 25 kV). Finally, at the point of use, the energy is transformed to low voltage (varying by country and customer requirements).

High-voltage direct current

High voltage direct current (HVDC) is used to transmit large amounts of power over long distances or for interconnections between asynchronous grids. When electrical energy is required to be transmitted over very long distances, it is more economical to transmit using direct current instead of alternating current. For a long transmission line, the lower losses and reduced construction cost of a DC line can offset the additional cost of converter stations at each end. Also, at high AC voltages, significant (although economically acceptable) amounts of energy are lost due to corona discharge, the capacitance between phases or, in the case of buried cables, between phases and the soil or water in which the cable is buried.

HVDC is also used for long submarine cables because over about 30 km length AC can no longer be applied. In that case special high voltage cables for DC are built. Many submarine cable connections - up to 600 km length - are in use nowadays.

HVDC links are sometimes used to stabilize against control problems with the AC electricity flow. In other words, to transmit AC power as AC when needed in either direction between Seattle and Boston would require the (highly challenging) continuous real-time adjustment of the relative phase of the two electrical grids. With HVDC instead the interconnection would: (1) Convert AC in Seattle into HVDC. (2) Use HVDC for the three thousand miles of cross country transmission. Then (3) convert the HVDC to locally synchronized AC in Boston, and optionally in other cooperating cities along the transmission route. One prominent example of such a transmission line is the Pacific DC Intertie located in the Western United States.

Limitations

The amount of power that can be sent over a transmission line is limited. The origins of the limits vary depending on the length of the line. For a short line, the heating of conductors due to line losses sets a thermal limit. If too much current is drawn, conductors may sag too close to the ground, or conductors and equipment may be damaged by overheating. For intermediate-length lines on the order of 100 km (62 mi), the limit is set by the voltage drop in the line. For longer AC lines, system stability sets the limit to the power that can be transferred. Approximately, the power flowing over an AC line is proportional to the sine of the phase angle of the voltage at the receiving and transmitting ends. Since this angle varies depending on system loading and generation, it is undesirable for the angle to approach 90 degrees. Very approximately, the allowable product of line length and maximum load is proportional to the square of the system voltage. Series capacitors or phase-shifting transformers are used on long lines to improve stability. High-voltage direct current lines are restricted only by thermal and voltage drop limits, since the phase angle is not material to their operation.

Up to now, it has been almost impossible to foresee the temperature distribution along the cable route, so that the maximum applicable current load was usually set as a compromise between understanding of operation conditions and risk minimization. The availability of industrial Distributed Temperature Sensing (DTS) systems that measure in real time temperatures all along the cable is a first step in monitoring the transmission system capacity. This monitoring solution is based on using passive optical fibers as temperature sensors, either integrated directly inside a high voltage cable or mounted externally on the cable insulation. A solution for overhead lines is also available. In this case the optical fiber is integrated into the core of a phase wire of overhead transmission lines (OPPC). The integrated Dynamic Cable Rating (DCR) or also called Real Time Thermal Rating (RTTR) solution enables not only to continuously monitor the temperature of a high voltage cable circuit in real time, but to safely utilize the existing network capacity to its maximum. Furthermore it provides the ability to the operator to predict the behavior of the transmission system upon major changes made to its initial operating conditions.

Control

To ensure safe and predictable operation the components of the transmission system are controlled with generators, switches, circuit breakers and loads. The voltage, power, frequency, load factor, and reliability capabilities of the transmission system are designed to provide cost effective performance for the customers.

Load balancing

The transmission system provides for base load and peak load capability, with safety and fault tolerance margins. The peak load times vary by region largely due to the industry mix. In very hot and very cold climates home air conditioning and heating loads have an effect on the overall load. They are typically highest in the late afternoon in the hottest part of the year and in mid-mornings and mid-evenings in the coldest part of the year. This makes the power requirements vary by the season and the time of day. Distribution system designs always take the base load and the peak load into consideration.

The transmission system usually does not have a large buffering capability to match the loads with the generation. Thus generation has to be kept matched to the load, to prevent overloading failures of the generation equipment.

Multiple sources and loads can be connected to the transmission system and they must be controlled to provide orderly transfer of power. In centralized power generation, only local control of generation is necessary, and it involves synchronization of the generation units, to prevent large transients and overload conditions.

In distributed power generation the generators are geographically distributed and the process to bring them online and offline must be carefully controlled. The load control signals can either be sent on separate lines or on the power lines themselves. To load balance the voltage and frequency can be used as a signaling mechanism.

In voltage signaling, the variation of voltage is used to increase generation. The power added by any system increases as the line voltage decreases. This arrangement is stable in principle. Voltage based regulation is complex to use in mesh networks, since the individual components and setpoints would need to be reconfigured every time a new generator is added to the mesh.

In frequency signaling, the generating units match the frequency of the power transmission system. In droop speed control, if the frequency decreases, the power is increased. (The drop in line frequency is an indication that the increased load is causing the generators to slow down.)

Wind turbines, v2g and other distributed storage and generation systems can be connected to the power grid, and interact with it to improve system operation.

Failure protection

Under excess load conditions, the system can be designed to fail gracefully rather than all at once. Brownouts occur when the supply power drops below the demand. Blackouts occur when the supply fails completely.

Rolling blackouts, or load shedding, are intentionally engineered electrical power outages, used to distribute insufficient power when the demand for electricity exceeds the supply.

Communications

Operators of long transmission lines require reliable communications for control of the power grid and, often, associated generation and distribution facilities. Fault-sensing protective relays at each end of the line must communicate to monitor the flow of power into and out of the protected line section so that faulted conductors or equipment can be quickly de-energized and the balance of the system restored. Protection of the transmission line from short circuits and other faults is usually so critical that common carrier telecommunications are insufficiently reliable, and in remote areas a common carrier may not be available. Communication systems associated with a transmission project may use:

- Microwaves
- Power line communication
- Optical fibers

Rarely, and for short distances, a utility will use pilot-wires strung along the transmission line path. Leased circuits from common carriers are not preferred since availability is not under control of the electric power transmission organization.

Transmission lines can also be used to carry data: this is called power-line carrier, or PLC. PLC signals can be easily received with a radio for the long wave range.

Optical fibers can be included in the stranded conductors of a transmission line, in the overhead shield wires. These cables are known as optical ground wire (*OPGW*). Sometimes a standalone cable is used, all-dielectric self-supporting (*ADSS*) cable, attached to the transmission line cross arms.

Some jurisdictions, such as Minnesota, prohibit energy transmission companies from selling surplus communication bandwidth or acting as a telecommunications common carrier. Where the regulatory structure permits, the utility can sell capacity in extra dark fibers to a common carrier, providing another revenue stream.

Electricity market reform

Some regulators regard electric transmission to be a natural monopoly and there are moves in many countries to separately regulate transmission.

Spain was the first country to establish a regional transmission organization. In that country transmission operations and market operations are controlled by separate companies. The transmission system operator is Red Eléctrica de España (REE) and the wholesale electricity market operator is Operador del Mercado Ibérico de Energía - Polo Español, S.A. (OMEL) . Spain's transmission system is interconnected with those of France, Portugal, and Morocco.

In the United States and parts of Canada, electrical transmission companies operate independently of generation and distribution companies.

Cost of electric power transmission

The cost of high voltage electricity transmission, (as opposed to the costs of electricity distribution) is comparatively low, compared to all other costs arising in a consumer's electricity bill. In the UK transmission costs are about 0.2p/kWh compared to a delivered domestic price of around 10 p/kWh.

Merchant transmission

Merchant transmission is an arrangement where a third party constructs and operates electric transmission lines through the franchise area of an unrelated utility. Advocates of merchant transmission claim that this will create competition to construct the most efficient and lowest cost additions to the transmission grid. Merchant transmission projects typically involve DC lines because it is easier to limit flows to paying customers.

Operating merchant transmission projects in the United States include the Cross Sound Cable from Long Island, New York to New Haven, Connecticut, Neptune RTS Transmission Line from Sayreville, N.J., to Newbridge, N.Y, ITC Holdings, Inc. transmission system in the midwest, and Path 15 in California. Additional projects are in development or have been proposed throughout the United States.

There is only one unregulated or market interconnector in Australia: Basslink between Tasmania and Victoria. Two DC links originally implemented as market interconnectors Directlink and Murraylink have been converted to regulated interconnectors. NEMMCO

A major barrier to wider adoption of merchant transmission is the difficulty in identifying who benefits from the facility so that the beneficiaries will pay the toll. Also, it is difficult for a merchant transmission line to compete when the alternative transmission lines are subsidized by other utility businesses.

Health concerns

The preponderance of evidence does not suggest that the low-power, low-frequency, electromagnetic radiation associated with household current constitutes a short or long term health hazard. Some studies have found statistical correlations between various diseases and living or working near power lines, but no adverse health effects have been substantiated for people not living close to powerlines.

There are established biological effects for acute *high* level exposure to magnetic fields well above 100 µT. In a residential setting, there is "limited evidence of carcinogenicity in humans and less than sufficient evidence for carcinogenicity in experimental animals", in particular, childhood leukaemia, *associated with* average exposure to residential power-frequency magnetic field above 0.3 to 0.4 µT. These levels exceed average residential power-frequency magnetic fields in homes which are about 0.07 µT in Europe and 0.11 µT in North America. Association is not the same as a cause-and-effect relationship.

Government policy

Historically, local governments have exercised authority over the grid and have significant disincentives to take action that would benefit states other than their own. Localities with cheap electricity have a disincentive to making interstate commerce in electricity trading easier, since other regions will be able to compete for local energy and drive up rates. Some regulators in Maine for example do not wish to address congestion problems because the congestion serves to keep Maine rates low. Further, vocal local constituencies can block or slow permitting by pointing to visual impact, environmental, and perceived health concerns. In the US, generation is growing 4 times faster than transmission, but big transmission upgrades require the coordination of multiple states, a multitude of interlocking permits, and cooperation between a significant portion of the 500 companies that own the grid. From a policy perspective, the control of the grid is balkanized, and even former energy secretary Bill Richardson refers to it as a *third world grid*. There have been efforts in the EU and US to confront the problem. The US national security interest in significantly growing transmission capacity drove passage of the 2005 energy act giving the Department of Energy the authority to approve transmission if states refuse to act. However, soon after using its power to designate two National Interest Electric Transmission Corridors, 14 senators signed a letter stating the DOE was being too aggressive.

Special transmission

Grids for railways

In some countries where electric trains run on low frequency AC (e.g., 16.7 Hz and 25 Hz) power, there are separate single phase traction power networks operated by the railways. These grids are fed by separate generators in some traction powerstations or by traction current converter plants from the public three phase AC network.

Superconducting cables

High-temperature superconductors promise to revolutionize power distribution by providing lossless transmission of electrical power. The development of superconductors with transition temperatures higher than the boiling point of liquid nitrogen has made the concept of superconducting power lines commercially feasible, at least for high-load applications. It has been estimated that the waste would be halved using this method, since the necessary refrigeration equipment would consume about half the power saved by the elimination of the majority of resistive losses. Some companies such as Consolidated Edison and American Superconductor have already begun commercial production of such systems. In one hypothetical future system called a SuperGrid, the cost of cooling would be eliminated by coupling the transmission line with a liquid hydrogen pipeline.

Superconducting cables are particularly suited to high load density areas such as the business district of large cities, where purchase of an easement for cables would be very costly.

Single wire earth return

Single-wire earth return (SWER) or single wire ground return is a single-wire transmission line for supplying single-phase electrical power for an electrical grid to remote areas at low cost. It is principally used for rural electrification, but also finds use for larger isolated loads such as water pumps, and light rail. Single wire earth return is also used for HVDC over submarine power cables.

Wireless power transmission

Both Nikola Tesla and Hidetsugu Yagi attempted to devise systems for large scale wireless power transmission, with no commercial success.

Wireless power transmission has been studied for transmission of power from solar power satellites to the earth. A high power array of microwave transmitters would beam power to a rectenna. Major engineering and economic challenges face any solar power satellite project.

Security of control systems

The Federal government of the United States admits that the power grid is susceptible to cyber-warfare. The United States Department of Homeland Security works with industry to identify vulnerabilities and to help industry enhance the security of control system networks, the federal government is also working to ensure that security is built in as the U.S. develops the next generation of 'smart grid' networks.

Records

- Highest capacity system: 6.3 GW HVDC Itaipu (Brazil) (±600 kV DC)
- Highest transmission voltage (AC): 1.15 MV on Powerline Ekibastuz-Kokshetau (Kazakhstan)
- Largest double-circuit transmission, Kita-Iwaki Powerline.
- Highest pylons: Yangtze River Crossing (height: 345 m/1,132 ft)
- Longest power line: Inga-Shaba (length: 1,700 kilometres / 1,056 miles)
- Longest span of power line: 5,376 m (17,638 ft) at Ameralik Span
- Longest submarine cables:
    - NorNed, North Sea - (length of submarine cable: 580 kilometres / 360 miles)
    - Basslink, Bass Strait - (length of submarine cable: 290 kilometres / 180 miles, total length: 370.1 kilometres / 230 miles)
    - Baltic-Cable, Baltic Sea - (length of submarine cable: 238 kilometres / 148 miles, HVDC length: 250 kilometres / 155 miles, total length: 262 kilometres / 163 miles)
- Longest underground cables:

- Murraylink, Riverland/Sunraysia - (length of underground cable: 180 kilometres / 112 miles)

Chapter 4

Power Electronics and Power System Protection

Power electronics

Power electronics is the application of solid-state electronics for the control and conversion of electric power.

Introduction

Power electronic converters can be found wherever there is a need to modify a form of electrical energy (i.e. change its voltage, current or frequency). The power range of these converters is from some milliwatts (as in a mobile phone) to hundreds of megawatts (e.g. in a HVDC transmission system). With "classical" electronics, electrical currents and voltage are used to carry information, whereas with power electronics, they carry power. Thus, the main metric of power electronics becomes the efficiency.

The first very high power electronic devices were mercury arc valves. In modern systems the conversion is performed with semiconductor switching devices such as diodes, thyristors and transistors. In contrast to electronic systems concerned with transmission and processing of signals and data, in power electronics substantial amounts of electrical energy are processed. An AC/DC converter (rectifier) is the most typical power electronics device found in many consumer electronic devices, e.g. television sets, personal computers, battery chargers, etc. The power range is typically from tens of watts to several hundred watts. In industry the most common application is the variable speed drive (VSD) that is used to control an induction motor. The power range of VSDs start from a few hundred watts and end at tens of megawatts.

The power conversion systems can be classified according to the type of the input and output power

- AC to DC (rectifier)
- DC to AC (inverter)
- DC to DC (DC to DC converter)
- AC to AC (AC to AC converter)

Principle

As efficiency is at a premium in a power electronic converter, the losses that a power electronic device generates should be as low as possible. The instantaneous dissipated power of a device is equal to the product of the voltage across the device and the current through it ($P = V \times I$). From this, one can see that the losses of a power device are at a minimum when the voltage across it is zero (the device is in the On-State) or when no current flows through it (Off-State). Therefore, a power electronic converter is built around one (or more) device operating in switching mode (either On or Off). With such a structure, the energy is transferred from the input of the converter to its output by bursts. To convert the power electronics by using rectifier

Applications

Power electronic systems are found in virtually every electronic device. For example:

- DC/DC converters are used in most mobile devices (mobile phones, PDA etc.) to maintain the voltage at a fixed value whatever the voltage level of the battery is. These converters are also used for electronic isolation and power factor correction.
- AC/DC converters (rectifiers) are used every time an electronic device is connected to the mains (computer, television etc.). These may simply change AC to DC or can also change the voltage level as part of their operation.
- AC/AC converters are used to change either the voltage level or the frequency (international power adapters, light dimmer). In power distribution networks AC/AC converters may be used to exchange power between utility frequency 50 Hz and 60 Hz power grids.
- DC/AC converters (inverters) are used primarily in UPS or emergency lighting systems. When mains power is available, it will charge the DC battery. If the mains fails, an inverter will be used to produce AC electricity at mains voltage from the DC battery.

Power semiconductor device

Power semiconductor devices are semiconductor devices used as switches or rectifiers in power electronic circuits (switch mode power supplies for example). They are also called **power devices** or when used in integrated circuits, called **power ICs**.

Most power semiconductor devices are only used in commutation mode (i.e they are either on or off), and are therefore optimized for this. Most of them should not be used in linear operation.

History

Power semiconductor devices first appeared in 1952 with the introduction of the power diode by R.N. Hall. It was made of Germanium and had a voltage capability of 200 volts and a current rating of 35 amperes.

The thyristor appeared in 1957. Thyristors are able to withstand very high reverse breakdown voltage and are also capable of carrying high current. One disadvantage of the thyristor for switching circuits is that once it is 'latched-on' in the conducting state it cannot be turned off by external control. The thyristor turn-off is passive, i.e., the power must be disconnected from the device.

The first bipolar transistors devices with substantial power handling capabilities were introduced in the 1960s. These components overcame some limitations of the thyristors because they can be turned on or off with an applied signal.

With the improvements of the Metal Oxide Semiconductor technology (initially developed to produce integrated circuits), power MOSFETs became available in the late 1970s. International Rectifier introduced a 25 A, 400 V power MOSFET in 1978. These devices allow operation at higher frequency than bipolar transistors, but are limited to the low voltage applications.

The Insulated Gate Bipolar Transistor (IGBT) developed in the 1980s became widely available in the 1990s. This component has the power handling capability of the bipolar transistor, with the advantages of the isolated gate drive of the power MOSFET.

Common power devices

Some common power devices are the power diode, thyristor, power MOSFET and IGBT. A power diode or MOSFET operates on similar principles to its low-power counterpart, but is able to carry a larger amount of current and typically is able to support a larger reverse-bias voltage in the *off-state*.

Structural changes are often made in power devices to accommodate the higher current density, higher power dissipation and/or higher reverse breakdown voltage. The vast majority of the discrete (i.e non integrated) power devices are built using a vertical structure, whereas small-signal devices employ a lateral structure. With the vertical structure, the current rating of the device is proportional to its area, and the voltage blocking capability is achieved in the height of the die. With this structure, one of the connections of the device is located on the bottom of the semiconductor die.

Common power semiconductor devices

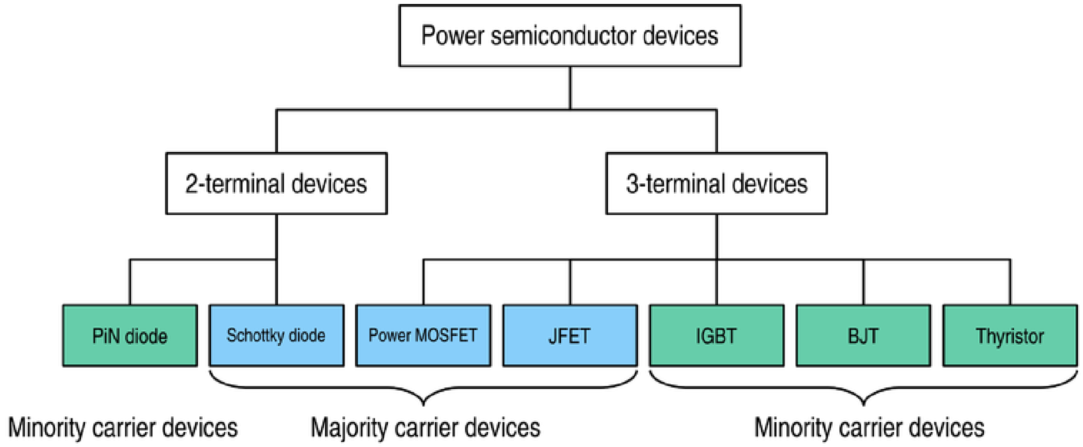


Fig. 1: The power devices family, showing the principal power switches.

The realm of power devices is divided into two main categories (see figure 1):

- The two-terminal devices (diodes), whose state is completely dependent on the external power circuit they are connected to;
- The three-terminal devices, whose state is not only dependent on their external power circuit, but also on the signal on their driving terminal (gate or base). Transistors and thyristors belong to that category.

A second classification is less obvious, but has a strong influence on device performance: Some devices are *majority carrier devices* (Schottky diode, MOSFET), while the others are *minority carrier devices* (Thyristor, bipolar transistor, IGBT). The former use only one type of charge carriers, while the latter use both (i.e electrons and holes). The majority carrier devices are faster, but the charge injection of minority carrier devices allows for better On-state performance.

Diodes

An ideal diode should have the following characteristics:

- When forward-biased, the voltage across the end terminals of the diode should be zero, whatever the current that flows through it (on-state);
- When reverse-biased, the leakage current should be zero, whatever the voltage (off-state).
- The transition between on and off states should be instantaneous.

In reality, the design of a diode is a trade-off between performance in on-state, off-state and commutation. Indeed, the same area of the device must sustain the blocking voltage in the off-state and allow current flow in the on-state. As the requirements for the two states are completely opposite, a diode has to be either optimised for one of them, or time must be allowed to switch from one state to the other (i.e slow down the commutation speed).

This trade-off between on-state/off-state and switching speed is the same for all power devices. A Schottky diode has excellent switching speed and on-state performance, but a high level of leakage current in off-state. On the other hand, PIN diodes are commercially available in different commutation speeds (so-called "fast" and "ultrafast" rectifiers), but any increase in speed is paid for by a lower performance in the on-state.

Switches

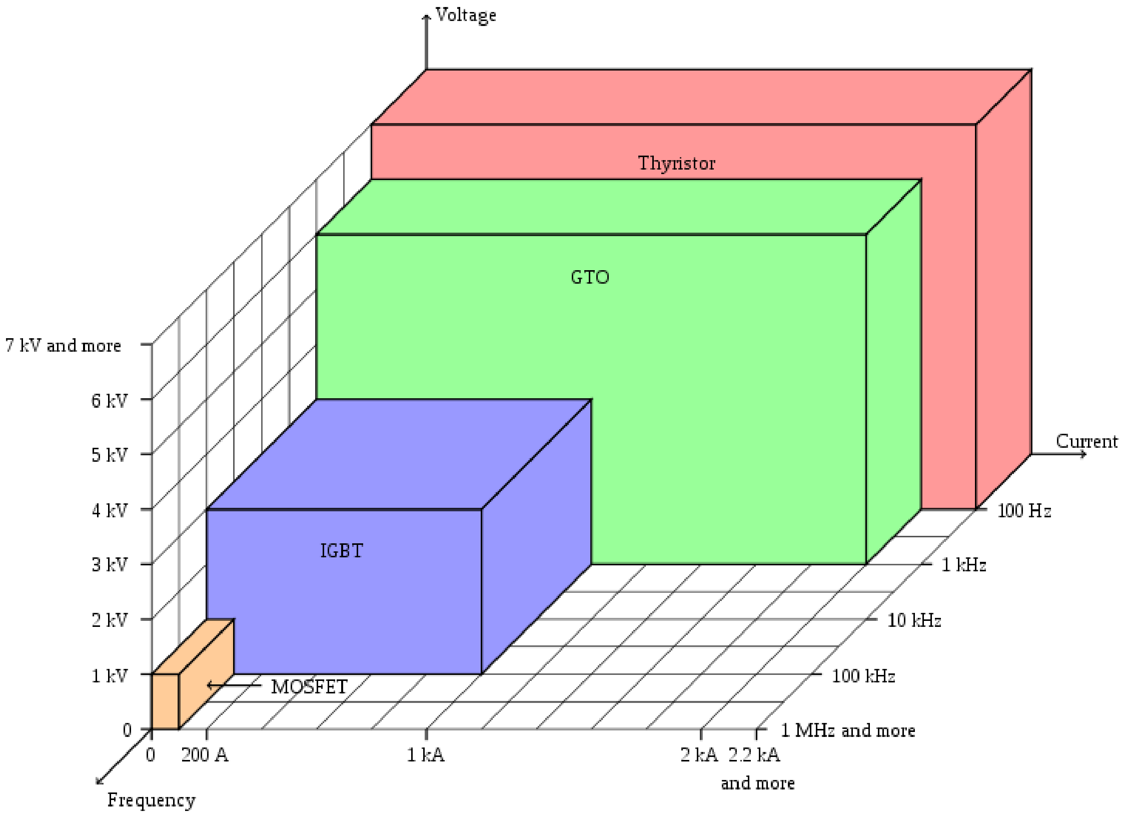


Fig.2 : Current/Voltage/switching frequency domains of the main power electronics switches.

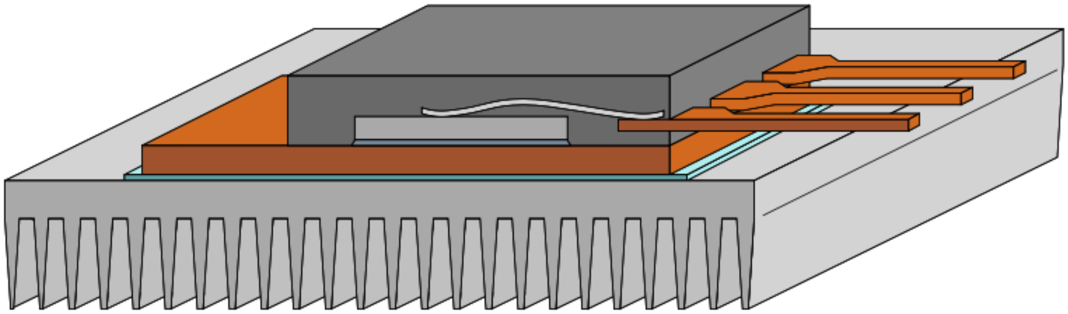
The trade-off between voltage, current and frequency ratings also exists for the switches. Actually, all power semiconductors rely on a PIN diode structure to sustain voltage. This can be seen in figure 2. The power MOSFET has the advantages of the majority carrier devices, so it can achieve very high operating frequency, but can't be used with high voltages. As it is a physical limit, no improvement is expected from silicon MOSFETs concerning their maximum voltage ratings. However, its excellent performance in low voltage make it the device of choice (actually the only choice) for applications below 200 V. By paralleling several devices, it is possible increase the current rating of a switch.

The MOSFET is particularly suited to this configuration because its positive thermal coefficient of resistance tends to balance current between individual devices.

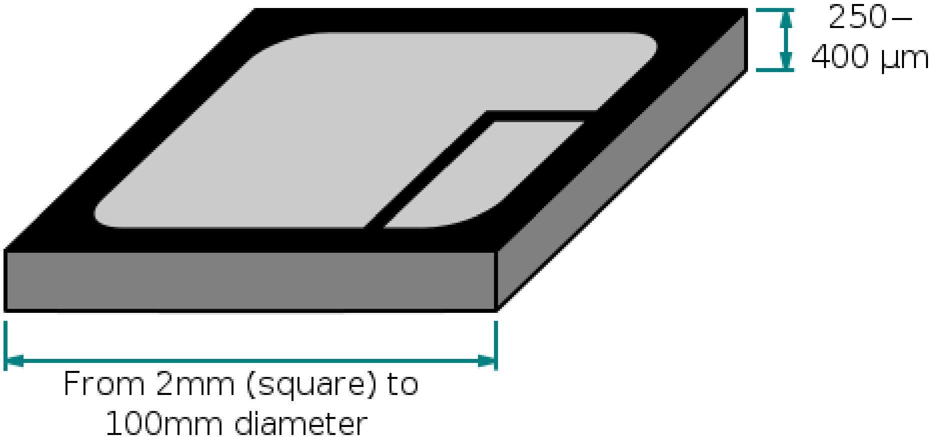
The IGBT is a recent component, so its performance improves regularly as technology evolves. It has already completely replaced the bipolar transistor in power applications, and the availability of power modules (in which several IGBT dice are connected in parallel) makes it attractive for power levels up to several megawatts, pushing further the limit where thyristors and GTOs become the only option. Basically, an IGBT is a bipolar transistor driven by a power MOSFET: it has the advantages of being a minority carrier device (good performance in on-state, even for high voltage devices), with the high input impedance of a MOSFET (it can be driven on or off with a very low amount of power). Its major limitation for low voltage applications is the high voltage drop it exhibits in on-state (2 to 4 V). Compared to the MOSFET, the operating frequency of the IGBT is relatively low (few devices are rated over 50 kHz), mainly because of a so-called 'current-tail' problem during turn-off. This problem is caused by the slow decay of the conduction current during turn-off resulting from slow recombination of large number of carriers, which flood the thick 'drift' region of the IGBT during conduction. The net result is that the turn-off switching loss of an IGBT is considerably higher than its turn-on loss. Generally, in datasheets, turn-off energy is mentioned as a measured parameter and one has to multiply that number with the switching frequency of the intended application to estimate the turn-off loss.

At very high power levels, thyristor-based devices (SCRs, GTOs, MCTs) are still the only choice. Though driving a thyristor is somewhat complicated, as this device can only be turned on. It turns off by itself as soon as no more current flows through it. This requires a circuit with the means to divert current, or specific applications where current is known to cancel regularly (i.e. Alternating Current). MCTs and GTOs have been developed to overcome this limitation; these components are widely used in power distribution applications.

Parameters of power semiconductor devices



A power device is usually attached to a heatsink to remove the heat caused by operation losses.



The power semiconductor die of a three-terminal device (IGBT, MOSFET or BJT). Two contacts are on top of the die, the remaining one is on the back.

1. **Breakdown voltage**: Often there is a trade-off between breakdown voltage rating and on-resistance, because increasing the breakdown voltage by incorporating a thicker and lower doped drift region leads to higher on-resistance.
2. **On-resistance**: Higher current rating lowers the on-resistance due to greater numbers of parallel cells. This increases overall capacitance and slows down the speed.
3. **Rise and fall times** for switching between on and off states.
4. **Safe-operating area** (from thermal dissipation and "latch-up" consideration)
5. **Thermal resistance**: This is an oft-ignored but extremely important parameter from practical design point of view. Semiconductors do not perform well at elevated temperature but due to large current conduction, all power semiconductor devices heat up. Therefore they need to be cooled by removing that heat continuously. Packaging and heatsinks provide a means of removing heat from the semiconductor device by conducting it to the external environment. Generally, large current devices have large die and packaging surface areas and lower thermal resistance.

Research and development

Packaging

The role of packaging is to:

- connect a die to the external circuit;
- provide a way to remove the heat generated by the device;
- protect the die from the external environment (moisture, dust);

Many of the reliability issues of power device are either related to excessive temperature of fatigue due to thermal cycling. Research is currently carried out on the following topics:

- improve the cooling performance.
- improve the resistance to thermal cycling by closely matching the Coefficient of thermal expansion of the packaging to that of the silicon.
- increase the maximum operating temperature of the packaging material.

Research is also ongoing on electrical issues such as reducing the parasitic inductance of packaging. This inductance limits the operating frequency as it generates losses in the devices during commutation.

Low-voltage MOSFETs are also limited by the parasitic resistance of the packages, as their intrinsic on-state resistance can be as low as one or two milliohms.

Some of the most common type of power semiconductor packages include TO-220, TO-247, TO-262, TO-3, D^2Pak, etc.

Improvement of structures

IGBTs are still under development and we can expect increased operating voltages in the future. At the high-power end of the range, MOS-Controlled Thyristor are promising devices. A major improvement over conventional MOSFET structure is achieved by employing superjunction charge-balance principle to the design. Essentially, it allows the thick drift region of a power MOSFET to be heavily doped (thereby reducing the electrical resistance for electron flow) without compromising the breakdown voltage. An adjacent region of similarly doped (but of opposite carrier polarity - *holes*) is created within the structure. These two similar but opposite doped regions effectively cancel out their mobile charge and develop a 'depleted region' which supports the high voltage during off-state. On the other hand, during conducting state, the higher doping of the drift region allows easier flow of carrier thereby reducing on-resistance. Commercial devices, based on this principle, have been developed by International Rectifier and Infineon in the name of CoolMOS^{TM}.

Wide band-gap semiconductors

The major breakthrough in power semiconductor devices is expected from the replacement of silicon by a wide band-gap semiconductor. At the moment, silicon carbide (SiC) is considered to be the most promising. SiC Schottky diodes with a breakdown voltage of 1200 V are commercially available, as are 1200 V JFETs. As both are majority carrier devices, they can operate at high speed. Bipolar devices are being developed for higher voltages, up to 20 kV. Among its advantages, silicon carbide can operate at higher temperature (up to 400°C) and has a lower thermal resistance than silicon, allowing better cooling.

Power system protection

Power system protection is a branch of electrical power engineering that deals with the protection of electrical power systems from faults through the isolation of faulted parts from the rest of the electrical network. The objective of a protection scheme is to keep the power system stable by isolating only the components that are under fault, whilst leaving as much of the network as possible still in operation. Thus, protection schemes must apply a very pragmatic and pessimistic approach to clearing system faults. For this reason, the technology and philosophies utilized in protection schemes can often be old and well-established because they must be very reliable.

Components

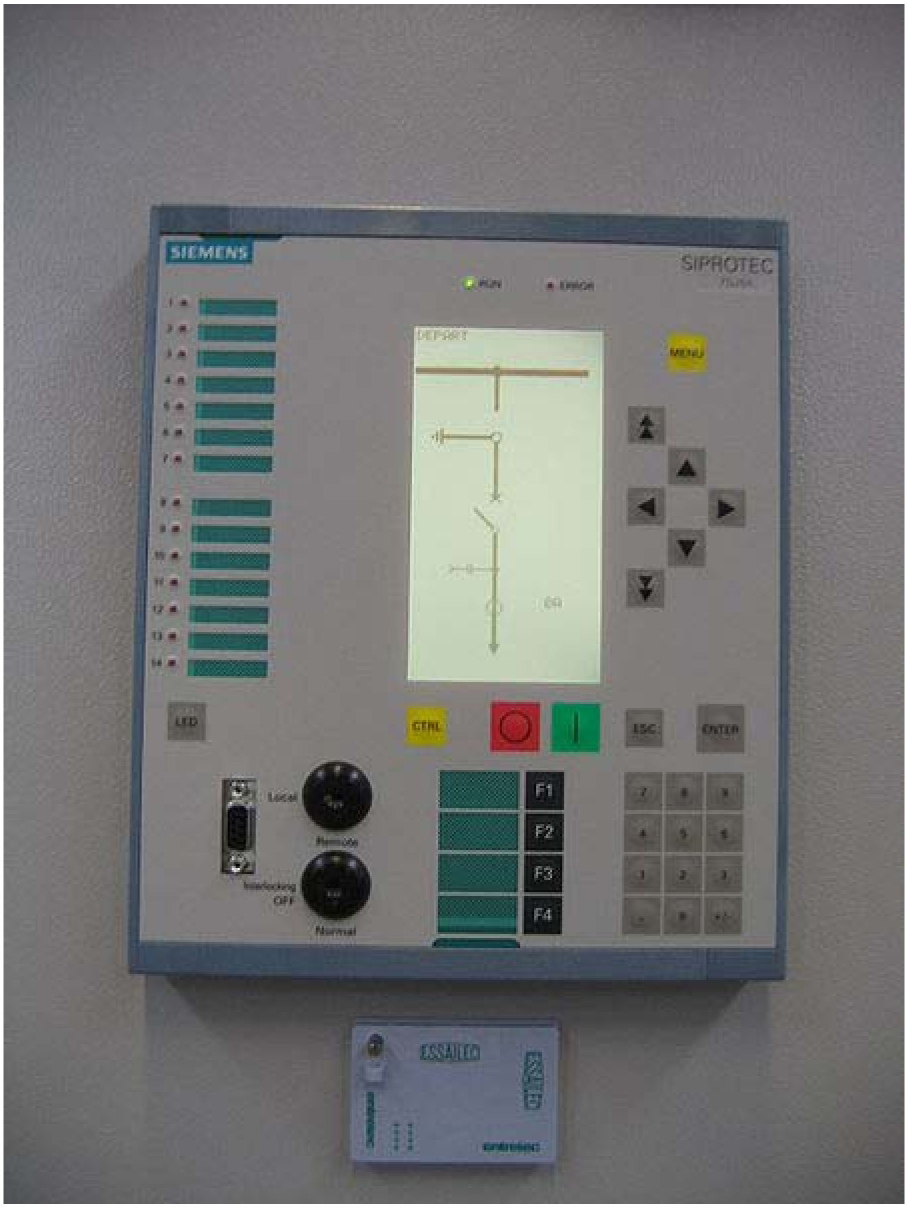
Protection systems usually comprise five components:

- Current and voltage transformers to step down the high voltages and currents of the electrical power system to convenient levels for the relays to deal with;
- Protective relays to sense the fault and initiate a trip, or disconnection, order;
- Circuit breakers to open/close the system based on relay and autorecloser commands;
- Batteries to provide power in case of power disconnection in the system.
- Communication channels to allow analysis of current and voltage at remote terminals of a line and to allow remote tripping of equipment.

For parts of a distribution system, fuses are capable of both sensing and disconnecting faults.

Failures may occur in each part, such as insulation failure, fallen or broken transmission lines, incorrect operation of circuit breakers, short circuits and open circuits. Protection devices are installed with the aims of protection of assets, and ensure continued supply of energy. The three classes of protective devices are:

Protective devices



protective relay for distribution networks

- Protective relays control the tripping of the circuit breakers surrounding the faulted part of the network
- Automatic operation, such as auto-reclosing or system restart
- Monitoring equipment which collects data on the system for post event analysis

While the operating quality of these devices, and especially of the protective relays, is always critical, different strategies are considered for protecting the different parts of the system. Very important equipment may have completely redundant and independent protective systems, while a minor branch distribution line may have very simple low-cost protection.

Types of protection

- Generator sets – In a power plant, the protective relays are intended to prevent damage to alternators or of the transformers in case of abnormal conditions of operation, due to internal failures, as well as insulating failures or regulation malfunctions. Such failures are unusual, so the protective relays have to operate very rarely. If a protective relay fails to detect a fault, the damage to the alternator or to the transformer may have important financial consequences for the repair or replacement of equipment and the value of the energy that otherwise would have been sold.

- High voltage transmission network – Protection on the transmission and distribution serves two functions: Protection of plant and protection of the public (including employees). At a basic level protection looks to disconnect equipment which experience an overload or a connection to earth. Some items in substations such as transformers may require additional protection based on temperature or gassing among others.

- Overload – Overload protection requires a current transformer which simply measures the current in a circuit. If this current exceeds a pre-determined level, a circuit breaker or fuse should operate.

- Earth fault – Earth fault protection again requires current transformers and senses an imbalance in a three-phase circuit. Normally a three-phase circuit is in balance, so if a single (or multiple) phases are connected to earth an imbalance in current is detected. If this imbalance exceeds a pre-determined value a circuit breaker should operate.

- Distance – Distance protection detects both voltage and current. A fault on a circuit will generally create a sag in the voltage level. If this voltage falls below a pre-determined level and the current is above a certain level the circuit breaker should operate. This is useful on long lines where if a fault was experienced at the end of the line the impedance of the line itself may inhibit the rise in current. Since a voltage sag is required to trigger the protection the current level can actually be set below the normal load on the line.

- Back-up – At all times the objective of protection is to remove only the affected portion of plant and nothing else. Sometimes this does not occur for various reasons which can include:
    - Mechanical failure of a circuit breaker to operate
    - Incorrect protection setting
    - Relay failures

A failure of primary protection will usually result in the operation of back-up protection which will generally remove both the affected and unaffected items of plant to remove the fault.

- Low-voltage networks – The low voltage network generally relies upon fuses or low-voltage circuit breakers to remove both overload and earth faults.

Coordination

Protective device coordination is the process of determining the "best fit" timing of current interruption when abnormal electrical conditions occur. The goal is to minimize an outage to the greatest extent possible. Historically, protective device coordination was done on translucent log-log paper. Modern methods normally include detailed computer based analysis and reporting.

Disturbance monitoring equipment (DME)

Disturbance monitoring equipment monitors and records system data pertaining to a fault. DME accomplish three main purposes: 1) Model validation, 2) disturbance investigation, and 3) assessment of system protection performance. DME devices include :

- Sequence of event recorders, which record equipment response to the event

- Fault recorders, which record actual waveform data of the system primary voltages and currents.

- Dynamic Disturbance Recorders (DDRs), which record incidents that portray power system behavior during dynamic events such as low frequency (0.1 Hz – 3 Hz) oscillations and abnormal frequency or voltage excursions

Chapter 5

Electric Power System

A steam turbine used to provide electric power.

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 in the remainder of this section. 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)or nuclear energy, or falling water (hydroelectric power), and wind (wind power).

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.

Electricity grid systems connect multiple generators and loads operating at the same frequency and number of phases, 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

Power systems deliver energy to loads that 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

Power systems contain protective devices to prevent injury or damage during failures. 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, interrupting the circuit. 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. This section introduces some common power system types and briefly explains their operation.

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 6

Power Flow Study & Power Quality Compression Algorithm

Power flow study

In power engineering, the **power flow study** (also known as **load-flow study**) is an important tool involving numerical analysis applied to a power system. Unlike traditional circuit analysis, a power flow study usually uses simplified notation such as a one-line diagram and per-unit system, and focuses on various forms of AC power (ie: reactive, real, and apparent) rather than voltage and current. It analyzes the power systems in normal steady-state operation. There exist a number of software implementations of power flow studies.

In addition to a power flow study, sometimes called the *base case*, many software implementations perform other types of analysis, such as short-circuit fault analysis and economic analysis. In particular, some programs use linear programming to find the *optimal power flow*, the conditions which give the lowest cost per kilowatthour delivered.

Power flow or load-flow studies are important for planning future expansion of power systems as well as in determining the best operation of existing systems. The principal information obtained from the power flow study is the magnitude and phase angle of the voltage at each bus, and the real and reactive power flowing in each line.

Commercial power systems are usually too large to allow for hand solution of the power flow. Special pupose network analyzers were built between 1929 and the early 1960s to provide laboratory models of power systems; large-scale digital computers replaced the analog methods.

Power flow problem formulation

The goal of a power flow study is to obtain complete voltage angle and magnitude information for each bus in a power system for specified load and generator real power and voltage conditions. Once this information is known, real and reactive power flow on each branch as well as generator reactive power output can be analytically determined.

Due to the nonlinear nature of this problem, numerical methods are employed to obtain a solution that is within an acceptable tolerance.

The solution to the power flow problem begins with identifying the known and unknown variables in the system. The known and unknown variables are dependent on the type of bus. A bus without any generators connected to it is called a Load Bus. With one exception, a bus with at least one generator connected to it is called a Generator Bus. The exception is one arbitrarily-selected bus that has a generator. This bus is referred to as the Slack Bus.

In the power flow problem, it is assumed that the real power P_D and reactive power Q_D at each Load Bus are known. For this reason, Load Buses are also known as PQ Buses. For Generator Buses, it is assumed that the real power generated P_G and the voltage magnitude $|V|$ is known. For the Slack Bus, it is assumed that the voltage magnitude $|V|$ and voltage phase Θ are known. Therefore, for each Load Bus, both the voltage magnitude and angle are unknown and must be solved for; for each Generator Bus, the voltage angle must be solved for; there are no variables that must be solved for the Slack Bus. In a system with N buses and R generators, there are then $2(N-1)-(R-1)$ unknowns.

In order to solve for the $2(N-1)-(R-1)$ unknowns, there must be $2(N-1)-(R-1)$ equations that do not introduce any new unknown variables. The possible equations to use are power balance equations, which can be written for real and reactive power for each bus. The real power balance equation is:

$$0=-P_i+\sum_{k=1}^{N}|V_i||V_k|(G_{ik}\cos\theta_{ik}+B_{ik}\sin\theta_{ik})$$

where P_i is the net power injected at bus i, G_{ik} is the real part of the element in the bus admittance matrix Y_{BUS} corresponding to the ith row and kth column, B_{ik} is the imaginary part of the element in the Y_{BUS} corresponding to the ith row and kth column and θ_{ik} is the difference in voltage angle between the ith and kth buses. The reactive power balance equation is:

$$0=-Q_i+\sum_{k=1}^{N}|V_i||V_k|(G_{ik}\sin\theta_{ik}-B_{ik}\cos\theta_{ik})$$

where Q_i is the net reactive power injected at bus i.

Equations included are the real and reactive power balance equations for each Load Bus and the real power balance equation for each Generator Bus. Only the real power balance equation is written for a Generator Bus because the net reactive power injected is not assumed to be known and therefore including the reactive power balance equation would result in an additional unknown variable. For similar reasons, there are no equations written for the Slack Bus.

Newton-Raphson solution method

There are several different methods of solving the resulting nonlinear system of equations. The most popular is known as the Newton-Raphson Method. This method begins with initial guesses of all unknown variables (voltage magnitude and angles at Load Buses and voltage angles at Generator Buses). Next, a Taylor Series is written, with the higher order terms ignored, for each of the power balance equations included in the system of equations . The result is a linear system of equations that can be expressed as:

$$\begin{bmatrix} \Delta\theta \\ \Delta|V| \end{bmatrix} = -J^{-1}\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix}$$

where ΔP and ΔQ are called the mismatch equations:

$$\Delta P_i = -P_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\text{cos}\theta_{ik} + B_{ik}\text{sin}\theta_{ik})$$

$$\Delta Q_i = -Q_i + \sum_{k=1}^{N} |V_i||V_k|(G_{ik}\text{sin}\theta_{ik} - B_{ik}\text{cos}\theta_{ik})$$

and J is a matrix of partial derivatives known as a Jacobian: $J = \begin{bmatrix} \frac{\partial \Delta P}{\partial \theta} & \frac{\partial \Delta P}{\partial |V|} \\ \frac{\partial \Delta Q}{\partial \theta} & \frac{\partial \Delta Q}{\partial |V|} \end{bmatrix}$.

The linearized system of equations is solved to determine the next guess (m + 1) of voltage magnitude and angles based on:

$$\theta^{m+1} = \theta^m + \Delta\theta$$

$$|V|^{m+1} = |V|^m + \Delta|V|$$

The process continues until a stopping condition is met. A common stopping condition is to terminate if the norm of the mismatch equations are below a specified tolerance.

A rough outline of solution of the power flow problem is:

1. Make an initial guess of all unknown voltage magnitudes and angles. It is common to use a "flat start" in which all voltage angles are set to zero and all voltage magnitudes are set to 1.0 p.u.
2. Solve the power balance equations using the most recent voltage angle and magnitude values.

3. Linearize the system around the most recent voltage angle and magnitude values
4. Solve for the change in voltage angle and magnitude
5. Update the voltage magnitude and angles
6. Check the stopping conditions, if met then terminate, else go to step 2.

Power quality compression algorithm

A **Power Quality Compression Algorithm** is an algorithm used in power quality analysis. Electricity today is classed as one of the most important commodities, and has a particular characteristic that it is either impossible or uneconomical to store. Hence, electricity must be consumed as soon as it is produced. In order to provide high quality electric power service, it is essential to monitor the quality of the electric signals also termed as Power Quality (PQ) at different locations along an electrical power network. Electrical utilities carefully monitor waveforms and currents at various network locations constantly, in order for them to understand what lead up to any unforeseen events such as a power outage and blackouts. This is particularly critical at sites where the environment and public safety are at risk (institutions such as hospitals, sewage treatment plants, mines, etc.).

Power Quality Challenges

Engineers have at their disposal many meters , that are able to read and display electrical power waveforms and calculating parameters of the waveforms. These parameters may include, for example, current and voltage RMS, phase relationship between waveforms of a multi-phase signal, power factor, frequency, power factor, THD, harmonics, active power (KWatt), reactive power (KVAR), apparent power (KVA) and active energy (KWh), reactive energy (KVARH) and apparent energy (KVAh) and many more. In order to sufficiently monitor unforeseen events, Ribeiro et al. explains that it is not enough to display these parameters, but to also capture voltage waveform data at all times. This virtually impracticable due to the large amounts of data involved, causing what is known the "bottle effect". For instance at a sampling rate of 32 samples per cycle, 1,920 samples are collected per second. For three-phase meters that measure both voltage and current waveforms, the data is 6-8 times as much. More practical solutions developed in recent years, store data only when an event occurs (e.g., High levels of power system harmonics that creates voltage distortion) or alternatively to store the RMS of power the electrical signals . This data, however, is not always sufficient to determine the exact nature of problems.

Data Compression Algorithm

Nisenblat *et al.* proposes the idea of Power Quality (PQ) compression algorithm (similar to the Lossy Compression method) that enables meters to continuously store the waveform of one or more power signals, regardless whether or not an event of interest was identified. This algorithm referred to as PQZip empowers a processor with a memory that is sufficient enough to store the waveform, under normal power conditions, over a long period of time, of at least a month, two months or even a year. The compression is performed in real time, as the signals are acquired; it calculates a compression decision before all the compressed data is received. For instance should 1 parameter remain constant, and various others fluctuate, the compression decision retains only what is relevant from the constant data, and retains all the fluctuation data. It then decomposes the waveform of the power signal of numerous components, over various periods of the waveform. It concludes the process by compressing the values of at least some of these components over different periods, separately. This real time compression algorithm, performed independent of the sampling, prevents data gaps and has a typical 1000:1 compression ratio.

Conclusion - Importance of Compression Algorithm

Optimizing the distribution and consumption of our energy resources in particular electricity, is vital for the preservation of such resources, especially considering the status of the planet today. Development aforementioned ideas have been crucial in understanding and prevention of unforeseen events during the distribution and consumption of electricity. The challenge today is not only to identify that an event happened and when the event happened. It is also crucial to have sufficient data at hand to ensure that contingency plans are in place, and preventative action will be taken. Efficient compression algorithm prevents “bottle effect” mentioned above, and ensures that data is considered and processed responsibly for efficient and effective use.

Chapter 7

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 resulting "asymmetrical fault" becomes more complicated to analyse due to the simplifying assumption of equal current magnitude in all phases being no longer applicable. The analysis of this type of fault is often simplified by using methods such as symmetrical components.

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 8

Per-unit System

In the power transmission field of electrical engineering, a **per-unit system** is the expression of system quantities as fractions of a defined base unit quantity. Calculations are simplified because quantities expressed as per-unit are the same regardless of the voltage level. Similar types of apparatus will have impedances, voltage drops and losses that are the same when expressed as a per-unit fraction of the equipment rating, even if the unit size varies widely. Conversion of per-unit quantities to volts, ohms, or amperes requires a knowledge of the base that the per-unit quantities were referenced to.

A per-unit system provides units for power, voltage, current, impedance, and admittance. Only two of these are independent, usually power and voltage. All quantities are specified as multiples of selected base values. For example, the base power might be the rated power of a transformer, or perhaps an arbitrarily selected power which makes power quantities in the system more convenient. The base voltage might be the nominal voltage of a bus. Different types of quantities are labeled with the same symbol (**pu**); it should be clear from context whether the quantity is a voltage, current, etc.

Per-unit is used primarily in power flow studies; however, because parameters of transformers and machines (electric motors and electrical generators) are often specified in terms of per-unit, it is important for all power engineers to be familiar with the concept.

Purpose

There are several reasons for using a per-unit system:

- Similar apparatus (generators, transformers, lines) will have similar per-unit impedances and losses expressed on their own rating, regardless of their absolute size.
- Use of the constant $\sqrt{3}$is reduced in three-phase calculations.
- Per-unit quantities are the same on either side of a transformer, independent of voltage level
- By normalizing quantities to a common base, both hand and automatic calculations are simplified.

The per unit system was developed to make manual analysis of power systems easier. Although power system analysis is now done by computer, results are often expressed as per-unit values on a convenient system-wide base.

Base quantities

Generally base values of power and voltage are chosen. The base power may be the rating of a single piece of apparatus such as a motor or generator. If a system is being studied, the base power is usually chosen as a convenient round number such as 10 MVA or 100 MVA. The base voltage is chosen as the nominal rated voltage of the system. All other base quantities are derived from these two base quantities. Once the base power and the base voltage are chosen, the base current and the base impedance are determined by the natural laws of electrical circuits.

Relationship between units

The relationship between units in a per-unit system depends on whether the system is single phase or three phase.

Single phase

Assuming that the independent base values are power and voltage, we have:

$$P_{base} = 1pu$$
$$V_{base} = 1pu$$

Alternatively, the base value for power may be given in terms of reactive or apparent power, in which case we have, respectively,

$$Q_{base} = 1pu$$

or

$$S_{base} = 1pu$$

The rest of the units can be derived from power and voltage using the equations $S = IV$, $P = Scos(\varphi)$, $Q = Ssin(\varphi)$ and $\underline{V} = \underline{IZ}$(Ohm's law), Z being represented by $\underline{Z} = R + jX = Zcos(\phi) + jZsin(\phi)$. We have:

$$I_{base} = \frac{S_{base}}{V_{base}} = 1pu$$

$$Z_{base} = \frac{V_{base}}{I_{base}} = \frac{V_{base}^2}{I_{base}V_{base}} = \frac{V_{base}^2}{S_{base}} = 1pu$$
$$Y_{base} = \frac{1}{Z_{base}} = 1pu$$

Three phase

Power and voltage are specified in the same way as single phase systems. However, due to differences in what these terms usually represent in three phase systems, the relationships for the derived units are different. Specifically, power is given as total (not per-phase) power, and voltage is line to line voltage. In three phase systems the equations $P = Scos(\varphi)$ and $Q = Ssin(\varphi)$ also hold. The apparent power S now equals $S_{base} = \sqrt{3}V_{base}I_{base}$

$$I_{base} = \frac{S_{base}}{V_{base} \times \sqrt{3}} = 1pu$$
$$Z_{base} = \frac{V_{base}}{I_{base} \times \sqrt{3}} = \frac{V_{base}^2}{S_{base}} = 1pu$$
$$Y_{base} = \frac{1}{Z_{base}} = 1pu$$

Example of per-unit

As an example of how per-unit is used, consider a three phase power transmission system that deals with powers on the order of 500 MW and uses a nominal voltage of 138 kV for transmission. We arbitrarily select S_{base} = 500 MVA, and use the nominal voltage 138 kV as the base voltage V_{base}. We then have:

$$I_{base} = \frac{S_{base}}{V_{base} \times \sqrt{3}} = 2.09\,\mathrm{kA}$$
$$Z_{base} = \frac{V_{base}}{I_{base} \times \sqrt{3}} = \frac{V_{base}^2}{S_{base}} = 38.1\,\Omega$$
$$Y_{base} = \frac{1}{Z_{base}} = 26.3\,\mathrm{mS}$$

If, for example, the actual voltage at one of the buses is measured to be 136 kV, we have:

$$V_{pu} = \frac{V}{V_{base}} = \frac{136\,\mathrm{kV}}{138\,\mathrm{kV}} = 0.9855\,\mathrm{pu}$$

Chapter 9

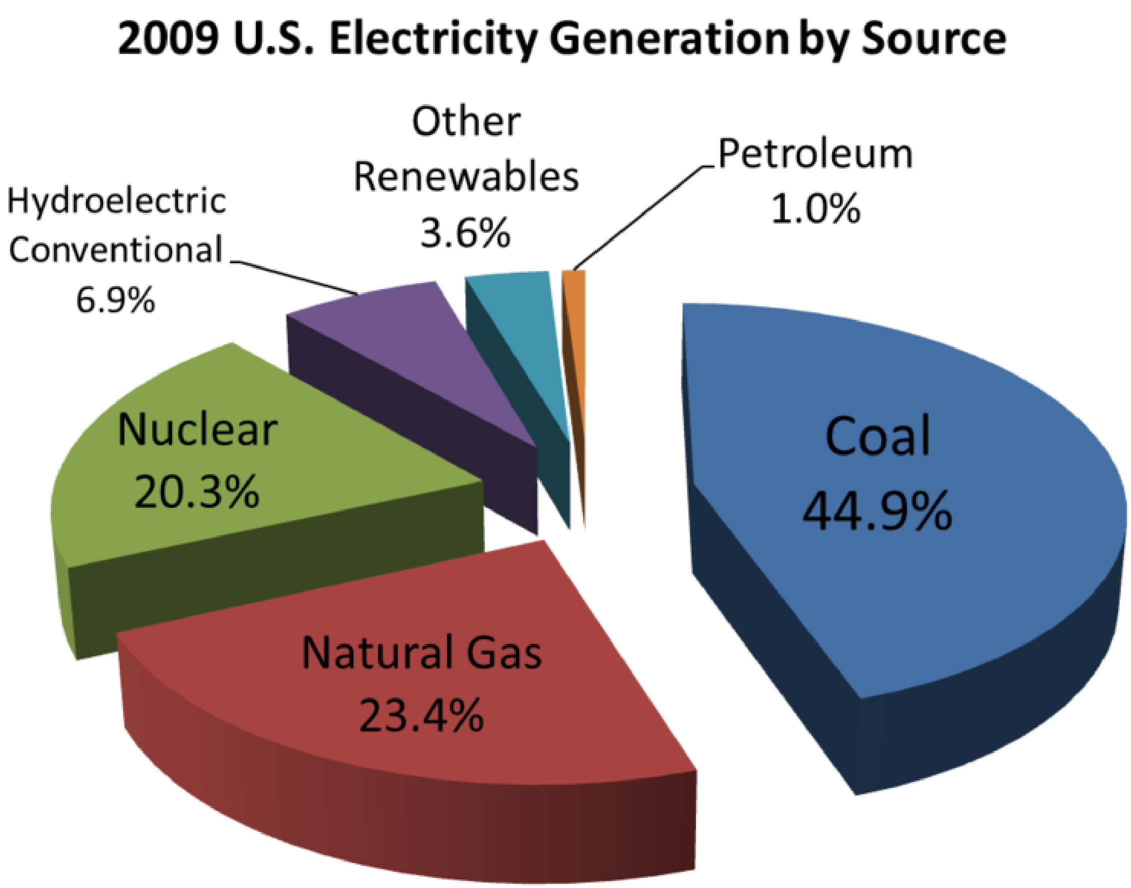
Electricity Generation

Electricity generation is the process of generating electric energy from other forms of energy.

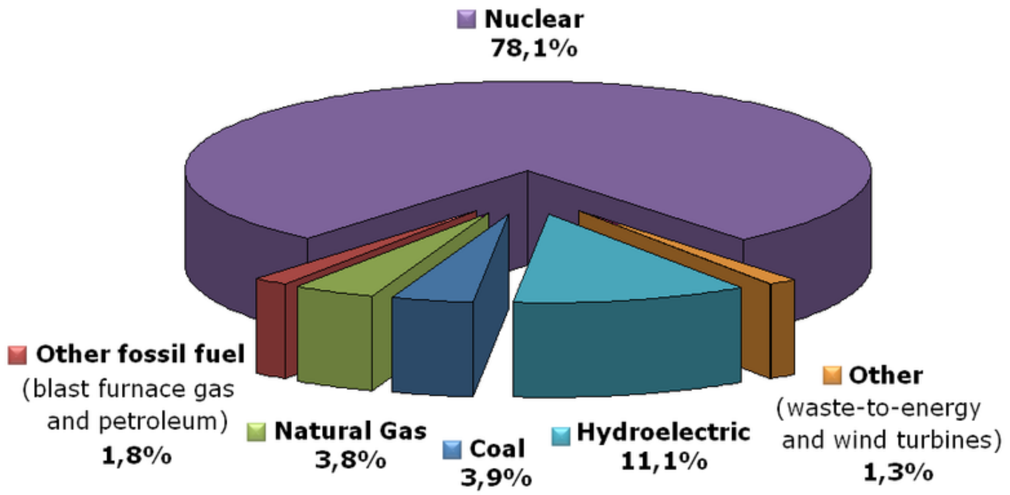
The fundamental principles of electricity generation were discovered during the 1820s and early 1830s by the British scientist Michael Faraday. His basic method is still used today: electricity is generated by the movement of a loop of wire, or disc of copper between the poles of a magnet.

For electric utilities, it is the first process in the delivery of electricity to consumers. The other processes, electricity transmission, distribution, and electrical power storage and recovery using pumped storage methods are normally carried out by the electric power industry.

Electricity is most often generated at a power station by electromechanical generators, primarily driven by heat engines fueled by chemical combustion or nuclear fission but also by other means such as the kinetic energy of flowing water and wind. There are many other technologies that can be and are used to generate electricity such as solar photovoltaics and geothermal power.



Sources of electricity in the U.S. in 2009 fossil fuel generation (mainly coal) was the largest source.



Sources of electricity in France in 2006; nuclear power was the main source.

History

Centralised power generation became possible when it was recognised that alternating current power lines can transport electricity at very low costs across great distances by taking advantage of the ability to raise and lower the voltage using power transformers.

Electricity has been generated at central stations since 1881. The first power plants were run on water power or coal, and today we rely mainly on coal, nuclear, natural gas, hydroelectric, and petroleum with a small amount from solar energy, tidal harnesses, wind generators, and geothermal sources.

Methods of generating electricity

There are seven fundamental methods of directly transforming other forms of energy into electrical energy:

- Static electricity, from the physical separation and transport of charge (examples: triboelectric effect and lightning)
- Electromagnetic induction, where an electrical generator, dynamo or alternator transforms kinetic energy (energy of motion) into electricity
- Electrochemistry, the direct transformation of chemical energy into electricity, as in a battery, fuel cell or nerve impulse
- Photoelectric effect, the transformation of light into electrical energy, as in solar cells
- Thermoelectric effect, direct conversion of temperature differences to electricity, as in thermocouples, thermopiles, and Thermionic converters.

- Piezoelectric effect, from the mechanical strain of electrically anisotropic molecules or crystals
- Nuclear transformation, the creation and acceleration of charged particles (examples: betavoltaics or alpha particle emission)

Static electricity was the first form discovered and investigated, and the electrostatic generator is still used even in modern devices such as the Van de Graaff generator and MHD generators. Electrons are mechanically separated and transported to increase their electric potential.

Almost all commercial electrical generation is done using electromagnetic induction, in which mechanical energy forces an electrical generator to rotate. There are many different methods of developing the mechanical energy, including heat engines, hydro, wind and tidal power.

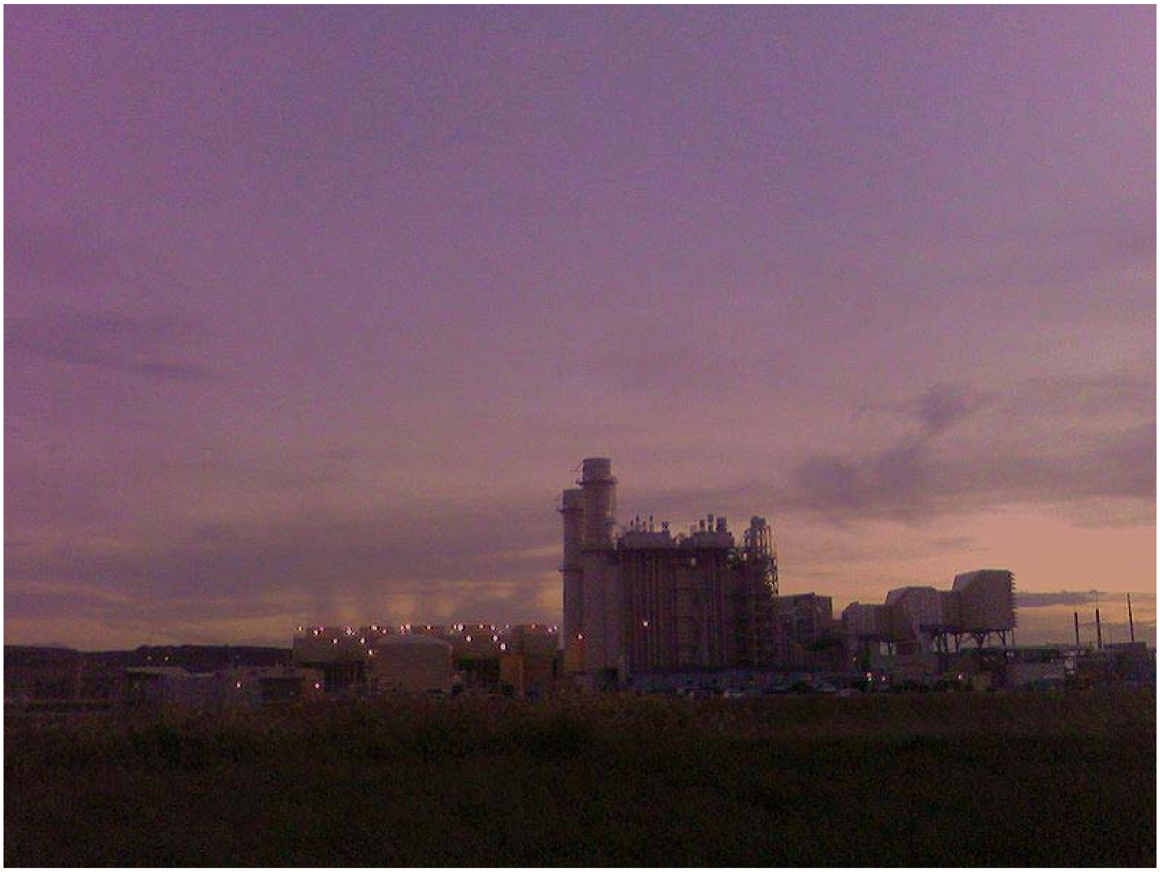
The direct conversion of nuclear energy to electricity by beta decay is used only on a small scale. In a full-size nuclear power plant, the heat of a nuclear reaction is used to run a heat engine. This drives a generator, which converts mechanical energy into electricity by magnetic induction.

Most electric generation is driven by heat engines. The combustion of fossil fuels supplies most of the heat to these engines, with a significant fraction from nuclear fission and some from renewable sources. The modern steam turbine invented by Sir Charles Parsons in 1884 - today generates about 80 percent of the electric power in the world using a variety of heat sources.

Turbines

Large dams such as Three Gorges Dam in China can provide large amounts of hydroelectric power; it will have a 22.5 GW capability.

Susquehanna Steam Electric Station, a nuclear power plant.



A combined cycle natural gas power plant near Orem, Utah.

All turbines are driven by a fluid acting as an intermediate energy carrier. Many of the heat engines just mentioned are turbines. Other types of turbines can be driven by wind or falling water.

Sources include:

- **Steam** - Water is boiled by:
    - Nuclear fission,
    - The burning of fossil fuels (coal, natural gas, or petroleum). In hot gas (gas turbine), turbines are driven directly by gases produced by the combustion of natural gas or oil. Combined cycle gas turbine plants are driven by both steam and natural gas. They generate power by burning natural gas in a gas turbine and use residual heat to generate additional electricity from steam. These plants offer efficiencies of up to 60%.
    - Renewables. The steam generated by:
        - Biomass
        - The sun as the heat source: solar parabolic troughs and solar power towers concentrate sunlight to heat a heat transfer fluid, which is then used to produce steam.

        - Geothermal power. Either steam under pressure emerges from the ground and drives a turbine or hot water evaporates a low boiling liquid to create vapour to drive a turbine.
        - Ocean thermal energy conversion (OTEC): uses the small difference between cooler deep and warmer surface ocean waters to run a heat engine usually a turbine.

- Other renewable sources:
    - **Water** (hydroelectric) - Turbine blades are acted upon by flowing water, produced by hydroelectric dams or tidal forces.
    - **Wind** - Most wind turbines generate electricity from naturally occurring wind. Solar updraft towers use wind that is artificially produced inside the chimney by heating it with sunlight, and are more properly seen as forms of solar thermal energy.

Reciprocating engines

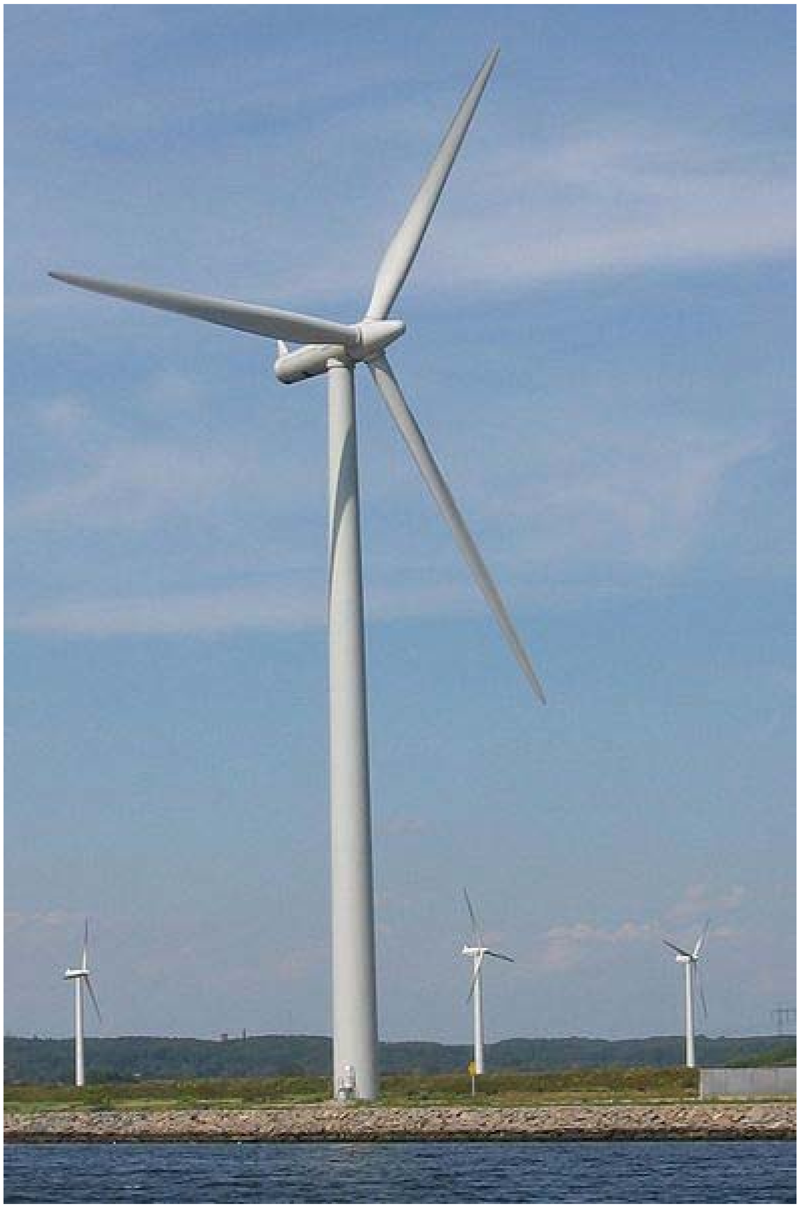
Small electricity generators are often powered by reciprocating engines burning diesel, biogas or natural gas. Diesel engines are often used for back up generation, usually at low voltages. However most large power grids also use diesel generators, originally provided as emergency back up for a specific facility such as a hospital, to feed power into the grid during certain circumstances. Biogas is often combusted where it is produced, such as a landfill or wastewater treatment plant, with a reciprocating engine or a microturbine, which is a small gas turbine.

A coal-fired power plant in Laughlin, Nevada U.S.A. Owners of this plant ceased operations after declining to invest in pollution control equipment to comply with pollution regulations.

Photovoltaic panels

Unlike the solar heat concentrators mentioned above, photovoltaic panels convert sunlight directly to electricity. Although sunlight is free and abundant, solar electricity is still usually more expensive to produce than large-scale mechanically generated power due to the cost of the panels. Low-efficiency silicon solar cells have been decreasing in cost and multijunction cells with close to 30% conversion efficiency are now commercially available. Over 40% efficiency has been demonstrated in experimental systems. Until recently, photovoltaics were most commonly used in remote sites where there is no access to a commercial power grid, or as a supplemental electricity source for individual homes and businesses. Recent advances in manufacturing efficiency and photovoltaic technology, combined with subsidies driven by environmental concerns, have dramatically accelerated the deployment of solar panels. Installed capacity is growing by 40% per year led by increases in Germany, Japan, California and New Jersey.

Other generation methods



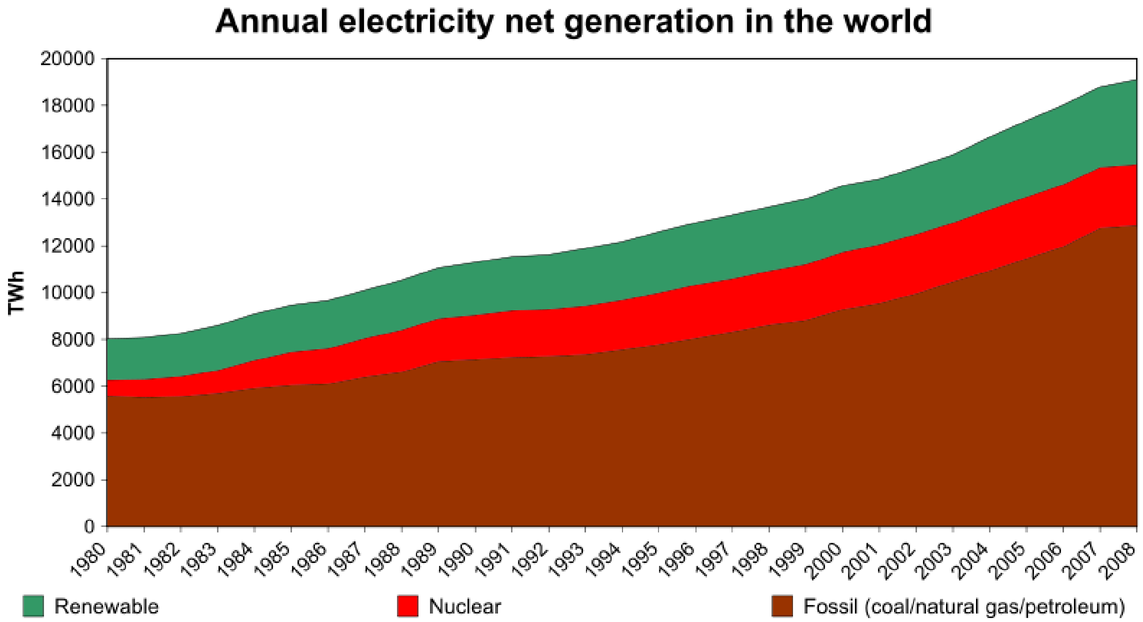
Wind-powered turbines usually provide electrical generation in conjunction with other methods of producing power.

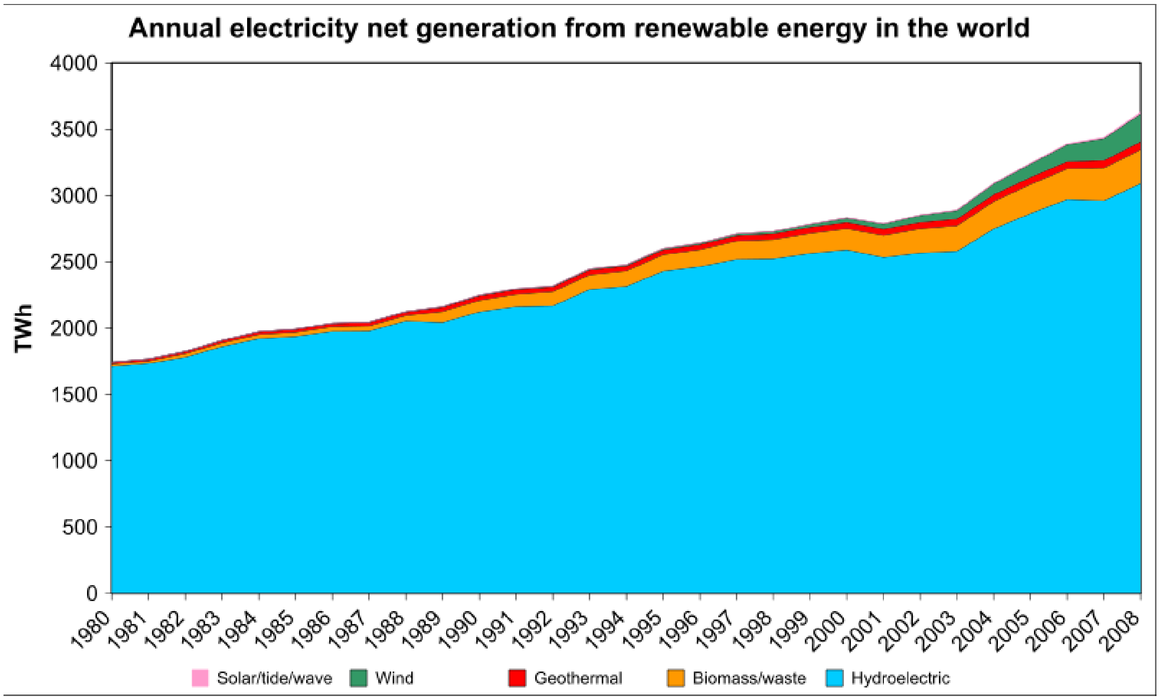
Various other technologies have been studied and developed for power generation. Solid-state generation (without moving parts) is of particular interest in portable applications. This area is largely dominated by thermoelectric (TE) devices, though thermionic (TI) and thermophotovoltaic (TPV) systems have been developed as well. Typically, TE devices are used at lower temperatures than TI and TPV systems. Piezoelectric devices are used for power generation from mechanical strain, particularly in power harvesting. Betavoltaics are another type of solid-state power generator which produces electricity from radioactive decay. Fluid-based magnetohydrodynamic (MHD) power generation has been studied as a method for extracting electrical power from nuclear reactors and also from more conventional fuel combustion systems. Osmotic power finally is another possibility at places where salt and sweet water merges (e.g. deltas, ...)

Electrochemical electricity generation is also important in portable and mobile applications. Currently, most electrochemical power comes from closed electrochemical cells ("batteries"), which are arguably utilized more as storage systems than generation systems, but open electrochemical systems, known as fuel cells, have been undergoing a great deal of research and development in the last few years. Fuel cells can be used to extract power either from natural fuels or from synthesized fuels (mainly electrolytic hydrogen) and so can be viewed as either generation systems or storage systems depending on their use.

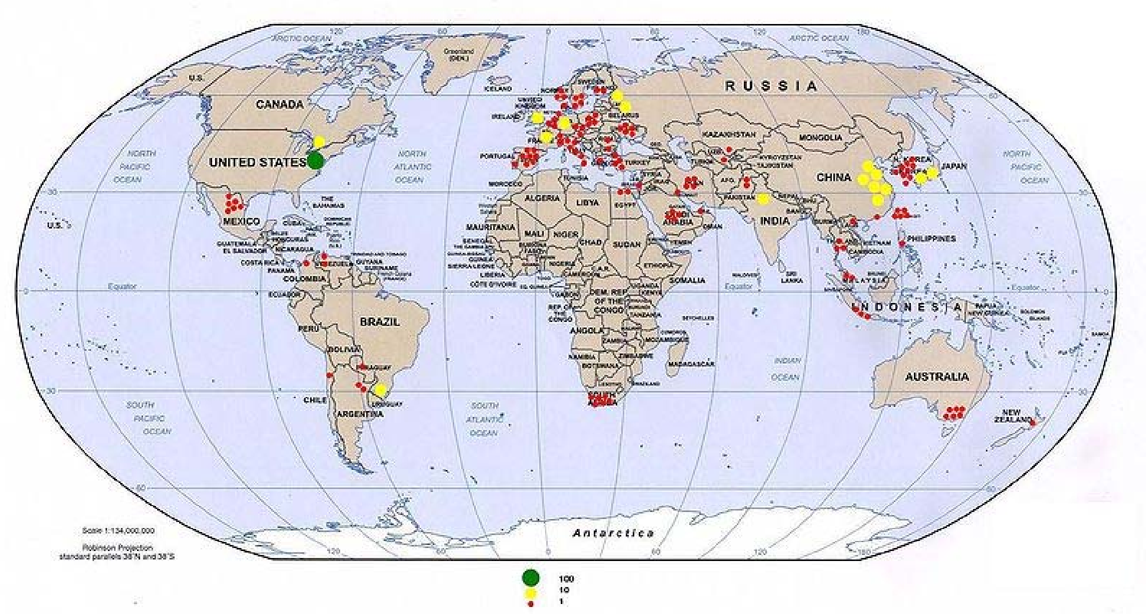
Cost of generating electricity

Production


Annual electricity net generation in the world


Annual electricity net generation from renewable energy in the world

Production by country



Electricity output in 2005

The United States has long been the largest producer and consumer of electricity, with a global share in 2005 of at least 25%, followed by China, Japan, Russia, and India.

As of Jan-2010, total electricity generation for the 2 largest generators were as follows:

USA: 3992 billion kWh (3992 TWh)

China: 3715 billion kWh (3715 TWh)

Environmental Concerns

Most scientists agree that emissions of pollutants and greenhouse gases from fossil fuel-based electricity generation account for a significant portion of world greenhouse gas emissions; in the United States, electricity generation accounts for nearly 40 percent of emissions, the largest of any source. Transportation emissions are close behind, contributing about one-third of U.S. production of carbon dioxide.

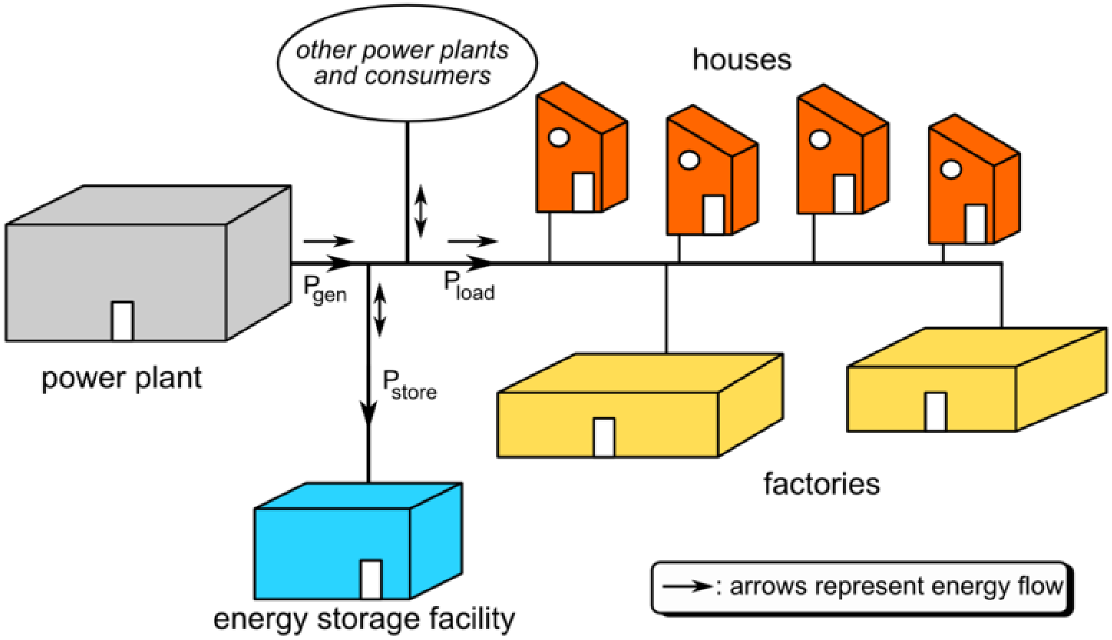
In the United States, fossil fuel combustion for electric power generation is responsible for 65% of all emissions of sulfur dioxide, the main component of acid rain. Electricity generation is the fourth highest combined source of NOx, carbon monoxide, and particulate matter in the US.

Water Consumption

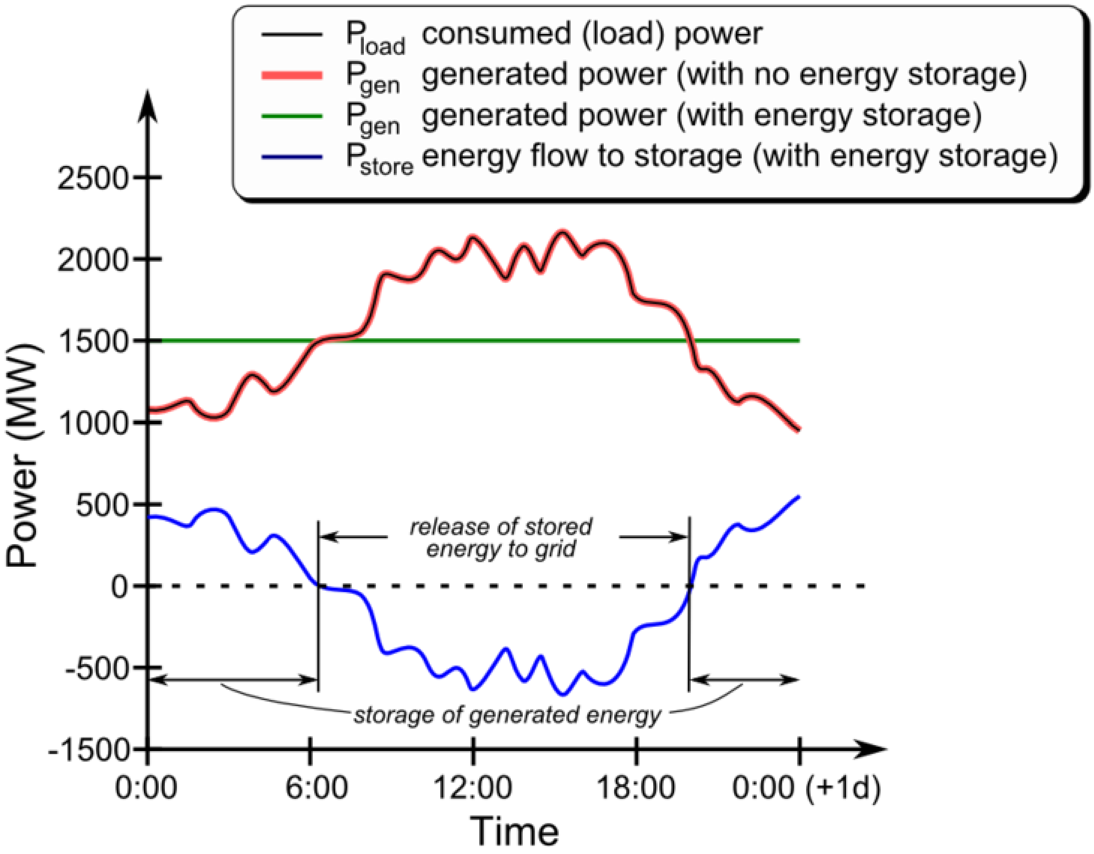
Most large scale conventional electricity-only fossil fueled power stations consume considerable amounts of water for cooling purposes and boiler water make up - 1 L/kWh for once through (e.g. river cooling), and 1.7 L/kWh for cooling tower cooling. Water abstraction for cooling water accounts for about 40% of European total water abstraction, although most of this is returned to the original water body - river / lake albeit slightly warmer

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

Intermittent Energy Source

An **intermittent energy source** is any source of energy that is not continuously available due to some factor outside direct control. The intermittent source may be quite predictable, for example, tidal power, but cannot be dispatched to meet the demand of a power system. Examples of intermittent sources include wind and solar power. Effective use of intermittent sources in an electric power grid usually relies on using the intermittent sources to displace fuel that would otherwise be consumed by non-renewable power stations, or by storing energy in the form of renewable pumped storage, compressed air or ice, for use when needed, or as electrode heating for district heating schemes.

The storage of energy to fill the shortfall intermittency or for emergencies is part of a reliable energy supply. The capacity of a reliable renewable energy supply, can additionally be fulfilled by the use of latency measures and backup or extra infrastructure and technology, using mixed renewables to produce electricity above the intermittent average, which may be utilised to meet regular and unanticipated supply demands.

The penetration of intermittent renewables in most power grids is low, but wind for example generates 11% of electric energy in Spain and Portugal, 9% in the Republic of Ireland, and 7% in Germany. Wind provides nearly 20% of the electricity generated in Denmark, however this percentage forces Denmark to import and export large amounts of energy to and from the EU grid, to balance supply with demand.

The use of small amounts of intermittent power has little effect on grid operations. Using larger amounts of intermittent power may require upgrades or even a redesign of the grid infrastructure.

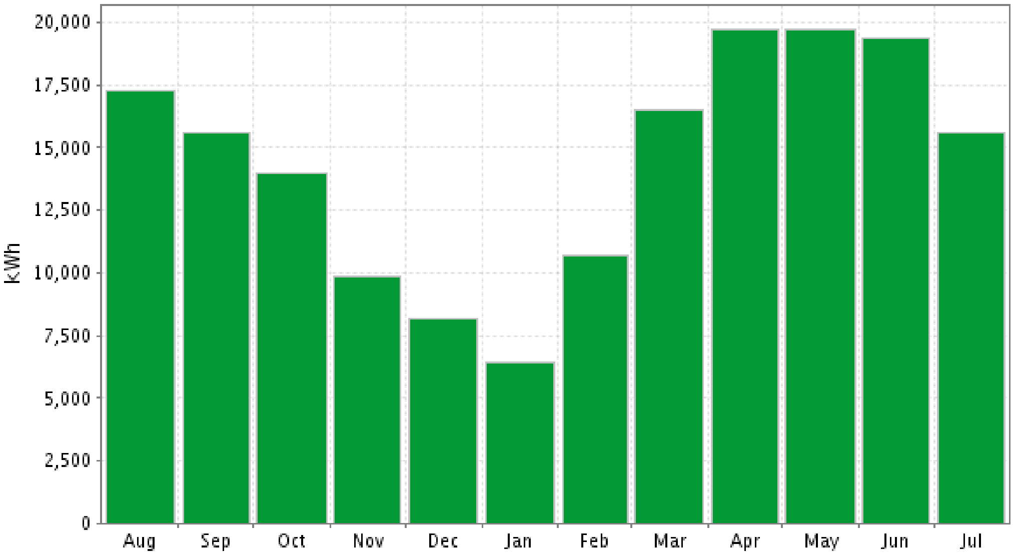
Terminology

Several key terms are useful for understanding the issue of intermittent power sources. These terms are not standardized, and variations may be used. Most of these terms also apply to traditional power plants.

- **Intermittency** can mean the extent to which a power source is unintentionally stopped or unavailable, but intermittency is frequently used as though it were synonymous with **variability**.
- **Variability** is the extent to which a power source may exhibit undesired or uncontrolled changes in output.
- **Dispatchability** or **maneuverability** is the ability of a given power source to increase and/or decrease output quickly on demand. The concept is distinct from intermittency; maneuverability is one of several ways grid operators match output (supply) to system demand.
- **Nominal** or **nameplate capacity**, or **maximum effect** refers to the normal maximum output of a generating source. This is the most common number used and is typically expressed in megawatts (MW).
- **Capacity factor**, **average capacity factor**, or **load factor** is the average expected output of a generator, usually over an annual period. Expressed as a percentage of the nameplate capacity or in decimal form (e.g. 30% or 0.30).
- **Capacity credit**: generally, the amount of output from a power source that may be statistically relied upon, expressed as a percentage.
- **Penetration** in this context is generally used to refer to the amount of energy generated as a percentage of annual consumption.

Intermittency of various power sources

Solar energy



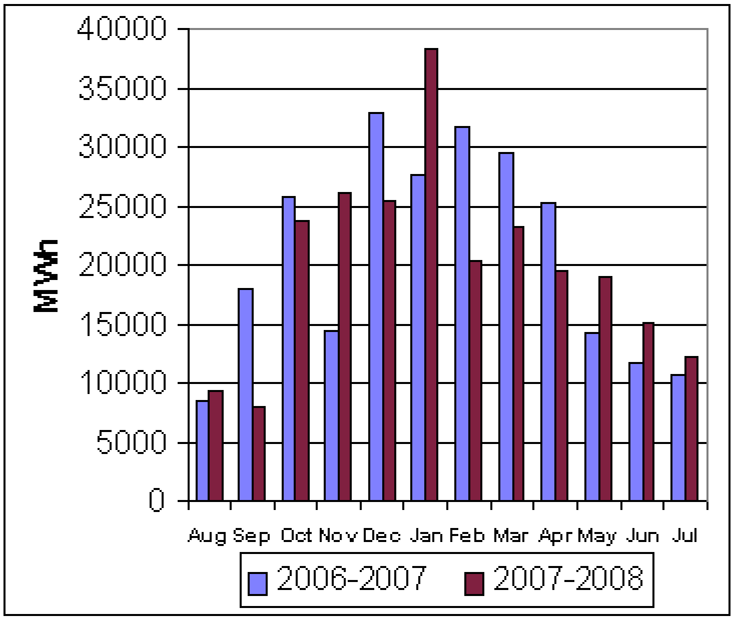
Seasonal variation of the output of the solar panels at AT&T park in San Francisco.

Intermittency inherently affects solar energy, as the production of electricity from solar sources depends on the amount of light energy in a given location. Solar output varies throughout the day and through the seasons, and is affected by cloud cover. These factors are fairly predictable, and some solar thermal systems make use of heat storage to produce power when the sun is not shining.

- **Intermittency:** In the absence of an energy storage system, solar does not produce power at night.
- **Capacity factor** Photovoltaic solar in Massachusetts 12-15%. Photovoltaic solar in Arizona 19% Thermal solar parabolic trough 56% Thermal solar power tower 73%

The extent to which the intermittency of solar-generated electricity is an issue will depend to some extent on the degree to which the generation profile of solar corresponds to demand. For example, solar thermal power plants such as Nevada Solar One are somewhat matched to summer peak loads in areas with significant cooling demands, such as the south-western United States. Thermal energy storage systems can improve the degree of match between supply and consumption. The increase in capacity factor of thermal systems does not represent an increase in efficiency, but rather a spreading out of the time over which the system generates power.

Wind energy



Erie Shores Wind Farm monthly output over a two year period

A wind farm in Muppandal, Tamil Nadu, India

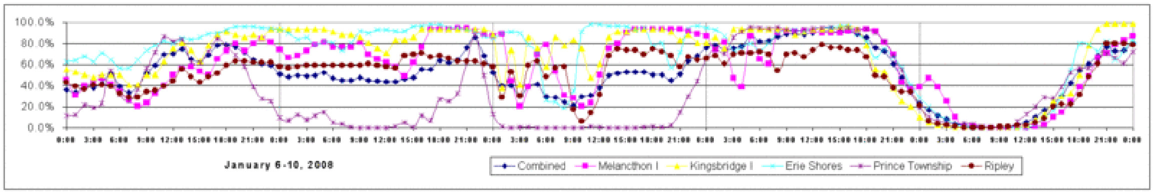
Wind-generated power is a variable resource, and the amount of electricity produced at any given point in time by a given plant will depend on wind speeds, air density, and turbine characteristics (among other factors). If wind speed is too low (less than about 2.5 m/s) then the wind turbines will not be able to make electricity, and if it is too high (more than about 25 m/s) the turbines will have to be shut down to avoid damage. While the output from a single turbine can vary greatly and rapidly as local wind speeds vary, as more turbines are connected over larger and larger areas the average power output becomes less variable.

- **Intermittence:** A single wind turbine is highly intermittent. Theoretical arguments often claim that a large wind farm spread over a geographically diverse area will as a whole rarely stop producing power altogether, however this is in contradiction to the observed variability in total power output of wind turbines installed in Ireland and Denmark.
- **Capacity Factor:** Wind power typically has a capacity factor of 20-40%.
- **Dispatchability:** Wind power is "highly non-dispatchable".
- **Capacity Credit:** At low levels of penetration, the capacity credit of wind is about the same as the capacity factor. As the concentration of wind power on the grid rises, the capacity credit percentage drops.
- **Variability:** Site dependent. Sea breezes are much more constant than land breezes.
- **Reliability:** A wind farm is highly reliable (although highly intermittent). That is, the output at any given time will only vary gradually due to falling wind speeds or storms (the latter necessitating shut downs). A typical wind farm is unlikely to have to shut down in less than half an hour at the extreme, whereas an equivalent sized power station can fail totally instantaneously and without warning. The total shut down of wind turbines is predictable via weather forecasting.

According to a study of wind in the United States, ten or more widely-separated wind farms connected through the grid could be relied upon for from 33 to 47% of their average output (15–20% of nominal capacity) as reliable, baseload power, as long as minimum criteria are met for wind speed and turbine height. When calculating the generating capacity available to meet peak demand, [ERCOT] (manages Texas grid) counts wind generation at 8.7% of nameplate capacity.

Because wind power is generated by large numbers of small generators, individual failures do not have large impacts on power grids. This feature of wind has been referred to as resiliency.

Wind power is affected by air temperature because colder air is more dense and therefore more effective at producing wind power. As a result, wind power is affected seasonally (more output in winter than summer) and by daily temperature variations. During the 2006 California heat storm output from wind power in California significantly decreased to an average of 4% of capacity for 7 days. A similar result was seen during the 2003 European heat wave, when the output of wind power in France, Germany, and Spain fell below 10% during peak demand times.



5 days of hourly output of five wind farms in Ontario

According to an article in EnergyPulse, "the development and expansion of well-functioning day-ahead and real time markets will provide an effective means of dealing with the variability of wind generation."

Nuclear power

Amory Lovins points out that *all* sources of electricity sometimes fail, differing only in how, when, and why. Even giant power plants are intermittent: "they fail unexpectedly in billion-watt chunks, often for long periods". For example in the United States, 132 nuclear plants were built, and 21% were permanently and prematurely closed due to reliability or cost problems, while another 27% have at least once completely failed for a year or more. The remaining U.S. nuclear plants produce approximately 90% of their full-time full-load potential, but even they must shut down (on average) for 39 days every 17 months for refueling and maintenance. To cope with such intermittence by nuclear (and centralized fossil-fuelled) power plants, utilities install a “reserve margin” of roughly 15% extra capacity spinning ready for instant use.

Lovins says that nuclear plants have an additional disadvantage: for safety, they must instantly shut down in a power failure, but for nuclear-physics reasons, they can’t be restarted quickly. For example, during the Northeast Blackout of 2003, nine perfectly operating U.S. nuclear units had to shut down and were later restarted. Lovins states that "twelve days of painfully slow restart later, their average capacity loss had exceeded 50 percent. For the first three days, just when they were most needed, their output was below 3% of normal".

Solving intermittency

Mark Z. Jacobson has studied how wind, water and solar technologies can be integrated to provide the majority of the world's energy needs. He advocates a "smart mix" of renewable energy sources to reliably meet electricity demand:

Because the wind blows during stormy conditions when the sun does not shine and the sun often shines on calm days with little wind, combining wind and solar can go a long way toward meeting demand, especially when geothermal provides a steady base and hydroelectric can be called on to fill in the gaps.

Mark A. Delucchi and Mark Z. Jacobson report that there are at least seven ways to design and operate renewable energy systems so that they will reliably satisfy electricity demand:

- (A) interconnect geographically-dispersed naturally-variable energy sources (e.g., wind, solar, wave, tidal), which smoothes out electricity supply (and demand) significantly.
- (B) use complementary and non-variable energy sources (such as hydroelectric power) to fill temporary gaps between demand and wind or solar generation.
- (C) use “smart” demand-response management to shift flexible loads to a time when more renewable energy is available.
- (D) store electric power, at the site of generation, (in batteries, hydrogen gas, compressed air, pumped hydroelectirc power, and flywheels), for later use.
- (E) over-size renewable peak generation capacity to minimize the times when available renewable power is less than demand and to provide spare power to produce hydrogen for flexible transportation and heat uses.
- (F) store electric power in electric-vehicle batteries, known as "vehicle to grid" or V2G.
- (G) forecast the weather (winds, sunlight, waves, tides and precipitation) to better plan for energy supply needs.

Technological solutions to mitigate large scale wind energy type intermittency exist such as increased interconnection (the European super grid), Demand response, load management, diesel generators (in National Grid), Frequency Response / National Grid Reserve Service type schemes, and use of existing power stations on standby. Studies by academics and grid operators indicate that the cost of compensating for intermittency is expected to be high at levels of penetration above the low levels currently in use today Large, distributed power grids are better able to deal with high levels of penetration than small, isolated grids. For a hypothetical European-wide power grid, analysis has shown that wind energy penetration levels as high as 70% are viable, and that the cost of the extra transmission lines would be only around 10% of the turbine cost, yielding power at around present day prices. Smaller grids may be less tolerant to high levels of penetration.

Matching power demand to supply is not a problem specific to intermittent power sources. Existing power grids already contain elements of uncertainty including sudden and large changes in demand and unforeseen power plant failures. Though power grids are already designed to have some capacity in excess of projected peak demand to deal with these problems, significant upgrades may be required to accommodate large amounts of intermittent power. The International Energy Agency (IEA) states: "In the case of wind power, operational reserve is the additional generating reserve needed to ensure that differences between forecast and actual volumes of generation and demand can be met. Again, it has to be noted that already significant amounts of this reserve are operating on the grid due to the general safety and quality demands of the grid. Wind imposes additional demands only inasmuch as it increases variability and unpredictability. However, these factors are nothing completely new to system operators. By adding another variable, wind power changes the degree of uncertainty, but not the kind..."

Denmark

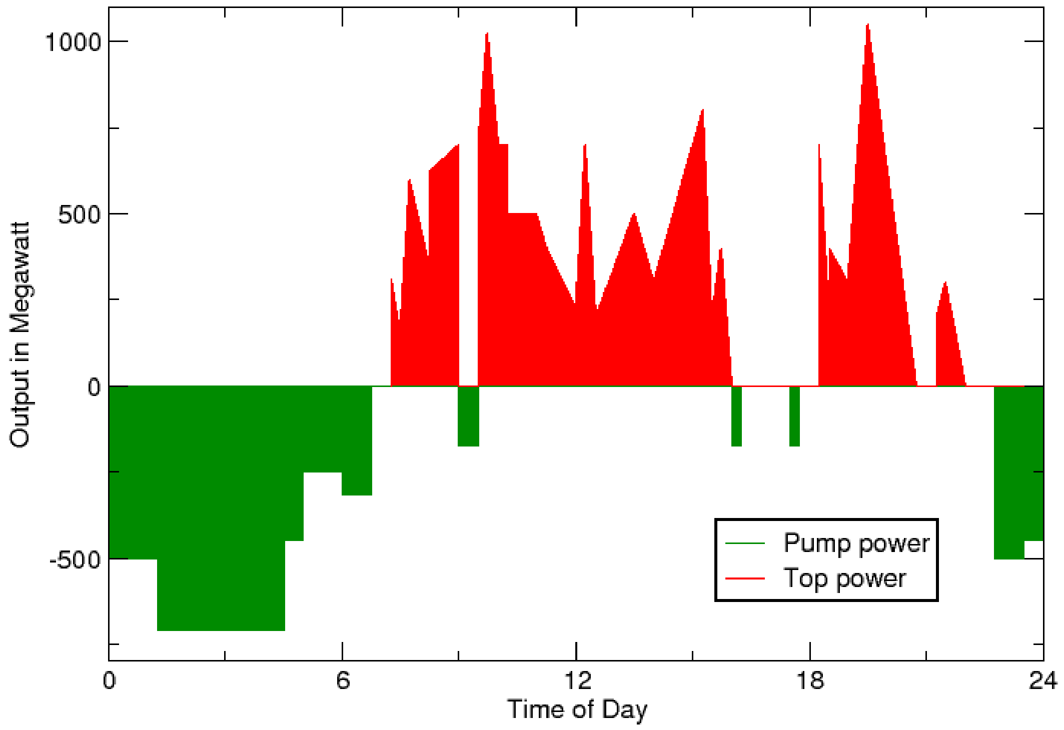
A November 2006 analysis found that "wind power may be able to cover more than 50% of the Danish electricity consumption in 2025" under conditions of high oil prices and higher costs for CO_2 allowances. Denmark's two grids (covering West Denmark and East Denmark separately) each incorporate high-capacity interconnectors to neighbouring grids where some of the variations from wind are absorbed.

Capacity credit, fuel saving and need for extra back-up

Many commentators concentrate on whether or not wind has any "capacity credit" without defining what they mean by this and its relevance. Wind does have a capacity credit, using a widely accepted and meaningful definition, equal to about 20% of its rated output (but this figure varies depending on actual circumstances). This means that reserve capacity on a system equal in MW to 20% of added wind could be retired when such wind is added without affecting system security or robustness.

UK academic commentator Graham Sinden, of Oxford University, argues that this issue of capacity credit is a "red herring" in that the value of wind generation is largely due to the value of displaced fuel, not any perceived capacity credit – it being well understood by the wind energy proponents that conventional capacity will be retained to "fill in" during periods of low or no wind. The main value of wind, (in the UK, 5 times the capacity credit value) is its fuel and CO_2 savings. Wind does not require any extra back-up, as is often wrongly claimed, since it uses the existing power stations, which are already built, as back-up, and which are started up during low wind periods, just as they are started up now, during the non availability of other conventional plant. More spinning reserve, of existing plant, is required, but this again is already built and has a low cost comparatively.

Hydroelectricity



Power output of a pumped-storage plant. Green areas show excess power being stored, and red areas show power being given back when needed.

Hydroelectric power is usually extremely dispatchable and more reliable than other renewable energy sources. Many dams can provide hundreds of megawatts within seconds of demand. The exact nature of the power availability depends on the type of plant.

In run-of-the-river hydroelectricity, power availability is highly dependent on the flow of the river, making this type of generation mostly suitable only at locations where flow levels are controlled by upstream dams.

In conventional hydroelectric plants, there is a reservoir and a one-way generator. The water flow through its turbines can be adjusted frequently to meet changing demand throughout the day by running the generator when demand is high and not running it when demand is low.

Pumped-storage hydroelectricity can make an even more significant contribution to peaking ability of the grid. These just move water between reservoirs and are powered by power *from* the grid when demand is low and put power back *into* the grid when demand is high. There also exist combined pump-storage plants that use river flow as well as extra pumping when demand is low, such as the 240 MW Lewiston Pump-Generating Plant.

Direct pumped-storage does not contribute any net generation to the grid, in fact, it increases the fuel used by other power plants because there is inefficiency in the turbine/generator. The economic benefit of pumped-storage plants lies only in increasing the capacity of the grid. This type of plant works well on a grid with many nuclear or renewable energy plants because the fuel is very cheap or essentially free, so it costs very little to keep them running at high power during the night when demand is low. Both pump-storage plants and natural flow hydro plants can help allow for intermittency of other plants by running at higher capacity for short times, but assistance is limited by the total capacity of the hydroelectric plant.

Conventional power stations

Once a conventional power station has come offline it may stay that way for more than a week.

Conventional power plants (as well as nuclear plants) use water for cooling, and water shortages during hot summer months have occasionally resulted in periods when output has had to be curtailed, notably in France in 2006.

Conventional power plant failures can remove large amounts of capacity from the grid suddenly, resulting in blackouts.

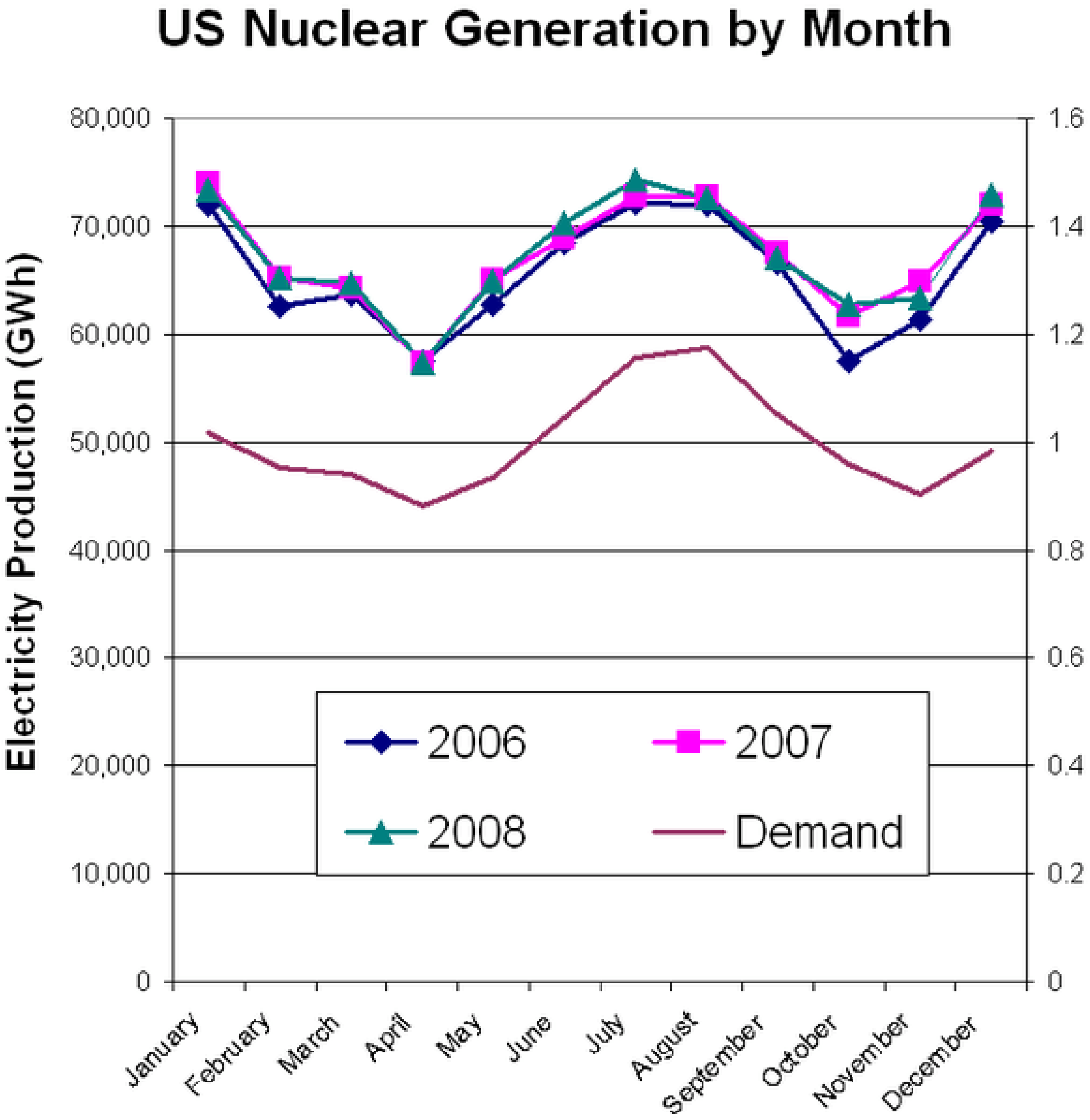
- **Capacity factor**: Base load coal plant 70–90%

Gas-fired generation

Gas-fired plants are typically very reliable and dispatchable. These kinds of plants also often have the ability to quickly vary their output to adjust to the frequent jumps and changes in consumer demand. Thus these are very good as peaking units. These benefits are weighted against the high price of gas when deployed in the grid.

- **Capacity factor**: about 60%.

Nuclear power



Seasonal variation in total nuclear power delivered to the grid in the United States compared to the demand cycle.

Nuclear power is considered a **base load** power source, in that its output is nearly constant and other types of plants are adjusted with changes in demand. This is done because output changes can only be made in small increments, and because of small fuel costs - there is little marginal cost between running at a low power and a high power, therefore it is cheapest for the system to run the nuclear plants at high power.

Every year or two (depending on the plant), the plant must be shut down for planned outages for about a month. This is typically done in the spring or autumn (fall) when electricity demand is lower, as such, on a national scale power output from nuclear increases corresponding with demand during the peak summer and winter months. This change in output commonly occurs on a yearly basis.

It is rare that nuclear power plants adjust their power output to correspond with demand on a daily basis because pressurized water reactors (PWR, which are the vast majority of nuclear power plants) use a chemical shim in the moderator–coolant to control their power level. (Boiling water reactors (BWR), however, can use a combination of control rods and recirculation water flow speed to control their power level, and so in markets such as Chicago, Illinois where half of the local utility's fleet is BWRs it is common to load-follow although less economic to do so.)

- **Intermittence**: Unplanned outages worldwide caused power losses varying from 3.1% and 1.4% of capacity between 1995 and 2005. Over that same period reactors worldwide encountered an average of 1.1 to 0.6 SCRAMs per 7,000 hours critical (about a year of operation.) An automatic SCRAM is a protective measure that shuts the reactor down suddenly for safety reasons.
- **Capacity factor**: U.S. average 92%. Worldwide average varied between about 81% to 87% between 1995 and 2005.

In the UK one of the key criteria for determining the amount of required spinning reserve is the possible loss of Sizewell B, a 1.2 GW nuclear power plant. At one point in the fall of 2007, out of 16 nuclear power stations in the UK, seven were offline due to a combination of planned and unplanned outages.

Diesel engine generation

Small high-speed diesels are very commonly used within large power grids throughout North America and Europe. France uses about 5 GW of such diesels to cover the intermittency of their nuclear stations; these are all in private hands - at small scales factories and the like - with their usage being triggered semi-randomly by a special tariff - EJP - which encourages these users to start their diesels.

In USA and UK these diesels have usually been purchased for other reasons e.g. for emergency standby, in water works, hotels, hospitals, etc. and in some cases for electricity substations - e.g. Cuyahoga Falls, USA (10 × 1.6 MW Caterpillar) and Tregarron Mid Wales UK (3 × 1.6 MW Caterpillar), but can be readily used to automatically synchronize and feed into the grid.

In the UK 500 MW of such plant is routinely started within a few minutes; this is perfectly acceptable to the engines' service life in a scheme operated by National Grid called National Grid Reserve Service. It has been established that there is 20 GW of such diesel plant in the UK and it has been pointed out that there is no technical reason why this quantity could not be brought into the Reserve Service scheme to assist handling very rapid changes in renewable output, whilst conventional plant is started or indeed stopped.

Compensating for variability

All sources of electrical power have some degree of unpredictability, and demand patterns routinely drive large swings in the amount of electricity that suppliers feed into the grid. Wherever possible, grid operations procedures are designed to match supply with demand at high levels of reliability, and the tools to influence supply and demand are well-developed. The introduction of large amounts of highly variable power generation may require changes to existing procedures and additional investments.

Operational reserve

All managed grids already have existing operational and "spinning" reserve to compensate for existing uncertainties in the power grid. The addition of intermittent resources such as wind does not require 100% "back-up" because operating reserves and balancing requirements are calculated on a system-wide basis, and not dedicated to a specific generating plant.

- Some coal, gas, or hydro power plants are partially loaded and then controlled to change as demand changes or to replace rapidly lost generation. The ability to change as demand changes is termed "response." The ability to quickly replace lost generation, typically within timescales of 30 seconds to 30 minutes, is termed "spinning reserve."
- Generally thermal plants running as peaking plants will be less efficient than if they were running as base load.
- Hydroelectric facilities with storage capacity (such as the traditional dam configuration) may be operated as base load or peaking plants.
- In practice, as the power output from wind varies, partially loaded conventional plants, which are already present to provide response and reserve, adjust their output to compensate.
- While low penetrations of intermittent power may utilize existing levels of response and spinning reserve, the larger overall variations at higher penetrations levels will require additional reserves or other means of compensation.

Demand reduction or increase

- Demand response refers to the use of communication and switching devices which can release deferrable loads quickly, or absorb additional energy to correct supply/demand imbalances. Incentives have been widely created in the American, British and French systems for the use of these systems, such as favorable rates or capital cost assistance, encouraging consumers with large loads to take them off line or to start diesels whenever there is a shortage of capacity, or conversely to increase load when there is a surplus.
- Load Control allows the power company to turn loads off remotely if insufficient power is available. In France large users such as CERN cut power usage as required by the System Operator - EDF under the encouragement of the EJP tarrif.

- Energy demand management refers to incentives to adjust use of electricity, such as higher rates during peak hours.
- Real-time variable electricity pricing can encourage users to adjust usage to take advantage of periods when power is cheaply available and avoid periods when it is more scarce and expensive.
- Instantaneous demand reduction. Most large systems also have a category of loads which instantly disconnect when there is a generation shortage, under some mutually beneficial contract. This can give instant load reductions (or increases).

- Diesel generators, originally or primarily installed for emergency power supply are often also connected to the National Grid in the UK to help deal with short term demand supply mismatches.

Storage and demand loading

At times of low or falling demand where wind output may be high or increasing, grid stability may require lowering the output of various generating sources or even increasing demand, possibly by using energy storage to time-shift output to times of higher demand. Such mechanisms can include:

- Pumped storage hydropower is the most prevalent existing technology used, and can substantially improve the economics of wind power. The availability of hydropower sites suitable for storage will vary from grid to grid. Typical round trip efficiency is 80%.
- Thermal energy storage stores heat. Stored heat can be used directly for heating needs or converted into electricity.
- Ice storage air conditioning Ice can be stored inter seasonally and can be used as a source of air-conditioning during periods of high demand. Present systems only need to store ice for a few hours but are well developed.
- Hydrogen can be created through electrolysis and stored for later use. NREL found that a kilogram of hydrogen (roughly equivalent to a gallon of gasoline) could be produced for between $5.55 in the near term and $2.27 in the long term.
- Rechargeable flow batteries can serve as a large capacity, rapid-response storage medium.
- Some loads such as desalination plants and electric boilers, are able to store their output (water and heat.) These "opportunistic loads" are able to take advantage of "burst electricity" when it is available.
- Various other potential applications are being considered, such as charging plug-in electric vehicles during periods of low demand and high production; such technologies are not widely used at this time.

Storage of electrical energy results in some lost energy because storage and retrieval are not perfectly efficient. Storage may also require substantial capital investment and space for storage facilities.

Geographic diversity

The variability of production from a single wind turbine can be high. Combining any additional number of turbines (for example, in a wind farm) results in lower statistical variation, as long as the correlation between the output of each turbine is imperfect, and the correlations are always imperfect due to the distance between each turbine. Similarly, geographically distant wind turbines or wind farms have lower correlations, reducing overall variability. Since wind power is dependent on weather systems, there is a limit to the benefit of this geographic diversity for any power system.

Multiple wind farms spread over a wide geographic area and gridded together produce power more constantly and with less variability than smaller installations. Wind output can be predicted with some degree of confidence using weather forecasts, especially from large numbers of turbines/farms. The ability to predict wind output is expected to increase over time as data is collected, especially from newer facilities.

Complementary power sources and matching demand

- Electricity produced from solar energy could be a counter balance to the fluctuating supplies generated from wind. In some locations, it tends to be windier at night and during cloudy or stormy weather, so there is likely to be more sunshine when there is less wind.
- In some locations, electricity demand may have a high correlation with wind output, particularly in locations where cold temperatures drive electric consumption (as cold air is denser and carries more energy).
- The allowable penetration may be further increased by increasing the amount of part-loaded generation available. Systems with existing high levels of hydroelectric generation may be able to incorporate substantial amounts of wind, although high hydro penetration may indicate that hydro is already a low-cost source of electricity; Norway, Quebec, and Manitoba all have high levels of existing hydroelectric generation (Quebec produces over 90% of its electricity from hydropower, and the local utility, Hydro-Québec, is the largest single hydropower producer in the world). The US Pacific Northwest has been identified as another region where wind energy is complemented well by existing hydropower, and there were "no fundamental technical barriers" to integrating up to 6,000 MW of wind capacity. Storage capacity in hydropower facilities will be limited by size of reservoir, and environmental and other considerations.
- The Institute for Solar Energy Supply Technology of the University of Kassel, Germany pilot-tested a combined power plant linking solar, wind, biogas and hydrostorage to provide load-following power around the clock, entirely from renewable sources.

Export & import arrangements with neighboring systems

- It is often feasible to export energy to neighboring grids at times of surplus, and import energy when needed. This practice is common in Western Europe and North America.
- Integration with other grids can lower the effective concentration of variable power. Denmark's 44% penetration, in the context of the German/Dutch/Scandinavian grids with which it has interconnections, is considerably lower as a proportion of the total system. This effect is diminished if more neighboring grids also have high penetration levels of variable power.
- Integration of grids may decrease the overall variability of both supply and demand by increasing geographical diversity.
- Methods of compensating for power variability in one grid, such as peaking-plants or pumped-storage hydro-electricity, may be taken advantage of by importing variable power from another grid that is short on such capabilities.
- The capacity of power transmission infrastructure may have to be substantially upgraded to support export/import plans.
- Some energy is lost in transmission.
- The economic value of exporting variable power depends in part on the ability of the exporting grid to provide the importing grid with useful power at useful times for an attractive price.

Penetration

Penetration refers to the proportion of a power source on a system, expressed as a percentage. There are several ways that this can be calculated, with the different methods yielding different penetrations. It can be calculated either as:

- the nominal capacity of a power source divided by peak demand; or
- the nominal capacity of a power source divided by total capacity; or
- the average power generated by a power source, divided by the average system demand.

The level of penetration of intermittent variable sources is significant for the following reasons:

- As penetration increases, the variations in power produced for the grid become larger and the costs and complexity of compensating for these variations increases.
- Large, geographically distributed networks may accept a higher penetration of wind than small networks because fluctuations in supply and demand across the entire grid can be averaged out.
- Power grids with significant amounts pumped storage, hydropower or other peaking power plants such as natural gas-fired power plants are more inherently capable of accommodating fluctuations from intermittent power.

- If an intermittent source produces more power than can be used, stored, or exported at that time, then that excess power will be lost.
- Wind power generation tends to be higher in the winter and at night (due to higher air density), so the appropriateness of wind power in high concentrations may crucially depend on the prevalence of air conditioning in a given jurisdiction. Wind power may be weakest in the hot summer months, and particularly during the day when air conditioning demand is highest. Conversely, systems where heat is electrical may be well-suited to higher penetration of wind power.
- Isolated, relatively small systems with only a few wind plants may only be stable and economic with a lower fraction of wind energy (e.g. Ireland), although mixed wind/diesel systems have been used in isolated communities with success at relatively high penetration levels.

The maximum proportion of intermittent power allowable in a power system will thus depend on many factors, including the size of the system, the attainable geographical diversity, the ability of the system to transmit power to where it is needed, storage capabilities, demand control capabilities, the conventional plant mix (coal, gas, nuclear, hydroelectric) and seasonal load factors (heating in winter, air-conditioning in summer) and their statistical correlation with power output.

There is no generally accepted maximum level of penetration, as each system's capacity to compensate for intermittency differs, and the systems themselves will change over time. Discussion of acceptable or unacceptable penetration figures should be treated and used with caution, as the relevance or significance will be highly dependent on local factors, grid structure and management, and existing generation capacity.

For most systems worldwide, existing penetration levels are significantly lower than practical or theoretical maximums; for example, a UK study found that "it is clear that intermittent generation need not compromise electricity system reliability at any level of penetration foreseeable in Britain over the next 20 years, although it may increase costs." As of 2006, Denmark has more than 40% penetration and at least two other countries (Portugal and Germany) have penetration levels (nominal to peak demand) of more than 20%.

Maximum penetration limits

There is no generally accepted maximum penetration of wind energy that would be feasible in any given grid. Rather, economic efficiency and cost considerations are more likely to dominate as critical factors; technical solutions may allow higher penetration levels to be considered in future, particularly if cost considerations are secondary.

High penetration scenarios may be feasible in certain circumstances:

- Power generation for periods of little or no wind generation can be provided by retaining the existing power stations. The cost of using existing power stations for this purpose may be low since fuel costs dominate the operating costs. The actual cost of paying to keep a power station idle, but usable at short notice, may be estimated from published spark spreads and dark spreads. As existing traditional plant ages, the cost of replacing or refurbishing these facilities will become part of the cost of high-penetration wind if they are used only to provide operational reserve.

- Automatic load shedding of large industrial loads and its subsequent automatic reconnection is established technology and used in the UK and US, and known as Frequency Service contractors in the UK. Several GW are switched off and on each month in the UK in this way. Reserve Service contractors offer fast response gas turbines and even faster diesels in the UK, France and US to control grid stability.

- In a close-to-100% wind scenario, surplus wind power can be allowed for by increasing the levels of the existing Reserve and Frequency Service schemes and by extending the scheme to domestic-sized loads. Energy can be stored by advancing deferrable domestic loads such as storage heaters, water heaters, fridge motors, or even hydrogen production, and load can be shed by turning such equipment off.

- Alternatively or additionally, power can be exported to neighboring grids and re-imported later. HVDC cables are efficient with 3% loss per 1000 km and may be inexpensive in certain circumstances. For example an 8 GW link from UK to France would cost about £1 billion using high-voltage direct current cables. Under such scenarios, the amount of transmission capacity required may be many times higher than currently available.

Penetration Studies

Studies have been conducted to assess the viability of specific penetration levels in specific energy markets.

European super grid

A series of detailed modelling studies by Dr. Gregor Czisch, which looked at the European wide adoption of renewable energy and interlinking power grids the European super grid using HVDC cables, indicates that the entire European power usage could come from renewables, with 70% total energy from wind at the same sort of costs or lower than at present. This proposed large European power grid has been called a "super grid."

The model deals with intermittent power issues by using base-load renewables such as hydroelectric and biomass for a substantial portion of the remaining 30% and by heavy use of HVDC to shift power from windy areas to non-windy areas. The report states that "electricity transport proves to be one of the keys to an economical electricity supply" and underscores the importance of "international co-operation in the field of renewable energy use [and] transmission."

Dr. Czisch described the concept in an interview, saying "For example, if we look at wind energy in Europe. We have a winter wind region where the maximum production is in winter and in the Sahara region in northern Africa the highest wind production is in the summer and if you combine both, you come quite close to the needs of the people living in the whole area - let's say from northern Russia down to the southern part of the Sahara."

Grid study in Ireland

A study of the grid in Ireland indicates that it would be feasible to accommodate 42% (of demand) renewables in the electricity mix. This acceptable level of renewable penetration was found in what the study called Scenario 5, provided 47% of electrical capacity (different from demand) with the following mix of renewable energies:

- 6,000 MW wind
- 360 MW base load renewables
- 285 MW additional variable renewables (other intermittent sources)

The study cautions that various assumptions were made that "may have understated dispatch restrictions, resulting in an underestimation of operational costs, required wind curtailment, and CO_2 emissions" and that "The limitations of the study may overstate the technical feasibility of the portfolios analyzed..."

Scenario 6, which proposed renewables providing 59% of electrical capacity and 54% of demand had problems. Scenario 6 proposed the following mix of renewable energies:

- 8,000 MW wind
- 392 MW base load renewables
- 1,685 MW additional variable renewables (other intermittent sources)

The study found that for Scenario 6, "a significant number of hours characterized by extreme system situations occurred where load and reserve requirements could not be met. The results of the network study indicated that for such extreme renewable penetration scenarios, a system re-design is required, rather than a reinforcement exercise." The study declined to analyze the cost effectiveness of the required changes because "determination of costs and benefits had become extremely dependent on the assumptions made" and this uncertainty would have impacted the robustness of the results.

Canada

A study published in October, 2006, by the Ontario Independent Electric System Operator (IESO) found that "there would be minimal system operation impacts for levels of wind capacity up to 5,000 MW," which corresponds to a peak penetration of 17%

Economic impacts of variability

Estimates of the cost of wind energy may include estimates of the "external" costs of wind variability, or be limited to the cost of production. All electrical plant has costs that are separate from the cost of production, including, for example, the cost of any necessary transmission capacity or reserve capacity in case of loss of generating capacity. Many types of generation, particularly fossil fuel derived, will also have cost externalities such as pollution, greenhouse gas emission, and habitat destruction which are generally not directly accounted for. The magnitude of the economic impacts is debated and will vary by location, but is expected to rise with higher penetration levels. At low penetration levels, costs such as operating reserve and balancing costs are believed to be insignificant.

Intermittency may introduce additional costs that are distinct from or of a different magnitude than for traditional generation types. These may include:

- Transmission capacity: transmission capacity may be more expensive than for nuclear and coal generating capacity due to lower load factors. Transmission capacity will generally be sized to projected peak output, but average capacity for wind will be significantly lower, raising cost per unit of energy actually transmitted. However transmission costs are a low fraction of total energy costs.
- Additional operating reserve: if additional wind does not correspond to demand patterns, additional operating reserve may be required compared to other generating types, however this does not result in higher capital costs for additional plants since this is merely existing plants running at low output - spinning reserve. Contrary to statements that all wind must be backed by an equal amount of "back-up capacity", intermittent generators contribute to base capacity "as long as there is some probability of output during peak periods." Back-up capacity is not attributed to individual generators, as back-up or operating reserve "only have meaning at the system level."
- Balancing costs: to maintain grid stability, some additional costs may be incurred for balancing of load with demand. The ability of the grid to balance supply with demand will depend on the rate of change of the amount of energy produced (by wind, for example) and the ability of other sources to ramp production up or scale production down. Balancing costs have generally been found to be low.
- Storage, export and load management: at high penetrations (more than 30%), solutions (described below) for dealing with high output of wind during periods of low demand may be required. These may require additional capital expenditures, or result in lower marginal income for wind producers.

Analyses of costs

Studies have been performed to determine the costs of variability. RenewableUK states:

> “ A review of integration studies, worldwide, suggests that the additional costs of integrating wind are around £2/MWh with 10% wind, rising to £3/MWh with 20% wind. ”

Colorado - Separate reports by Xcel and UCS

An official at Xcel Energy claimed that at 20 percent penetration, additional standby generators to compensate for wind in Colorado would cost $8 per MWh, adding between 13% and 16% to the $50–$60 cost per MWh of wind energy.

The Union of Concerned Scientists conducted a study of the costs to increase the renewable penetration in Colorado to 10% and found that for an average residential bill "customers of municipal utilities and rural electric cooperatives that opt out of the solar energy requirement" would save 4 cents per month, but that for Xcel Energy customers there would be additional cost of about 10 cents per month. Total impact on all consumers would be $4.5 million or 0.01% over two decades.

UK Studies

A detailed study for UK National Grid (a private power company) states "We have estimated that for the case with 8,000 MW of wind needed to meet the 10% renewables target for 2010, balancing costs can be expected to increase by around £2 per MWh of wind production. This would represent an additional £40million per annum, just over 10% of existing annual balancing costs."

In evidence to the UK House of Lords Economic Affairs Select Committee, National Grid have quoted estimates of balancing costs for 40% wind and these lie in the range £500-1000M per annum. "These balancing costs represent an additional £6 to £12 per annum on average consumer electricity bill of around £390."

National Grid notes that "increasing levels of such renewable generation on the system would increase the costs of balancing the system and managing system frequency."

A 2003 report by Carbon Trust and the UK Department of Trade and Industry (DTI) found that the costs for reinforcement and new build of transmission and distribution systems to support 10% renewable electricity in the UK by 2010 would be £1.6 to £2.4 billion. The study classified "Intermittency" as "Not a significant issue" for the 2010 target. The same 2003 study found that achieving 20% renewable electricity in the UK by 2020 would cost £3.2bn to £4.5bn in transmission and distribution system construction and reinforcement. The study classified "Intermittency" as a "Significant Issue" for the 2020 target.

Minnesota

Minnesota study on wind penetration levels and found that "total integration operating cost for up to 25% wind energy" would be less than $0.0045 per kWh (additional).

Intermittency and renewable energy

There are differing views about some sources of renewable energy and intermittency. The World Nuclear Association argues that the sun, wind, tides and waves cannot be controlled to provide directly either continuous base-load power, or peak-load power when it is needed. Proponents of renewable energy use argue that the issue of intermittency of renewables is over-stated, and that practical experience demonstrates this.] In any case, geothermal renewable energy has no intermittency.

Views of critics of high penetration renewable energy use

The World Nuclear Association states that:

"Obviously sun, wind, tides and waves cannot be controlled to provide directly either continuous base-load power, or peak-load power when it is needed,..." "In practical terms non-hydro renewables are therefore able to supply up to some 15–20% of the capacity of an electricity grid, though they cannot directly be applied as economic substitutes for most coal or nuclear power, however significant they become in particular areas with favourable conditions." "If the fundamental opportunity of these renewables is their abundance and relatively widespread occurrence, the fundamental challenge, especially for electricity supply, is applying them to meet demand given their variable and diffuse nature. This means either that there must be reliable duplicate sources of electricity beyond the normal system reserve, or some means of electricity storage." "Relatively few places have scope for pumped storage dams close to where the power is needed, and overall efficiency is less than 80%. Means of storing large amounts of electricity as such in giant batteries or by other means have not been developed."

On December 10, 2007 Patrick Moore, co-chair of the Clean & Safe Energy Coalition - a pro-nuclear group funded by the Nuclear Energy Institute - wrote:

> “ Greenpeace is deliberately misleading the public into thinking that wind and solar energy, both of which are inherently intermittent and unreliable, can replace baseload power that is continuous and reliable. Only three technologies can produce large amounts of baseload power: fossil fuels, hydroelectric plants and nuclear power. Given that we want to reduce fossil fuels and that potential hydroelectric sites are becoming scarce, nuclear power is the main option... Over the past 10 years, Germany and Denmark have poured billions of taxpayers' euros into wind and solar energy in the vain hope that this would allow them to shut down fossil fuel and nuclear plants. They have not ”

> succeeded because every solar panel and every wind turbine must be backed up by reliable power when the sun isn't shining and the wind isn't blowing.

Mr. Moore is a co-founder and former leader of Greenpeace, but he has not been involved with Greenpeace since 1986.

Views of proponents of high penetration renewable energy use

The US Federal Energy Regulatory Commission (FERC) Chairman Jon Wellinghoff has stated that "baseload capacity is going to become an anachronism" and that no new nuclear or coal plants may ever be needed in the United States. This however is a minority viewpoint within President Obama's administration which via expanded federal loan guarantees in the proposed 2011 budget is supporting a nuclear renaissance.

Australian researchers at the University of New South Wales claim to have solved the energy storage problem for solar and wind power with the development of vanadium redox batteries. (U.S. patent issued in 1986).

Some renewable electricity sources have identical variability to coal-fired power stations, so they are base-load, and can be integrated into the electricity supply system without any additional back-up. Examples include:

- Bio-energy, based on the combustion of crops and crop residues, or their gasification followed by combustion of the gas.
- Hot dry rock geothermal power, which is being developed in Australia and the United States.
- Solar thermal electricity, with overnight heat storage in water or rocks, or a thermochemical store as with Nevada Solar One and Solar Tres.

Furthermore, supporters argue that the total electricity generated from a large-scale array of dispersed wind farms, located in different wind regimes, cannot be accurately described as intermittent, because it does not start up or switch off instantaneously at irregular intervals. With a small amount of supplementary peak-load plant, which operates infrequently, large-scale distributed wind power can substitute for some base-load power and be equally reliable.

Hydropower can be intermittent and/or dispatchable, depending on the configuration of the plant. Typical hydroelectric plants in the dam configuration may have substantial storage capacity, and be considered dispatchable. Run of the river hydroelectric generation will typically have limited or no storage capacity, and will be variable on a seasonal or annual basis (dependent on rainfall and snow melt).

Amory Lovins suggests a few basic strategies to deal with these issues:

> "The variability of sun, wind and so on, turns out to be a non-problem if you do several sensible things. One is to diversify your renewables by technology, so that weather conditions bad for one kind are good for another. Second, you diversify by site so they're not all subject to the same weather pattern at the same time because they're in the same place. Third, you use standard weather forecasting techniques to forecast wind, sun and rain, and of course hydro operators do this right now. Fourth, you integrate all your resources — supply side and demand side..."

Moreover, efficient energy use and energy conservation measures can reliably reduce demand for base-load and peak-load electricity.

Several studies have demonstrated the technical feasibility of integrating intermittent power at levels substantially higher than is common in most countries (from 15-30% penetration), and at least three countries have more than 20% wind penetration. Relatively few changes to large grids are normally required and the associated system costs are moderate. International groups are studying much higher penetrations (30-75%, corresponding to up to 20% of national electricity consumption) and preliminary conclusions are that these levels are also technically feasible. In the UK, one summary of other studies indicated that if assuming that wind power contributed less than 20% of UK power consumption, then the intermittency would cause only moderate cost.

Methods to manage wind power integration range from those that are commonly used at present (e.g. demand management) to potential new technologies for grid energy storage. Improved forecasting can also contribute as the daily and seasonal variations in wind and solar sources are to some extent predictable.

The Pembina Institute and the World Wide Fund for Nature state in the Renewable is Doable plan that resilience is a feature of renewable energy:

> Diversity and dispersal also add system security. If one wind turbine fails, the lights won't flicker. If an entire windfarm gets knocked out by a storm, only 40,000 people will lose power. If a single Darlington reactor goes down, 400,000 homes, or key industries, could face instant blackouts. To hedge this extra risk, high premiums have to be paid for decades to ensure large blocks of standby generation.

Chapter 12

Load Following Power Plant

A **load following power plant** is a power plant that adjusts its power output as demand for electricity fluctuates throughout the day. Load following plants are typically in-between base load and peaking power plants in efficiency, speed of startup and shutdown, construction cost, cost of electricity and capacity factor.

Base load and peaking power plants

Base load power plants operate at maximum output. They shut down or reduce power only to perform maintenance or repair. These plants produce electricity at the lowest cost of any type of power plant, and so are most economically used at maximum capacity. Base load power plants include coal, fuel oil, almost all nuclear, geothermal, hydroelectric, biomass and combined cycle natural gas plants.

Peaking power plants operate only during times of peak demand. In countries with widespread air conditioning, demand peaks around the middle of the afternoon, so a typical peaking power plant may start up a couple of hours before this point and shut down a couple of hours after. However, the duration of operation for peaking plants varies from a good portion of the waking day to only a couple dozen hours per year. Peaking power plants include hydroelectric and gas turbine power plants. Many gas turbine power plants can be fueled with natural gas or diesel. Most plants burn natural gas, but a supply of diesel is sometimes kept on hand in case the gas supply is interrupted. Other gas turbines can only burn either diesel or natural gas.

Load following power plants

Load following power plants run during the day and early evening. They either shut down or greatly curtail output during the night and early morning, when the demand for electricity is the lowest. The exact hours of operation depend on numerous factors. One of the most important factors for a particular plant is how efficiently it can convert fuel into electricity. The most efficient plants, which are almost invariably the least costly to run per kilowatt-hour produced, are brought online first. As demand increases, the next most efficient plants are brought online and so on. The status of the electrical grid in that region, especially how much base load generating capacity it has, and the variation in demand are also very important. An additional factor for operational variability is that demand does not vary just between night and day. There are also significant variations in the time of year and day of the week. A region that has large variations in demand will require a large load following and/or peaking power plant capacity because base load power plants can only cover the capacity equal to that needed during times of lowest demand.

Load following power plants include hydroelectric power plants and steam turbine power plants that run on natural gas or heavy fuel oil, although heavy fuel oil plants make up a very small portion of the energy mix. A relatively efficient model of gas turbine that runs on natural gas can also make a decent load following plant.

Gas turbine power plants

Gas turbine power plants are the most flexible in terms of adjusting power level, but are also among the most expensive to operate. Therefore they are generally used as "peaking" units at times of maximum power demand. Gas turbines find only limited application as prime movers for power generation at military facilities. This is because gas turbine generators typically have significantly higher heat rates than steam turbine or diesel power plants; their higher fuel costs quickly outweigh their initial advantages in most applications. Applications to be evaluated include:

1. Supplying relatively large power requirements in a facility where space is at a significant premium, such as hardened structures.
2. Mobile, temporary or difficult access site such as a troop support or line-of-sight station.
3. Peak shaving, in conjunction with a more-efficient generating station.
4. Emergency power, where a gas turbine’s lightweight and relatively vibration-free operation are of greater importance than fuel consumption over short periods of operation. However, the starting time of gas turbines may not be suitable for a given application.
5. Combined cycle or cogeneration power plants where turbine exhaust waste heat can be economically used to generate additional power and thermal energy for process or space heating.

Hydroelectric power plants

Hydroelectric power plants can operate as base load, load following or peaking power plants. They have the ability to start within minutes, and in some cases seconds. How the plant operates depends heavily on its water supply. Many plants do not have enough water to operate anywhere near their full capacity on a continuous basis. Plants that have a large amount of water may operate as base load or as load following power plants. Those that have limited amounts of water may operate as peaking power plants.

Also, the plants may change their operating style depending on the time of year. For example, the plant may operate as a peaking power plant during the dry season, and as a base load or load following power plant during the wet season. This is often done when the reservoir frequently reaches full capacity and water either has to be used for electricity generation or be released through the spillway. Another factor is whether the plants have to release significant quantities of water downstream in order to maintain the stream habitat. Many plants have a base load capacity that is generated with the water released to maintain the stream habitat. For example, a 100 MW hydroelectric plant may generate 5 MW when it is releasing only enough water for downstream habitat.

Except when it is undergoing maintenance and the water is bypassed around the turbines, the plant will always be generating at least 5 MW. Some plants have a small turbine for these releases because it is inefficient to run a little bit of water through a large turbine. Run of the river hydroelectric plants do not have any water storage. They simply divert water from a stream, run it through the turbines and then return it to the stream. For this reason, they are always base load plants. However, they may be forced to shut down or reduce the amount of diverted water when the streamflow is insufficient to provide habitat for aquatic organisms while providing water for electricity generation.

Boiling water reactors

Boiling water reactors (BWR) and Advanced Boiling Water Reactors can use a combination of control rods and the speed of recirculation water flow to quickly reduce their power level down to under 60% of rated power, making them useful for overnight load-following. In markets such as Chicago, Illinois where half of the local utility's fleet is BWRs, it is common to load-follow (although less economic to do so).

Pressurized water reactors

Pressurized water reactors (PWR) use a chemical shim in the moderator/coolant to control power level, and so normally do not load follow. (In most PWRs, control rods are either fully withdrawn or fully inserted - variable control is difficult, partly due to the large bundle sizes.)

In France, however, nuclear power plants use load following. French PWRs use "grey" control rods, in order to replace chemical shim, without introducing a large perturbation of the power distribution. These plants have the capability to make power changes between 30% and 100% of rated power, with a slope of 5% of rated power per minute. Their licensing permits them to respond very quickly to the grid requirements.

Chapter 13

Black Start and Spark Spread

Black start

A **black start** is the process of restoring a power station to operation without relying on the external electric power transmission network.

Toronto during the Northeast Blackout of 2003, an event which required black-starting of generating stations.

Normally, the electric power used within the plant is provided from the station's own generators. If all of the plant's main generators are shut down, station service power is provided by drawing power from the grid through the plant’s transmission line. However, during a wide-area outage, off-site power supply from the grid will not be available. In the absence of grid power, a so-called black start needs to be performed to bootstrap the power grid into operation.

To provide a black start, some power stations have small diesel generators which can be used to start larger generators (of several megawatts capacity), which in turn can be used to start the main power station generators. Generating plants using steam turbines require station service power of up to 10% of their capacity for boiler feedwater pumps, boiler forced-draft combustion air blowers, and for fuel preparation. It is uneconomical to provide such a large standby capacity at each station, so black-start power must be provided over designated tie lines from another station. Often hydroelectric power plants are designated as the black-start sources to restore network interconnections. A hydroelectric station needs very little initial power to start (just enough to open the intake gates), and can put a large block of power on line very quickly to allow start-up of fossil-fueled or nuclear stations.

A black start sequence

A typical sequence (based on a real scenario) might be as follows:

1. A battery starts a small diesel generator installed in a hydroelectric generating station.
2. The power from the diesel generator is used to bring the hydroelectric generating station into operation.
3. Key transmission lines between the hydro station and other areas are energized.
4. The power from the hydro dam is used to start one of the coal-fired base load plants.
5. The power from the base load plant is used to restart all of the other power plants in the system including the nuclear power plants.

Power is finally re-applied to the general electricity distribution network and sent to the consumers. Often this will happen gradually; starting the entire grid at once may be unfeasible. In particular, after a lengthy outage during summer, all buildings will be warm, and if the power were restored at once, the demand from air conditioning units alone would be more than the grid could supply. In colder climates a similar issue can occur in winter with the use of heating devices.

In a larger grid, black start will often involve starting multiple "islands" of generation (each supplying local load areas) and then synchronising and reconnecting these islands to form a complete grid. The power stations involved have to be able to accept large step changes in load as the grid is reconnected.

Procurement of black start services

In the United Kingdom the grid operator has commercial agreements in place with some generators to provide black start capacity, recognising that black start facilities are often not economic in normal grid operation.

In the North American Independent System Operators the procurement of black start varies somewhat. Traditionally black start was provided by integrated utilities and the costs were rolled into a broad tariff for cost recovery from ratepayers. In those areas which are not part of organized electricity markets this is still the usual procurement mechanism. In the deregulated environment this legacy of cost-based provision has persisted, and even recent overhauls of black start procurement practices, such as that by the ISO New England, have not necessarily shifted to competitive procurement, despite the fact that deregulated jurisdictions have a bias for market solutions rather than Cost-of-Service (COS) solutions.

In the United States, there are currently three methods of procuring black start. The most common is Cost of Service, as it is the simplest and is the traditional method. It is currently used by the California Independent System Operator (CAISO), the PJM Interconnection and the New York Independent System Operator (NYISO). Although the exact mechanisms differ somewhat the same approach is used, namely that units are identified for black start and their documented costs are then funded and rolled into a tariff for cost recovery. The second method is a new method used by the Independent System Operator of New England (ISO-NE). The new methodology is a flat rate payment which increases black start remuneration to encourage provision. The monthly compensation paid to a generator is determined by multiplying a flat rate (in $/KWyr and referred to as the $Y value) by the unit's Monthly Claimed Capability for that month. The purpose of this change was to simplify procurement and incent provision of black start. The final method of procurement is competitive procurement as used by the Electric Reliability Council of Texas (ERCOT). Under this approach ERCOT runs a market for black start services. Interested participants submit an hourly standby cost in $/hr (e.g. $70 per hour), often termed an availability bid, that is unrelated to the capacity of the unit. Using various criteria ERCOT evaluates these bids and the selected units are paid as bid, presuming an 85% availability. Each black start unit must be able to demonstrate that it can startup another unit in close proximity to begin the islanding and synchronization of the grid.

In other jurisdictions there are differing methods of procurement. The New Zealand System Operator procures the blackstart capability via competitive tender. Other jurisdictions also appear to have some sort of competitive procurement, although not as structured as ERCOT. These include the Alberta Electric System Operator, as well as Independent Electric System Operator of Ontario , both of which use a long-term "Request For Proposals" approach similar to New Zealand and ERCOT.

Limitations on black start sources

Not all generating plants are suitable for black-start capability. Wind turbines are not suitable for black start because wind may not be available when needed. Wind turbines, mini-hydro or micro-hydro plants, are often connected to induction generators which are incapable of providing power to a de-energized network. The black-start unit must also be stable when operated with the large reactive load of a long transmission line. Many high-voltage direct current converter stations cannot operate into a "dead" system, either, since they require commutation power from the system at the load end. This is not true of PWM-based (voltage-source converter) HVDC schemes.

Spark spread

The **spark spread** is the theoretical gross margin of a gas-fired power plant from selling a unit of electricity, having bought the fuel required to produce this unit of electricity. All other costs (operation and maintenance, capital and other financial costs) must be covered from the spark spread.

The term **dark spread** refers to the similarly defined difference between cash streams (spread) for coal-fired power plants. These indicators of power plant economics are useful for tracing energy markets. For operating or investment decisions published "spread" data are not applicable. Local market conditions, actual plant efficiencies and other plant costs have to be considered.

Further definition of **clean spread** indicators include the price of carbon dioxide emission allowances (see: Emission trading).

Definition of spark spread

Spark Spread = Price of Electricity - [(Cost of Gas) * (Heat Rate)] = $/MWh - [($/MMBtu) * (MMBtu / MWh)]

Both prices in the above formula must be in the same currency and must refer to the same energy unit (usually MWh).

A precise definition of a spark spread has to be given by the source publishing such indicators. Definitions should specify energy (electricity and fuel) prices considered (delivery point & conditions) and the plant efficiency used for the calculation. Also, any plant operating costs that may be included should be stated. (see: Methodology of Powernext).

Typically, an efficiency of 0.5 (50 %) is considered for gas fired plants, and 0.38 (38%) for coal fired plants (see: Methodology of Powernext). In the UK, a non-rounded efficiency of 49.13% is used for calculating the spark spread.

Both the UK and German Spark Spread tables use a fuel efficiency factor of 49.13% for the gas conversion. In reality, each gas-fired plant has a different fuel efficiency, but 49.13% is used as a standard in the UK market because it provides an easy conversion between gas and power volumes (25,000 therms of gas = 15 MWh of energy). The spark spread value is therefore the power price minus the gas price divided by 0.4913, i.e. Spark Spread = Power Price – (Gas price/0.4913).

As of August 2006,UK dark spreads were in the range of 10–30 £/MWh, while UK spark spreads were in the range of 4–9 £/MWh.

Clean spread

In countries that are covered by the European Union Emissions Trading Scheme, generators have to consider also the cost of carbon dioxide emission allowances that will be under a cap and trade regime. Emission trading has started in the EU in January 2005.

The Clean Spark Spread is calculated using a gas emissions intensity factor of 0.411 tCO2/MWh. Therefore the clean spark spread is calculated by subtracting the carbon price per tonne (multiplied by 0.411) from the 'dirty' spark spread, i.e. Clean Spark Spread = Spark Spread – (Carbon Price*0.411).

Clean spark spread or "spark green spread" represents the net revenue a generator makes from selling power, having bought gas and the required number of carbon allowances. This spread is calculated by adjusting the cost of natural gas in MMBtu for the efficiency of the generation and subsequently applying the market cost of procuring or opportunity cost of setting aside an emissions allowance such as a European Union Allowance (EUA) in the European Union Emissions Trading Scheme (EU ETS).

Let S: spark spread, E: electricity price, G: gas price, Ng: number of carbon credits necessary to cover gas operation, Pcc: price of a carbon credit.

Then, Clean spark spread = E - G - Ng*Pcc = S - Ng*Pcc

Clean dark spread or "dark green spread" refers to an analogous indicator for coal fired generation of electricity. The spark green spread and the dark green spread are especially important in areas where coal fired electricity generation is prevalent as the convergence of the spreads will lead to an important decision point.

Let D: dark spread, E: electricity price, C: coal price, Nc: number of carbon credits necessary to cover coal operation (2–2.5x that of gas), Pcc: price of a carbon credit.

Then, Clean dark spread = E - C - Nc*Pcc = D - Nc*Pcc

Climate spread: The difference between the dark green spread and the spark green spread is known as the "Climate Spread".

Climate spread = Clean dark spread - Clean spark spread = (D - Nc*Pcc) - (S - Ng*Pcc) = (D - S) - (Nc - Ng)*Pcc.

Note: (D - S) and (Nc - Ng) are positive numbers.

In a carbon constrained economy a power producer in a geographic area where coal is currently the preferred method by which electricity is generated may eventually encounter a negative climate spread if carbon credit prices rise. This would mean that when taking into consideration the cost to produce plus the cost of compliance with a cap and trade (coal is on average 2.5 times as polluting as natural gas for the same MWh of electricity), natural gas would be a better decision. This would begin to cause more internal abatement via power generation fuel switching and less reliance on flexible mechanisms. This is important due to concerns regarding supplementarity.

Climate spread is also interesting in that it is the fundamental driver for the price of carbon credits. Since the ETS cap-and-trade system covers the major polluting industries, power generation by coal and gas fired power plants, by far the largest power sources, create the most carbon credit demand within the ETS. To cover emissions on an ever tightening ration of free EUA allowances, a coal fired powered power plant will either have to abate internally or buy credits. If the price of marginal internal abatement is lower than the price of carbon credits, the firm will choose internal abatement. However marginal abatement becomes more and more expensive, at some point forcing the plant to buy credits – thus the carbon credit price is equal to the marginal cost of abatement to the extent that European power plants have chosen to abate.

Clean Dark Spreads are a reflection of the cost of generating power from coal after taking into account fuel (coal) and carbon allowance costs. A positive spread effectively means that it is profitable to generate electricity on a Baseload basis for the period in question, while a negative spread means that generation would be a loss-making activity. However, it is important to note that the Clean Spark Spreads do not take into account additional generating charges (beyond fuel and carbon), such as operational costs.

Both the UK and German Dark Spread tables use a fuel efficiency factor of 35% for the coal conversion, and an energy conversion factor of 7.1 for converting tonnes/coal into MWh/electricity. In reality, each type of coal has a different energy value and each coal-fired plant has a different fuel efficiency, but 35% is accepted as a broad standard. At the time of writing (March 2007) there is no liquid Dark Spread traded market in either the UK or Germany. The Dark Spread value is the power price minus the coal price divided by 0.35, i.e. Dark Spread = Power price – (Coal price/0.35).

The Clean Dark Spread is calculated using a coal emissions intensity factor of 0.971 tCO2/MWh. Therefore the Clean Dark Spread is calculated by subtracting the carbon price (multiplied by 0.971) from the ‘dirty’ spark spread, i.e. Clean Dark Spread = Dark Spread – (Carbon Price*0.971).

Spark spread as cost of replacement power for intermittent renewables

Spark spread can be used to assess the loss of revenue if a power station is switched from a normal running scenario to one where it is held in reserve to provide power when a large population of wind, or other renewable generators, is unable to generate.

In theory, the power station operator would be indifferent to such non-running as long as he was paid the spread it would have earned during the normally expected number of hour run. In fact, if paid the expected spark spread for the hours it had expected to run in normal operating mode, the operator would be better off, because it would not incur the variable operating and maintenance costs, i.e. O&M costs, which are proportional to the electrical energy produced.

An assessment of the lost revenues is needed if some power plants, such as wind turbines, have absolute priority (must-run plants). A dispatching authority will in this case order the other plants to decrease power. Normally, plant operators are entitled to receive compensation for such interventions. In a competitive electricity market the situation can be handled by a balancing mechanism, in which any imbalance from the schedule (typically a day-ahead schedule) is penalized, either using the price from a balancing market or a calculated price.

Thus, since UK spark spreads were in the range of 4–9 £/MWh – on average £6.5/MWh, or 0.65 p/kWh, we can asses the likely cost of relegating existing power stations to a standby role for a large penetration of renewables as being around 0.65 p/kWh.

Chapter 14

Distributed Generation

Distributed generation, also called **on-site generation**, **dispersed generation**, **embedded generation**, **decentralized generation**, **decentralized energy** or **distributed energy**, generates electricity from many small energy sources.

Currently, industrial countries generate most of their electricity in large centralized facilities, such as fossil fuel (coal, gas powered) nuclear or hydropower plants. These plants have excellent economies of scale, but usually transmit electricity long distances and negatively affect the environment.

Economies of scale

Most plants are built this way due to a number of economic, health & safety, logistical, environmental, geographical and geological factors. For example, coal power plants are built away from cities to prevent their heavy air pollution from affecting the populace. In addition, such plants are often built near collieries to minimize the cost of transporting coal. Hydroelectric plants are by their nature limited to operating at sites with sufficient water flow. Most power plants are often considered to be too far away for their waste heat to be used for heating buildings.

Low pollution is a crucial advantage of combined cycle plants that burn natural gas. The low pollution permits the plants to be near enough to a city to be used for district heating and cooling.

Localised generation

Distributed generation is another approach. It reduces the amount of energy lost in transmitting electricity because the electricity is generated very near where it is used, perhaps even in the same building. This also reduces the size and number of power lines that must be constructed.

Typical distributed power sources in a Feed-in Tariff (FIT) scheme have low maintenance, low pollution and high efficiencies. In the past, these traits required dedicated operating engineers and large complex plants to reduce pollution. However, modern embedded systems can provide these traits with automated operation and renewables, such as sunlight, wind and geothermal. This reduces the size of power plant that can show a profit.

Distributed energy resources

Distributed energy resource (**DER**) systems are small-scale power generation technologies (typically in the range of 3 kW to 10,000 kW) used to provide an alternative to or an enhancement of the traditional electric power system. The usual problem with distributed generators are their high costs.

One popular source is solar panels on the roofs of buildings. The production cost is $0.99 to 2.00/W (2007) plus installation and supporting equipment unless the installation is Do it yourself (DIY) bringing the cost to $5.25 to 7.50 (2010). This is comparable to coal power plant costs of $0.582 to 0.906/W (1979), adjusting for inflation. Nuclear power is higher at $2.2 to $6.00/W (2007). Some solar cells ("thin-film" type) also have waste disposal issues, since "thin-film" type solar cells often contain heavy-metal electronic wastes, such as Cadmium telluride (CdTe) and Copper indium gallium selenide (CuInGaSe), and need to be recycled. As opposed to silicon semi-conductor type solar cells which is made from quartz. The plus side is that unlike coal and nuclear, there are no fuel costs, pollution, mining safety or operating safety issues. Solar also has a low duty cycle, producing peak power at local noon each day. Average duty cycle is typically 20%.

Another source is small wind turbines. These have low maintenance, and low pollution. Construction costs are higher ($0.80/W, 2007) per watt than large power plants, except in very windy areas. Wind towers and generators have substantial insurable liabilities caused by high winds, but good operating safety. In some areas of the US there may also be Property Tax costs involved with wind turbines that are not offset by incentives or accelerated depreciation. Wind also tends to be complementary to solar; on days there is no sun there tends to be wind and vice versa. Many distributed generation sites combine wind power and solar power such as Slippery Rock University, which can be monitored online.

Distributed cogeneration sources use natural gas-fired microturbines or reciprocating engines to turn generators. The hot exhaust is then used for space or water heating, or to drive an absorptive chiller for air-conditioning. The clean fuel has only low pollution. Designs currently have uneven reliability, with some makes having excellent maintenance costs, and others being unacceptable.

Cost factors

Cogenerators are also more expensive per watt than central generators. They find favor because most buildings already burn fuels, and the cogeneration can extract more value from the fuel.

Some larger installations utilize combined cycle generation. Usually this consists of a gas turbine whose exhaust boils water for a steam turbine in a Rankine cycle. The condenser of the steam cycle provides the heat for space heating or an absorptive chiller. Combined cycle plants with cogeneration have the highest known thermal efficiencies, often exceeding 85%.

In countries with high pressure gas distribution, small turbines can be used to bring the gas pressure to domestic levels whilst extracting useful energy. If the UK were to implement this countrywide an additional 2-4 GWe would become available. (Note that the energy is already being generated elsewhere to provide the high initial gas pressure - this method simply distributes the energy via a different route.)

Future generations of electric vehicles will have the ability to deliver power from the battery into the grid when needed. An electric vehicle network could also be an important distributed generation resource.

Microgrid

Picture of a local microgrid

A *microgrid* is a localized grouping of electricity generation, energy storage, and loads that normally operates connected to a traditional centralized grid (macrogrid). This single point of common coupling with the macrogrid can be disconnected. The microgrid can then function autonomously. Generation and loads in a microgrid are usually interconnected at low voltage. From the point of view of the grid operator, a connected microgrid can be controlled as if it was one entity. Microgrid generation resources can include fuel cells, wind, solar, or other energy sources. The multiple dispersed generation sources and ability to isolate the microgrid from a larger network would provide highly reliable electric power. Byproduct heat from generation sources such as microturbines could be used for local process heating or space heating, allowing flexible trade off between the needs for heat and electric power.

Modes of power generation

DER systems may include the following devices/technologies:

- Combined heat power (CHP)
- Fuel cells
- Micro combined heat and power (MicroCHP)
- Microturbines
- Photovoltaic Systems
- Reciprocating engines
- Small Wind power systems
- Stirling engines

Communication in DER systems

- IEC 61850-7-420 is under development as a part of IEC 61850 standards which deals with the complete object models as required for DER systems. It uses communication services mapped to MMS as per IEC 61850-8-1 standard.

- OPC is also used for the communication between different entities of DER system.

Legal requirements for distributed generation

In 2010 Colorado enacted a law requiring that by 2020 that 3% of the power generated in Colorado utilize distributed generation of some sort.

Chapter 15

Cogeneration

Cogeneration (also **combined heat and power**, **CHP**) is the use of a heat engine or a power station to simultaneously generate both electricity and useful heat.

All power plants must emit a certain amount of heat during electricity generation. This can be released into the natural environment through cooling towers, flue gas, or by other means. By contrast CHP captures some or all of the by-product heat for heating purposes, either very close to the plant, or—especially in Scandinavia and eastern Europe—as hot water for district heating with temperatures ranging from approximately 80 to 130 °C. This is also called Combined Heat and Power District Heating or CHPDH. Small CHP plants are an example of decentralized energy.

In the United States, Con Edison distributes 30 billion pounds of 350 °F/180 °C steam each year through its seven cogeneration plants to 100,000 buildings in Manhattan—the biggest steam district in the United States. The peak delivery is 10 million pounds per hour (corresponding to approx. 2.5 GW) This steam distribution system is the reason for the steaming manholes often seen in "gritty" New York movies.

Other major cogeneration companies in the U.S. include Recycled Energy Development and leading advocates include Tom Casten and Amory Lovins.

By-product heat at moderate temperatures (212-356°F/100-180°C) can also be used in absorption chillers for cooling. A plant producing electricity, heat and cold is sometimes called **trigeneration** or more generally: **polygeneration** plant. Cogeneration is a thermodynamically efficient use of fuel. In separate production of electricity some energy must be rejected as waste heat, but in cogeneration this thermal energy is put to good use.

Overview

Masnedø CHP power station in Denmark. This station burns straw as fuel. The adjacent greenhouses are heated by district heating from the plant.

Thermal power plants (including those that use fissile elements or burn coal, petroleum, or natural gas), and heat engines in general, do not convert all of their thermal energy into electricity. In most heat engines, a bit more than half is lost as excess heat (see: Second law of thermodynamics and Carnot's theorem). By capturing the excess heat, CHP uses heat that would be wasted in a conventional power plant, potentially reaching an efficiency of up to 89%, compared with 55% for the best conventional plants. This means that less fuel needs to be consumed to produce the same amount of useful energy.

Some tri-cycle plants have used a combined cycle in which several thermodynamic cycles produced electricity, and then a heating system was used as a condenser of the power plant's bottoming cycle. For example, the RU-25 MHD generator in Moscow heated a boiler for a conventional steam powerplant, whose condensate was then used for space heat. A more modern system might use a gas turbine powered by natural gas, whose exhaust powers a steam plant, whose condensate provides heat. Tri-cycle plants can have thermal efficiencies above 80%.

The viability of CHP (sometimes termed utilisation factor), especially in smaller CHP installations, depends upon a good baseload of operation, both in terms of an on-site (or near site) electrical demand and heat demand. In practice, an exact match between the heat and electricity needs rarely exists. A CHP plant can either meet the need for heat (*heat driven operation*) or be run as a power plant with some use of its waste heat. The latter being least advantageous in terms of its utilisation factor and thus overall efficiency. The viability can be greatly increased where opportunities for Trigeneration exist. In such cases the heat from the CHP plant is also used as a primary energy source to deliver cooling by means of an absorption chiller.

CHP is most efficient when the heat can be used on site or very close to it. Overall efficiency is reduced when the heat must be transported over longer distances. This requires heavily insulated pipes, which are expensive and inefficient; whereas electricity can be transmitted along a comparatively simple wire, and over much longer distances for the same energy loss.

A car engine becomes a CHP plant in winter, when the reject heat is useful for warming the interior of the vehicle. This example illustrates the point that deployment of CHP depends on heat uses in the vicinity of the heat engine.

Cogeneration plants are commonly found in district heating systems of cities, hospitals, prisons, oil refineries, paper mills, wastewater treatment plants, thermal enhanced oil recovery wells and industrial plants with large heating needs.

Thermally enhanced oil recovery (TEOR) plants often produce a substantial amount of excess electricity. After generating electricity, these plants pump leftover steam into heavy oil wells so that the oil will flow more easily, increasing production. TEOR cogeneration plants in Kern County, California produce so much electricity that it cannot all be used locally and is transmitted to Los Angeles.

CHP is one of the most cost efficient methods of reducing carbon emissions of heating in cold climates.

Types of plants

Topping cycle plants primarily produce electricity from a steam turbine. The exhausted steam is then condensed, and the low temperature heat released from this condensation is utilized for e.g. district heating or water desalination.

Bottoming cycle plants produce high temperature heat for industrial processes, then a waste heat recovery boiler feeds an electrical plant. Bottoming cycle plants are only used when the industrial process requires very high temperatures, such as furnaces for glass and metal manufacturing, so they are less common.

Large cogeneration systems provide heating water and power for an industrial site or an entire town. Common CHP plant types are:

- Gas turbine CHP plants using the waste heat in the flue gas of gas turbines. The gaseous fuel used is typically natural gas
- Gas engine CHP plants (in the US "gaseous fuelled") use a reciprocating gas engine which is generally more competitive than a gas turbine up to about 5 MW. The gaseous fuel used is normally natural gas. These plants are generally manufactured as fully packaged units that can be installed within a plantroom or external plant compound with simple connections to the site's gas supply and electrical distribution and heating systems.
- Biofuel engine CHP plants use an adapted reciprocating gas engine or diesel engine, depending upon which biofuel is being used, and are otherwise very similar in design to a Gas engine CHP plant. The advantage of using a biofuel is one of reduced hydrocarbon fuel consumption and thus reduced carbon emissions.

These plants are generally manufactured as fully packaged units that can be installed within a plantroom or external plant compound with simple connections to the site's electrical distribution and heating systems. Another variant is the wood gasifier CHP plant whereby a wood pellet or wood chip biofuel is gasified in a zero oxygen high temperature environment; the resulting gas is then used to power the gas engine.

- Combined cycle power plants adapted for CHP
- Steam turbine CHP plants that use the heating system as the steam condenser for the steam turbine.
- Molten-carbonate fuel cells have a hot exhaust, very suitable for heating.
- Nuclear Power plants can be fitted with steam drains after the high, mid, and/or low pressure turbines to provide heat to a heat system. With a heat system temperature of 95°C it is possible to extract about 10 MW heat for every MW electricity lost. With a temperature of 130°C the gain is slightly smaller, about 7 MW for every MWe lost.

Smaller cogeneration units may use a reciprocating engine or Stirling engine. The heat is removed from the exhaust and the radiator. These systems are popular in small sizes because small gas and diesel engines are less expensive than small gas- or oil-fired steam-electric plants.

Some cogeneration plants are fired by biomass , or industrial and municipal waste.

Heat Recovery Steam Generators

A Heat Recovery Steam Generator (HRSG) is a steam boiler that uses hot exhaust gases from the gas turbines or reciprocating engines in a CHP plant to heat up water and generate steam. This steam in turn drives a steam turbine and/or is used in industrial processes that require heat.

HRSGs used in the CHP industry are distinguished from conventional steam generators by the following main features:

- The HRSG is designed based upon the specific features of the gas turbine or reciprocating engine that it will be coupled to.
- Since the exhaust gas temperature is relatively low, heat transmission is accomplished mainly through convection.
- The exhaust gas velocity is limited by the need to keep head losses down. Thus, the transmission coefficient is low, which calls for a large heating surface area.
- Since the temperature difference between the hot gases and the fluid to be heated (steam or water) is low, and with the heat transmission coefficient being low as well, the evaporator and economizer are designed with plate fin heat exchangers.

Costs

Typically for gas engined plant, the fully installed cost per kW electrical, is around £400/kW, which is comparable with large central power stations.

History

Cogeneration in Europe

A cogeneration thermal power plant in Ferrera Erbognone (PV), Italy

Europe has actively incorporated cogeneration into its energy policy via the CHP Directive. In September 2008 at a hearing of the European Parliament's Urban Lodgment Intergroup, Energy Commissioner Andris Piebalgs is quoted as saying, "security of supply really starts with energy efficiency." Energy efficiency and cogeneration are recognized in the opening paragraphs of the European Union's Cogeneration Directive 2004/08/EC. This directive intends to support cogeneration and establish a method for calculating cogeneration abilities per country. The development of cogeneration has been very uneven over the years and has been dominated throughout the last decades by national circumstances.

As a whole, the European Union currently generates 11% of its electricity using cogeneration, saving Europe an estimated 35 Mtoe per annum a day. However, there is large difference between Member States with variations of the energy savings between 2% and 60%. Europe has the three countries with the world's most intensive cogeneration economies: Denmark, the Netherlands and Finland.

Other European countries are also making great efforts to increase their efficiency. Germany reported that at present, over 50% of the country's total electricity demand could be provided through cogeneration. So far Germany has set the target to double its electricity cogeneration from 12.5% of the country's electricity to 25% of the country's electricity by 2020 and has passed supporting legislation accordingly in "Federal Ministry of Economics and Technology, (BMWi), Germany, August 2007. The UK is also actively supporting combined heat and power. In light of UK's goal to achieve a 60% reduction in carbon dioxide emissions by 2050, the government has set the target to source at least 15% of its government electricity use from CHP by 2010. Other UK measures to encourage CHP growth are financial incentives, grant support, a greater regulatory framework, and government leadership and partnership.

According to the IEA 2008 modeling of cogeneration expansion for the G8 countries, expansion of cogeneration in France, Germany, Italy and the UK alone would effectively double the existing primary fuel savings by 2030. This would increase Europe's savings from today's 155.69 Twh to 465 Twh in 2030. It would also result in a 16% to 29% increase in each country's total cogenerated electricity by 2030.

Governments are being assisted in their CHP endeavors by organizations like COGEN Europe who serve as an information hub for the most recent updates within Europe's energy policy. COGEN is Europe's umbrella organization representing the interests of the cogeneration industry, users of the technology and promoting its benefits in the EU and the wider Europe. The association is backed by the key players in the industry including gas and electricity companies, ESCOs, equipment suppliers, consultancies, national promotion organisations, financial and other service companies.

Cogeneration in the United States

A 250 MW cogeneration plant in Cambridge, Massachusetts

Perhaps the first modern use of energy recycling was done by Thomas Edison. His 1882 Pearl Street Station, the world's first commercial power plant, was a combined heat and power plant, producing both electricity and thermal energy while using waste heat to warm neighboring buildings. Recycling allowed Edison's plant to achieve approximately 50 percent efficiency.

By the early 1900s, regulations emerged to promote rural electrification through the construction of centralized plants managed by regional utilities. These regulations not only promoted electrification throughout the countryside, but they also discouraged decentralized power generation, such as cogeneration. As Recycled Energy Development CEO Sean Casten testified to Congress, they even went so far as to make it illegal for non-utilities to sell power.

By 1978, Congress recognized that efficiency at central power plants had stagnated and sought to encourage improved efficiency with the Public Utility Regulatory Policies Act (PURPA), which encouraged utilities to buy power from other energy producers.

The U.S. DOE has an aggressive goal of having CHP comprise of *20% of the US generation capacity by the year 2030*. **Eight Clean Energy Application Centers** have been established across the nation whose mission is to develop the required technology application knowledge and educational infrastructure necessary to lead “clean energy” (**Combined Heat and Power, Waste Heat Recovery and District Energy**) technologies as viable energy options and reduce any perceived risks associated with their implementation. The focus of the Application Centers is to provide an outreach and technology deployment program for end users, policy makers, utilities, & industry stakeholders

Percentage of US energy produced by cogeneration

Cogeneration plants proliferated, soon producing about 8 percent of all energy in the U.S. However, the bill left implementation and enforcement up to individual states, resulting in little or nothing being done in many parts of the country.

In 2008 Tom Casten, chairman of Recycled Energy Development, said that "*We think we could make about 19 to 20 percent of U.S. electricity with heat that is currently thrown away by industry.*"

Outside the U.S., energy recycling is more common. Denmark is probably the most active energy recycler, obtaining about 55% of its energy from cogeneration and waste heat recovery. Other large countries, including Germany, Russia, and India, also obtain a much higher share of their energy from decentralized sources.

MicroCHP

"Micro cogeneration" is a so called distributed energy resource (DER). The installation is usually less than 5 kWe in a house or small business. Instead of burning fuel to merely heat space or water, some of the energy is converted to electricity in addition to heat. This electricity can be used within the home or business or, if permitted by the grid management, sold back into the electric power grid. In a comparison by Claverton Energy Research Group, it was found that in the UK case where heat would otherwise be produced by burning fossil fuels in a boiler, micro cogeneration is a more cost effective mean of reducing CO_2 emissions than photovoltaics.

MiniCHP

Mini cogeneration is a so called distributed energy resource (DER). The installation is usually more than 5 kWe and less than 500 kWe in a building or medium sized business. In this size range the viability or utilisation factor of the CHP plant is very important to consider since it will greatly affect the efficiency and cost effectiveness (payback) of the CHP plant. The utilisation factor is essentially the calculated hours of operation of the CHP plant expressed as a percentage of the total number of hours in a year. If less than 40% then the application of CHP is considered to be unviable. To be viable a good baseload for electrical demand and heat demand must exist. Such baseloads arise where building occupation or process activities are extended or continuous in operation. This typically includes for hospitals, prisons, manufacturing processes, swimming pools, airports, hotels, apartment blocks, etc.

Current (2007) Micro- and MiniCHP installations use five different technologies: microturbines, internal combustion engines, stirling engines, closed cycle steam engines and fuel cells. One author indicates that MicroCHP based on Stirling engines is the most cost effective of the so called microgeneration technologies in abating carbon emissions; however, advances in reciprocation engine technology are adding efficiency to CHP plant, particularly in the biogas field. MiniCHP has a large role to play in the field of CO2 reduction from buildings where more than 14% of emissions can be saved by 2010 using CHP in buildings according to the author.

Chapter 16

Power Station

The Susquehanna Steam Electric Station, a nuclear boiling water reactor power plant.

St. Clair Power Plant, a coal-fired plant in Michigan.

The Three Gorges Dam, a hydroelectric dam.

A **power station** (also referred to as a **generating station**, **power plant**, or **powerhouse**) is an industrial facility for the generation of electric energy.

At the center of nearly all power stations is a generator, a rotating machine that converts mechanical energy into electrical energy by creating relative motion between a magnetic field and a conductor. The energy source harnessed to turn the generator varies widely. It depends chiefly on which fuels are easily available and on the types of technology that the power company has access to.

History

The first power station was the *Edison Electric Light Station*, built in London at 57, Holborn Viaduct, which started operation in January 1882. This was an initiative of Thomas Edison that was organised and managed by his partner, Edward Johnson. A Babcock and Wilcox boiler powered a 125 horsepower steam engine that drove a 27 ton generator called Jumbo, after the celebrated elephant. This supplied electricity to premises in the area that could be reached through the culverts of the viaduct without digging up the road, which was the monopoly of the gas companies. The customers included the City Temple and the Old Bailey. Another important customer was the Telegraph Office of the General Post Office but this could not be reached though the culverts. Johnson arranged for the supply cable to be run overhead, via Holborn Tavern and Newgate.

Thermal power stations

Rotor of a modern steam turbine, used in power station.

In thermal power stations, mechanical power is produced by a heat engine that transforms thermal energy, often from combustion of a fuel, into rotational energy. Most thermal power stations produce steam, and these are sometimes called steam power stations. Not all thermal energy can be transformed into mechanical power, according to the second law of thermodynamics. Therefore, there is always heat lost to the environment. If this loss is employed as useful heat, for industrial processes or district heating, the power plant is referred to as a cogeneration power plant or CHP (combined heat-and-power) plant. In countries where district heating is common, there are dedicated heat plants called heat-only boiler stations. An important class of power stations in the Middle East uses by-product heat for the desalination of water.

The efficiency of a steam turbine is limited by the maximum temperature of the steam produced and is not directly a function of the fuel used. For the same steam conditions, coal, nuclear and gas power plants all have the same theoretical efficiency. Overall, if a system is on constantly (base load) it will be more efficient than one that is used intermittently(peak load)

Besides use of reject heat for process or district heating, one way to improve overall efficiency of a power plant is to combine two different thermodynamic cycles. Most commonly, exhaust gases from a gas turbine are used to generate steam for a boiler and steam turbine. The combination of a "top" cycle and a "bottom" cycle produces higher overall efficiency than either cycle can attain alone.

Classification

CHP plant in Warsaw, Poland.

Geothermal power station in Iceland.

Coal Power Station in Tampa, United States.

Thermal power plants are classified by the type of fuel and the type of prime mover installed.

By fuel

- Nuclear power plants use a nuclear reactor's heat to operate a steam turbine generator. About 20% of electric generation in the USA is produced by nuclear power plants.
- Fossil fuelled power plants may also use a steam turbine generator or in the case of natural gas fired plants may use a combustion turbine. A coal-fired power station produces electricity by burning coal to generate steam, and has the side-effect of producing a large amount of carbon dioxide, which is released from burning coal and contributes to global warming. About 50% of electric generation in the USA is produced by coal fired power plants
- Geothermal power plants use steam extracted from hot underground rocks.
- Renewable energy plants or biomass-fuelled power plants may be fuelled by waste from sugar cane, municipal solid waste, landfill methane, or other forms of biomass.
- In integrated steel mills, blast furnace exhaust gas is a low-cost, although low-energy-density, fuel.
- Waste heat from industrial processes is occasionally concentrated enough to use for power generation, usually in a steam boiler and turbine.
- Solar thermal electric plants use sunlight to boil water, which turns the generator.

By prime mover

- Steam turbine plants use the dynamic pressure generated by expanding steam to turn the blades of a turbine. Almost all large non-hydro plants use this system. About 80% of all electric power produced in the world is by use of steam turbines.
- Gas turbine plants use the dynamic pressure from flowing gases (air and combustion products) to directly operate the turbine. Natural-gas fuelled (and oil fueled) combustion turbine plants can start rapidly and so are used to supply "peak" energy during periods of high demand, though at higher cost than base-loaded plants. These may be comparatively small units, and sometimes completely unmanned, being remotely operated. This type was pioneered by the UK, Princetown being the world's first, commissioned in 1959.
- Combined cycle plants have both a gas turbine fired by natural gas, and a steam boiler and steam turbine which use the hot exhaust gas from the gas turbine to produce electricity. This greatly increases the overall efficiency of the plant, and many new baseload power plants are combined cycle plants fired by natural gas.
- Internal combustion reciprocating engines are used to provide power for isolated communities and are frequently used for small cogeneration plants. Hospitals, office buildings, industrial plants, and other critical facilities also use them to provide backup power in case of a power outage. These are usually fuelled by diesel oil, heavy oil, natural gas and landfill gas.
- Microturbines, Stirling engine and internal combustion reciprocating engines are low-cost solutions for using opportunity fuels, such as landfill gas, digester gas from water treatment plants and waste gas from oil production.

Cooling towers

Cooling towers evaporating water at Ratcliffe-on-Soar Power Station, United Kingdom.

All thermal power plants produce waste heat energy as a byproduct of the useful electrical energy produced. The amount of waste heat energy equals or exceeds the amount of electrical energy produced. Gas-fired power plants can achieve 50%* conversion efficiency while coal and oil plants achieve around 30-49%*. The waste heat produces a temperature rise in the atmosphere which is small compared to that of greenhouse-gas emissions from the same power plant. Natural draft wet cooling towers at many nuclear power plants and large fossil fuel fired power plants use large hyperbolic chimney-like structures (as seen in the image at the left) that release the waste heat to the ambient atmosphere by the evaporation of water. However, the mechanical induced-draft or forced-draft wet cooling towers in many large thermal power plants, nuclear power plants, fossil fired power plants, petroleum refineries, petrochemical plants, geothermal, biomass and waste to energy plants use fans to provide air movement upward through downcoming water and are not hyperbolic chimney-like structures. The induced or forced-draft cooling towers are typically rectangular, box-like structures filled with a material that enhances the contacting of the upflowing air and the downflowing water.

In areas with restricted water use a dry cooling tower or radiators, directly air cooled, may be necessary, since the cost or environmental consequences of obtaining make-up water for evaporative cooling would be prohibitive. These have lower efficiency and higher energy consumption in fans than a wet, evaporative cooling tower.

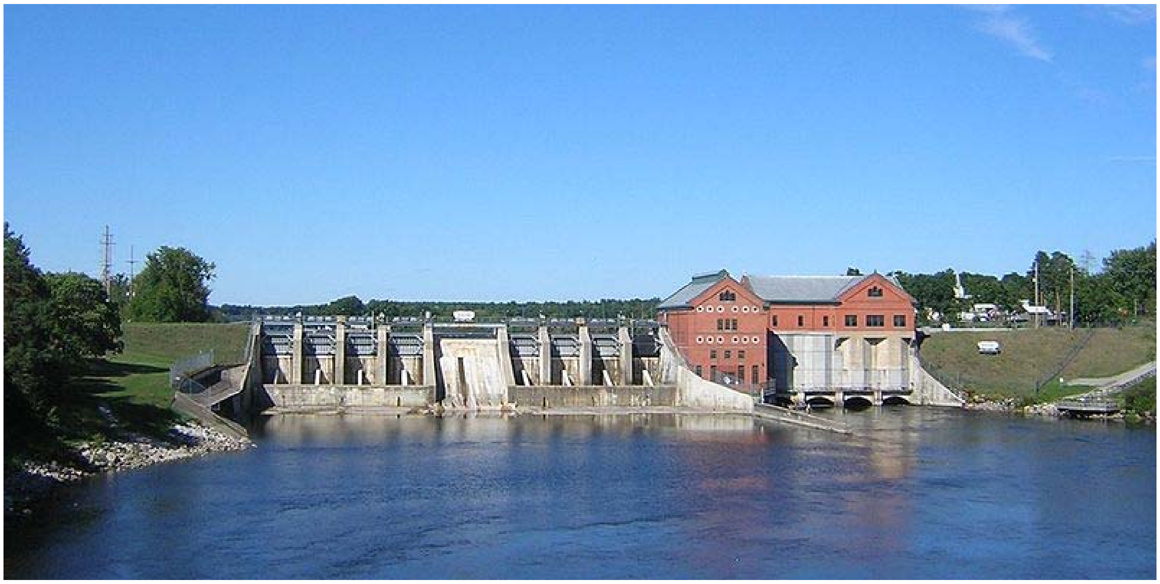
Where economically and environmentally possible, electric companies prefer to use cooling water from the ocean, or a lake or river, or a cooling pond, instead of a cooling tower. This type of cooling can save the cost of a cooling tower and may have lower energy costs for pumping cooling water through the plant's heat exchangers. However, the waste heat can cause the temperature of the water to rise detectably. Power plants using natural bodies of water for cooling must be designed to prevent intake of organisms into the cooling cycle. A further environmental impact would be organisms that adapt to the warmer plant water and may be injured if the plant shuts down in cold weather.

Water consumption by power stations is a developing issue.

In recent years, recycled wastewater, or grey water, has been used in cooling towers. The Calpine Riverside and the Calpine Fox power stations in Wisconsin as well as the Calpine Mankato power station in Minnesota are among these facilities.

Other sources of energy

Other power stations use the energy from wave or tidal motion, wind, sunlight or the energy of falling water, hydroelectricity. These types of energy sources are called renewable energy.



A hydroelectric dam and plant on the Muskegon river in Michigan, United States.

Hydroelectricity

Dams built to produce hydroelectricity impound a reservoir of water and release it through one or more water turbines, connected to generators, and generate electricity, from the energy provided by difference in water level upstream and downstream.

Pumped storage

A pumped-storage hydroelectric power plant is a net consumer of energy but decreases the price of electricity. Water is pumped to a high reservoir when the demand, and price, for electricity is low. During hours of peak demand, when the price of electricity is high, the stored water is released through turbines to produce electric power.

Solar

Nellis Solar Power Plant in the United States.

A solar photovoltaic power plant uses photovoltaic cells to convert sunlight into direct current electricity using the photoelectric effect. This type of plant does not use rotating machines for energy conversion.

Solar thermal power plants are another type of solar power plant. They use either parabolic troughs or heliostats to direct sunlight onto a pipe containing a heat transfer fluid, such as oil. The heated oil is then used to boil water into steam, which turns a turbine that drives an electrical generator. The central tower type of solar thermal power plant uses hundreds or thousands of mirrors, depending on size, to direct sunlight onto a receiver on top of a tower. Again, the heat is used to produce steam to turn turbines that drive electrical generators.

There is yet another type of solar thermal electric plant. The sunlight strikes the bottom of a water pond, warming the lowest layer of water which is prevented from rising by a salt gradient. A Rankine cycle engine exploits the temperature difference in the water layers to produce electricity.

Not many solar thermal electric plants have been built. Most of them can be found in the Mojave Desert of the United States although Sandia National Laboratory (again in the United States), Israel and Spain have also built a few plants.

Wind

Wind turbine in front of a thermal power station in Amsterdam, the Netherlands.

Wind turbines can be used to generate electricity in areas with strong, steady winds, sometimes offshore. Many different designs have been used in the past, but almost all modern turbines being produced today use a three-bladed, upwind design. Grid-connected wind turbines now being built are much larger than the units installed during the 1970s, and so produce power more cheaply and reliably than earlier models. With larger turbines (on the order of one megawatt), the blades move more slowly than older, smaller, units, which makes them less visually distracting and safer for airborne animals. Old turbines are still used at some wind farms, for example at Altamont Pass and Tehachapi Pass.

Typical power output

The power generated by a power station is measured in multiples of the watt, typically megawatts (10^6 watts) or gigawatts (10^9 watts). Power stations vary greatly in capacity depending on the type of power plant and on historical, geographical and economic factors. The following examples offer a sense of the scale.

The power generated by a large wind turbine is of the order of 1 or 2 megawatts. Wind turbines are typically installed in a group called a Wind farm.

The Port Alma Wind Farm in Ontario, has 44 turbines and a capacity of 101.2 megawatts. The largest wind farm in the world is Florida Power & Light's Horse Hollow Wind Energy Center, located in Taylor County, Texas, with 421 turbines and a capacity of 735 Megawatts.

Solar thermal power stations in the U.S. have the following output:

The country's largest solar facility at Kramer Junction has an output of 354 MW
The planned Blythe Solar Power Project will produce an estimated 968 MW

Large coal-fired, nuclear, and hydroelectric power stations can generate hundreds of Megawatts to multiple Gigawatts. Some examples:

The Three Mile Island Nuclear Generating Station in the USA has a rated capacity of 802 megawatts.
The coal-fired Ratcliffe-on-Soar Power Station in the UK has a rated capacity of 2 gigawatts.
The planned expansion of Vogtle Electric Generating Plant will add 2.3 Gigawatts with construction of 2 new AP1000 nuclear reactors.
The Aswan Dam hydro-electric plant in Egypt has a capacity of 2.1 gigawatts.
The Three Gorges Dam hydro-electric plant in China will have a capacity of 22.5 gigawatts when complete; 18.2 gigawatts capacity is operating as of 2010.

Gas turbine power plants can generate tens to hundreds of megawatts. Some examples:

The Indian Queens simple-cycle peaking power station in Cornwall UK, with a single gas turbine is rated 140 megawatts.
The Medway Power Station, a combined-cycle power station in Kent, UK with two gas turbines and one steam turbine, is rated 700 megawatts.

The rated capacity of a power station is nearly the maximum electrical power that that power station can produce. Some power plants are run at almost exactly their rated capacity all the time, as a non-load-following base load power plant, except at times of scheduled or unscheduled maintenance.

However, many power plants usually produce much less power than their rated capacity.

In some cases a power plant produces much less power than its rated capacity because it uses an intermittent energy source. Operators try to pull maximum available power from such power plants, because their marginal cost is practically zero, but the available power varies widely—in particular, it may be zero during heavy storms at night.

In some cases operators deliberately produce less power for economic reasons. The cost of fuel to run a load following power plant may be relatively high, and the cost of fuel to run a peaking power plant is even higher—they have relatively high marginal costs. Operators keep them turned off ("operational reserve") or running at minimum fuel consumption ("spinning reserve") most of the time. Operators feed more fuel into load following power plants only when the demand rises above what lower-cost plants (i.e., intermittent and base load plants) can produce, and then feed more fuel into peaking power plants only when the demand rises faster than the load following power plants can follow.

Operations

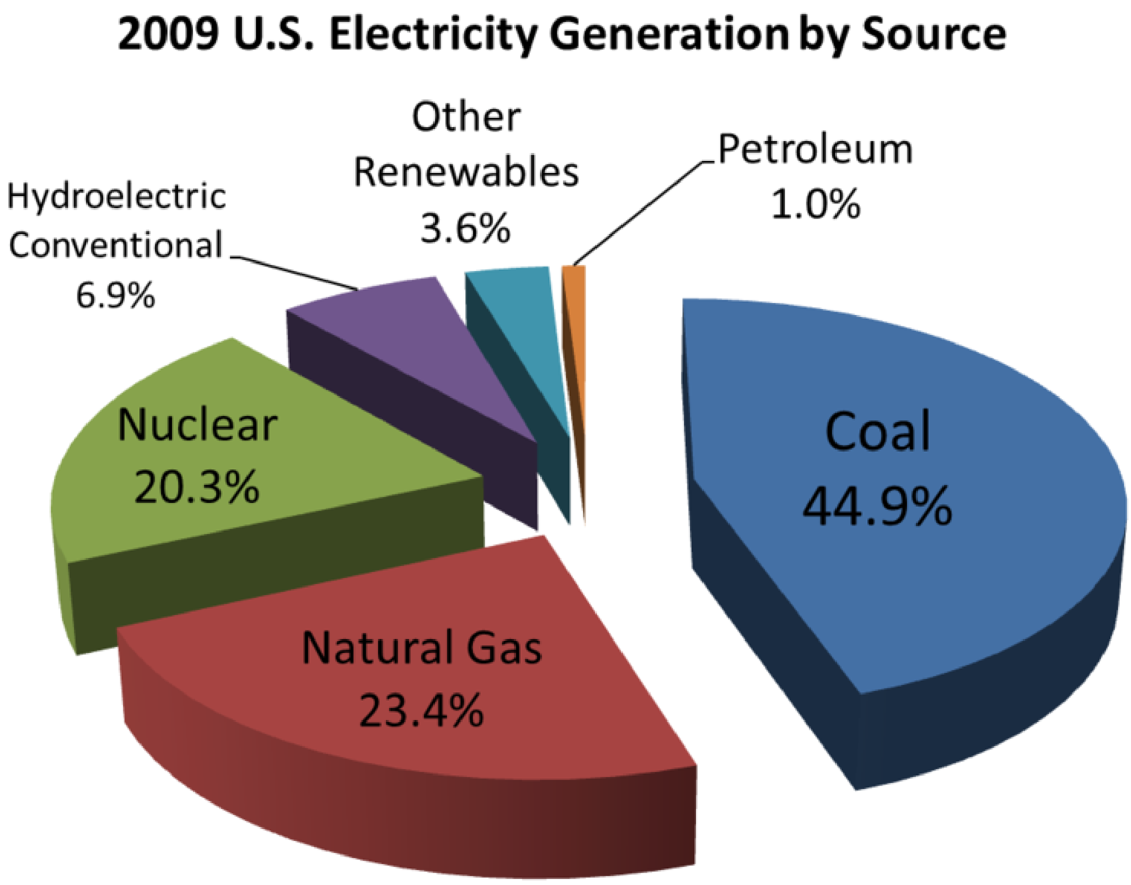
The **power station operator** has several duties in the electrical generating facility. Operators are responsible for the safety of the work crews that frequently do repairs on the mechanical and electrical equipment. They maintain the equipment with periodic inspections and log temperatures, pressures and other important information at regular intervals. Operators are responsible for starting and stopping the generators depending on need. They are able to synchronize and adjust the voltage output of the added generation with the running electrical system without upsetting the system. They must know the electrical and mechanical systems in order to troubleshoot problems in the facility and add to the reliability of the facility. Operators must be able to respond to an emergency and know the procedures in place to deal with it.

Chapter 17

Fossil Fuel Power Station

A working coal plant in Rochester, Minnesota

The St. Clair Power Plant, a large coal fired generating station in Michigan.



Sources of electricity in the U.S. in 2009.

A **fossil-fuel power station** is a power station that burns fossil fuels such as coal, natural gas or petroleum (oil) to produce electricity. Central station fossil-fuel power plants are designed on a large scale for continuous operation. In many countries, such plants provide most of the electrical energy used.

Fossil fuel power stations (except for MHD generators) have some kind of rotating machinery to convert the heat energy of combustion into mechanical energy, which then operate an electrical generator. The prime mover may be a steam turbine, a gas turbine or, in small isolated plants, a reciprocating internal combustion engine. All plants use the drop between the high pressure and temperature of the steam or combusting fuel and the lower pressure of the atmosphere or condensing vapour in the steam turbine.

Byproducts of power thermal plant operation need to be considered in both the design and operation. Waste heat due to the finite efficiency of the power cycle must be released to the atmosphere, using a cooling tower, or river or lake water as a cooling medium. The flue gas from combustion of the fossil fuels is discharged to the air; this contains carbon dioxide and water vapour, as well as other substances such as nitrogen, nitrogen oxides, sulfur oxides, and (in the case of coal-fired plants) fly ash, mercury and traces of other metals. Solid waste ash from coal-fired boilers must also be removed. Some coal ash can be recycled for building materials.

Fossil fueled power stations are major emitters of CO_2, the most important greenhouse gas (GHG) which according to the consensus of scientific organisations is a major contributor to the global warming observed over the last 100 years. Brown coal emits 3 times as much CO_2 as natural gas, black coal emits twice as much CO_2 per unit of electric energy. Carbon capture and storage of emissions are not expected to be available on a commercial economically viable basis until 2025.

Basic concepts

In a fossil fuel power plant the chemical energy stored in fossil fuels such as coal, fuel oil, natural gas or oil shale) and oxygen of the air is converted successively into thermal energy, mechanical energy and, finally, electrical energy for continuous use and distribution across a wide geographic area. Each fossil fuel power plant is a highly complex, custom-designed system. Construction costs, as of 2004, run to US$1,300 per kilowatt, or $650 million for a 500 MWe unit. Multiple generating units may be built at a single site for more efficient use of land, natural resources and labour. Most thermal power stations in the world use fossil fuel, outnumbering nuclear, geothermal, biomass, or solar thermal plants.

Heat into mechanical energy

The second law of thermodynamics states that any closed-loop cycle can only convert a fraction of the heat produced during combustion into mechanical work. The rest of the heat, called waste heat, must be released into a cooler environment during the return portion of the cycle. The fraction of heat released into a cooler medium must be equal or larger than the ratio of absolute temperatures of the cooling system (environment) and the heat source (combustion furnace). Raising the furnace temperature improves the efficiency but also increases the steam pressure, complicates the design and makes the furnace more expensive. The waste heat cannot be converted into mechanical energy without an even cooler cooling system. However, it may be used in cogeneration plants to heat buildings, produce hot water, or to heat materials on an industrial scale, such as in some oil refineries, plants, and chemical synthesis plants.

Typical thermal efficiency for electrical generators in the industry is around 33% for coal and oil-fired plants, and up to 50% for combined-cycle gas-fired plants. Plants designed to achieve peak effiency while operating at capacity will be less efficient when operating off-design (i.e. temperatures too low.)

The Carnot cycle is the theoretically most efficient closed thermodynamic cycle for conversion of heat energy into useful work, and practical fossil-fuel stations cannot exceed this limit. In principle, fuel cells do not have the same thermodynamic limits as they are not heat engines.

Fuel transport and delivery

Big Bend Coal Power Station in Apollo Beach, Florida in the United States.

Coal fired power plants provide about 50% of consumed electricity in the United States. This is the Castle Gate Plant near Helper, Utah.

Coal is delivered by highway truck, rail, barge, collier ship or coal slurry pipeline. Some plants are even built near coal mines and coal is delivered by conveyors. A large coal train called a "unit train" may be two kilometers (over a mile) long, containing 100 cars with 100 short tons of coal in each one, for a total load of 10,000 tons. A large plant under full load requires at least one coal delivery this size every day. Plants may get as many as three to five trains a day, especially in "peak season" during the hottest Summer and/or coldest Winter months (depending on local climate) when power consumption is high. A large thermal power plant such as the one in Nanticoke, Ontario stores several million metric tons of coal for winter use when the lakes are frozen.

Modern unloaders use rotary dump devices, which eliminate problems with coal freezing in bottom dump cars. The unloader includes a train positioner arm that pulls the entire train to position each car over a coal hopper. The dumper clamps an individual car against a platform that swivels the car upside down to dump the coal. Swiveling couplers enable the entire operation to occur while the cars are still coupled together. Unloading a unit train takes about three hours.

Shorter trains may use railcars with an "air-dump", which relies on air pressure from the engine plus a "hot shoe" on each car. This "hot shoe" when it comes into contact with a "hot rail" at the unloading trestle, shoots an electric charge through the air dump apparatus and causes the doors on the bottom of the car to open, dumping the coal through the opening in the trestle. Unloading one of these trains takes anywhere from an hour to an hour and a half. Older unloaders may still use manually operated bottom-dump rail cars and a "shaker" attached to dump the coal. Generating stations adjacent to a mine may receive coal by conveyor belt or massive diesel-electric-drive trucks.

A collier (cargo ship carrying coal) may hold 40,000 long tons of coal and takes several days to unload. Some colliers carry their own conveying equipment to unload their own bunkers; others depend on equipment at the plant. Colliers are large, seaworthy, self-powered ships. For transporting coal in calmer waters, such as rivers and lakes, flat-bottomed vessels called barges are often used. Barges are usually unpowered and must be moved by tugboats or towboats.

For start up or auxiliary purposes, the plant may use fuel oil as well. Fuel oil can be delivered to plants by pipeline, tanker, tank car or truck. Oil is stored in vertical cylindrical steel tanks with capacities as high as 90,000 barrels (14,000 m^3)' worth. The heavier no. 5 "bunker" and no. 6 fuels are typically steam-heated before pumping in cold climates.

Plants fueled by natural gas are usually built adjacent to gas transport pipelines or have dedicated gas pipelines extended to them.

Fuel processing

Coal is prepared for use by crushing the rough coal to pieces less than 2 inches (5 cm) in size. The coal is then transported from the storage yard to in-plant storage silos by rubberized conveyor belts at rates up to 4,000 short tons per hour.

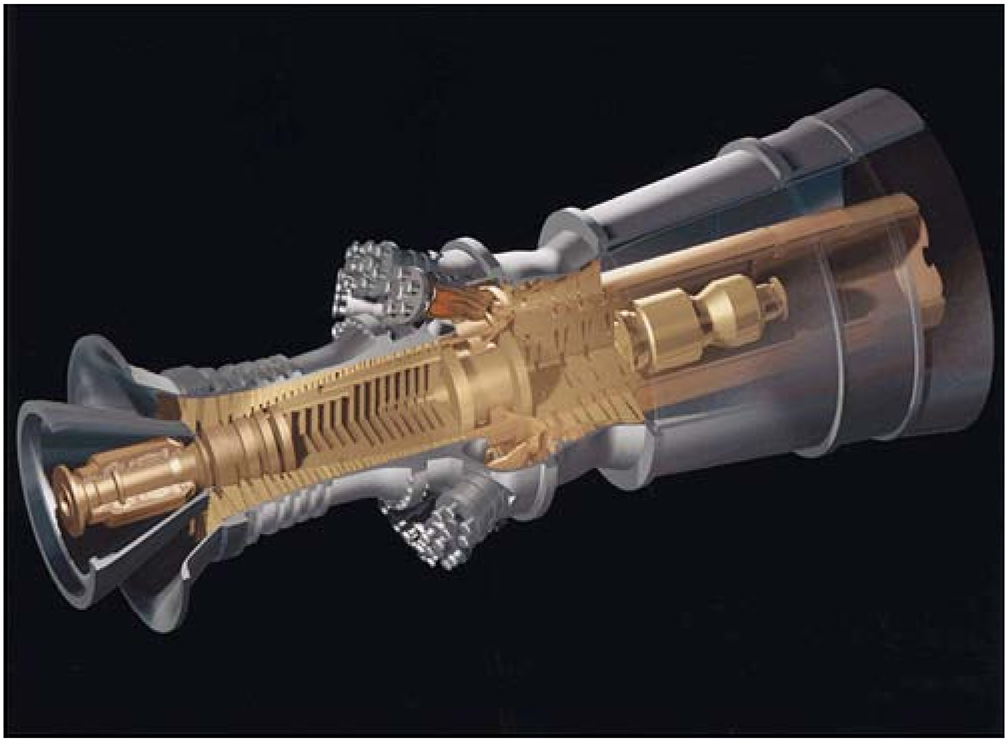
In plants that burn pulverized coal, silos feed coal pulverizers (coal mills) that take the larger 2-inch (51 mm) pieces, grind them to the consistency of face powder, sort them, and mix them with primary combustion air which transports the coal to the furnace and preheats the coal to drive off excess moisture content. A 500 MWe plant may have six such pulverizers, five of which can supply coal to the furnace at 250 tons per hour under full load.

In plants that do not burn pulverized coal, the larger 2-inch (51 mm) pieces may be directly fed into the silos which then feed either mechanical distributors that drop the coal on a traveling grate or the cyclone burners, a specific kind of combustor that can efficiently burn larger pieces of fuel.

Steam-electric

Most electric power made from fossil fuel is produced by thermal power stations. Reciprocating steam engines fell out of use rapidly after the first steam turbines were introduced around 1906.

Gas turbine plants



480 megawatt GE H series power generation gas turbine

Currant Creek Power Plant near Mona, Utah is a natural gas fired electrical plant.

One type of fossil fuel power plant uses a gas turbine in conjunction with a heat recovery steam generator (HRSG). It is referred to as a combined cycle power plant because it combines the Brayton cycle of the gas turbine with the Rankine cycle of the HRSG. The thermal efficiency of these plants has reached a record heat rate of 5690 Btu/(kW·h), or just under 60%, at a facility in Baglan Bay, Wales.

The turbines are fueled either with natural gas, syngas or fuel oil. While more efficient and faster to construct (a 1,000 MW plant may be completed in as little as 18 months from start of construction), the economics of such plants is heavily influenced by the volatile cost of fuel, normally natural gas. The combined cycle plants are designed in a variety of configurations composed of the number of gas turbines followed by the steam turbine. For example, a 3-1 combined cycle facility has three gas turbines tied to one steam turbine. The configurations range from (1-1), (2-1), (3-1), (4-1), (5-1), to (6-1)

Simple-cycle or open cycle gas turbine plants, without a steam cycle, are sometimes installed as emergency or peaking capacity; their thermal efficiency is much lower. The high running cost per hour is offset by the low capital cost and the intention to run such units only a few hundred hours per year. Other gas turbine plants are installed in stages, with an open cycle gas turbine the first stage and additional turbines or conversion to a closed cycle part of future project plans.

Reciprocating engines

Diesel engine generator sets are often used for prime power in communities not connected to a widespread power grid. Emergency (standby) power systems may use reciprocating internal combustion engines operated by fuel oil or natural gas. Standby generators may serve as emergency power for a factory or data center, or may also be operated in parallel with the local utility system to reduce peak power demand charge from the utility. Diesel engines can produce strong torque at relatively low rotational speeds, which is generally desirable when driving an alternator, but diesel fuel in long-term storage can be subject to problems resulting from water accumulation and chemical decomposition. Rarely-used generator sets may correspondingly be installed as natural gas or LPG to minimize the fuel system maintenance requirements.

Spark-ignition internal combustion engines operating on gasoline (petrol), propane, or LPG are commonly used as portable temporary power sources for construction work, emergency power, or recreational uses.

Reciprocating external combustion engines such as the Stirling engine can be run on a variety of fossil fuels, as well as renewable fuels or industrial waste heat. Installations of Stirling engines for power production are relatively uncommon.

Environmental impacts

The Mohave Power Station, a 1,580 MW coal power station near Laughlin, Nevada, out of service since 2005 due to environmental restrictions

The world's power demands are expected to rise 60% by 2030. With the worldwide total of active coal plants over 50,000 and rising, the International Energy Agency (IEA) estimates that fossil fuels will account for 85% of the energy market by 2030.

World organizations and international agencies, like the IEA, are concerned about the environmental impact of burning fossil fuels, and coal in particular. The combustion of coal contributes the most to acid rain and air pollution, and has been connected with global warming. Due to the chemical composition of coal there are difficulties in removing impurities from the solid fuel prior to its combustion. Modern day coal power plants pollute less than older designs due to new "scrubber" technologies that filter the exhaust air in smoke stacks; however emission levels of various pollutants are still on average several times greater than natural gas power plants. In these modern designs, pollution from coal-fired power plants comes from the emission of gases such as carbon dioxide, nitrogen oxides, and sulfur dioxide into the air.

Acid rain is caused by the emission of nitrogen oxides and sulfur dioxide. These gases may be only mildly acidic themselves, yet when they react with the atmosphere, they create acidic compounds such as sulfurous acid, nitric acid and sulfuric acid which fall as rain, hence the term acid rain. In Europe and the U.S.A., stricter emission laws and decline in heavy industries have reduced the environmental hazards associated with this problem, leading to lower emissions after their peak in 1960s.

European Environment Agency (EEA) gives fuel-dependent emission factors based on actual emissions from power plants in EU.

Pollutant	Hard coal	Brown coal	Fuel oil	Other oil	Gas
CO_2 (g/GJ)	94600	101000	77400	74100	56100
SO_2 (g/GJ)	765	1361	1350	228	0.68
NO_x (g/GJ)	292	183	195	129	93.3
CO (g/GJ)	89.1	89.1	15.7	15.7	14.5
Non methane organic compounds (g/GJ)	4.92	7.78	3.70	3.24	1.58
Particulate matter (g/GJ)	1203	3254	16	1.91	0.1
Flue gas volume total (m^3/GJ)	360	444	279	276	272

Carbon dioxide

Electricity generation using carbon based fuels is responsible for a large fraction of carbon dioxide (CO_2) emissions worldwide and for 41% of U.S. man-made carbon dioxide emissions. Of fossil fuels, coal combustion in thermal power stations result in greater amounts of carbon dioxide emissions per unit of electricity generated (2249 lbs/MWh) while oil produces less (1672 lb/(MW·h) or 211 kg/GJ) and natural gas produces the least 1135 lb/(MW·h) (143 kg/GJ).)

The Intergovernmental Panel on Climate Change states that carbon dioxide is a greenhouse gas and that increased quantities within the atmosphere will "very likely" lead to higher average temperatures on a global scale (global warming); concerns regarding the potential for such warming to change the global climate prompted IPCC recommendations calling for large cuts to CO_2 emissions worldwide.

Emissions may be reduced through more efficient and higher combustion temperature and through more efficient production of electricity within the cycle. Carbon capture and storage (CCS) of emissions from coal fired power stations is another alternative but the technology is still being developed and will increase the cost of fossil fuel-based production of electricity. CCS may not be economically viable, unless the price of emitting CO_2 to the atmosphere rises.

Particulate matter

Another problem related to coal combustion is the emission of particulates that have a serious impact on public health. Power plants remove particulate from the flue gas with the use of a bag house or electrostatic precipitator. Several newer plants that burn coal use a different process, Integrated Gasification Combined Cycle in which synthesis gas is made out of a reaction between coal and water. The synthesis gas is processed to remove most pollutants and then used initially to power gas turbines. Then the hot exhaust gases from the gas turbines are used to generate steam to power a steam turbine. The pollution levels of such plants are drastically lower than those of "classic" coal power plants.

Particulate matter from coal-fired plants can be harmful and have negative health impacts. Studies have shown that exposure to particulate matter is related to an increase of respiratory and cardiac mortality. Particulate matter can irritate small airways in the lungs, which can lead to increased problems with asthma, chronic bronchitis, airway obstruction, and gas exchange.

There are different types of particulate matter, depending on the chemical composition and size. The dominant form of particulate matter from coal-fired plants is coal fly ash, but secondary sulfate and nitrate also comprise a major portion of the particulate matter from coal-fired plants. Coal fly ash is what remains after the coal has been combusted, so it consists of the incombustible materials that are found in the coal.

The size and chemical composition of these particles affects the impacts on human health. Currently coarse (diameter greater than 2.5 μm) and fine (diameter between 0.1 μm and 2.5 μm) particles are regulated, but ultrafine particles (diameter less than 0.1 μm) are currently unregulated, yet they pose many dangers. Unfortunately much is still unknown as to which kinds of particulate matter pose the most harm, which makes it difficult to come up with adequate legislation for regulating particulate matter.

There are several methods of helping to reduce the particulate matter emissions from coal-fired plants. Roughly 80% of the ash falls into an ash hopper, but the rest of the ash then gets carried into the atmosphere to become coal-fly ash. Methods of reducing these emissions of particulate matter include:

1. a baghouse
2. an electrostatic precipitator (ESP)
3. cyclone collector

The baghouse has a fine filter that collects the ash particles, electrostatic precipitators use an electric field to trap ash particles on high-voltage plates, and cyclone collectors use centrifugal force to trap particles to the walls.

Radioactive trace elements

As most ores in the Earth's crust, coal also contains low levels of uranium, thorium, and other naturally occurring radioactive isotopes whose release into the environment leads to radioactive contamination. While these substances are present as very small trace impurities, enough coal is burned that significant amounts of these substances are released. A 1,000 MW coal-burning power plant could have an uncontrolled release of as much as 5.2 metric tons per year of uranium (containing 74 pounds (34 kg) of uranium-235) and 12.8 metric tons per year of thorium. In comparison, a 1,000 MW nuclear plant will generate about 500 pounds of plutonium and 30 short tons of high-level radioactive controlled waste. It is estimated that during 1982, US coal burning released 155 times as much uncontrolled radioactivity into the atmosphere as the Three Mile Island incident. The collective radioactivity resulting from all coal burning worldwide between 1937 and 2040 is estimated to be 2,700,000 curies or 0.101 EBq). It should also be noted that during normal operation, the effective dose equivalent from coal plants is 100 times that from nuclear plants.

Water and air contamination by coal ash

A study released in August 2010 that examined state pollution data in the United States by the organizations Environmental Integrity Project, the Sierra Club and Earthjustice found that coal ash produced by coal-fired power plants dumped at sites across 21 U.S. states has contaminated ground water with toxic elements. The contaminants including the poisons arsenic and lead.

Arsenic has been shown to cause skin cancer, bladder cancer and lung cancer, and lead damages the nervous system. Coal ash contaminants are also linked to respiratory diseases and other health and developmental problems, and have disrupted local aquatic life. Additional contaminants emitted include boron, which attacks the testes, kidney and brain, and the heavy metal mercury, a neurotoxicant particularly harmful to a child's development, causing nerve damage and impairment of a child's ability to write, read and learn. Coal ash also releases a variety of toxic contaminants into nearby air, posing a health threat to those who breath in fugitive coal dust.

Currently, the EPA does not regulate the disposal of coal ash; regulation is up to the states and the electric power industry has been lobbying to maintain this status quo. Most states require no monitoring of drinking water near coal ash dump sites. The study found an additional 39 contaminated U.S. sites and concluded that the problem of coal ash-caused water contamination is even more extensive in the United States than has been estimated. The study brought to 137 the number of ground water sites across the United States that are contaminated by power plant-produced coal ash.

Range of mercury contamination in fish

U.S. government scientists tested fish in 291 streams around the country for mercury contamination. They found mercury in every fish tested, according to the study by the U.S. Department of the Interior. They found mercury even in fish of isolated rural waterways. Twenty five percent of the fish tested had mercury levels above the safety levels determined by the U.S. Environmental Protection Agency for people who eat the fish regularly. The largest source of mercury contamination in the United States is coal-fueled power plant emissions.

Greening of fossil fuel power plants

At present, several methods exist to improve the efficiency of fossil fuel power plants. A frequently used and cost-efficient method is to convert a plant to run on a different fuel. This includes conversions as biomass and waste. Conversions to waste-fired power plants have the benefit that they can be used to eliminate existing landfills. In addition, waste fired power plants can be equipped with material recovery, allowing again additional environmental gain.

Regardless of the conversion, in order to become a truly green fossil fuel power plant, carbon capture and storage may be implemented. CCS means that the exhaust CO_2 is captured. This method allows any fossil fuel power plants to be converted to a emissionless power plant. Examples of a CCS fossil fuel power plant includes the Elsam power station near Esbjerg, Denmark.

Clean coal

"Clean coal" is the name attributed to a process whereby coal is chemically washed of minerals and impurities, sometimes gasified, burned and the resulting flue gases treated with steam, with the purpose of removing sulfur dioxide, and reburned so as to make the carbon dioxide in the flue gas economically recoverable. The coal industry uses the term "clean coal" to describe technologies designed to enhance both the efficiency and the environmental acceptability of coal extraction, preparation and use, but has provided no specific quantitative limits on any emissions, particularly carbon dioxide. Whereas contaminates like sulfur or mercury can be removed from coal, carbon cannot be effectively removed while still leaving a usable fuel, and clean coal plants without carbon sequestration and storage do not significantly reduce carbon dioxide emissions. James Hansen in an open letter to U.S. President Barack Obama has advocated a "moratorium and phase-out of coal plants that do not capture and store CO_2". In his book *Storms of My Grandchildren*, similarly, Hansen discusses his *Declaration of Stewardship* the first principle of which requires "a moratorium on coal-fired power plants that do not capture and sequester carbon dioxide".

Combined heat and power

Combined heat and power (CHP), also known as cogeneration, is the use of a power station to provide both electric power and process heat or district heating. While rejecting heat at a higher than normal temperature to enable building heating lowers overall plant electric power efficiency, the extra fuel burnt is more than offset by the reduction in fossil fuel that would otherwise be used for heating buildings. This technology is widely practiced in for example Denmark, other Scandinavian countries and parts of Germany. Calculations show that CHPDH is the cheapest method of carbon emissions reductions.

Alternatives to fossil fuel power plants

Alternatives to fossil fuel power plants include nuclear power, solar power, geothermal power, wind power, tidal power, hydroelectric power (hydroelectricity) and other renewable energies. Some of these are proven technologies on an industrial scale (i.e. nuclear, wind, tidal and hydroelectric power) others are still in prototype form.

Generally, the cost of electrical energy produced by non fossil fuel burning power plants is greater than that produced by burning fossil fuels. This statement however only includes the cost to produce the electrical energy and does not take into account indirect costs associated with the many pollutants created by burning fossil fuels (e.g. increased hospital admissions due respiratory diseases caused by fine smoke particles).

Relative cost by generation source

When comparing power plant costs, it is customary to start by calculating the cost of power at the generator terminals by considering several main factors. External costs such as connections costs, the effect of each plant on the distribution grid are considered separately as an additional cost to the calculated power cost at the terminals.

Initial factors considered are:

- Capital costs (including waste disposal and decommissioning costs for nuclear energy)
- Operating and maintenance costs
- Fuel costs (for fossil fuel and biomass sources, and which may be negative for wastes)
- Likely annual hours per year run or load factor (may be 30% for wind energy, but 90% for nuclear energy)

- Offset sales of heat (for example in combined heat and power district heating (CHP/DH)).

These costs occur over the 30–50 year life of the fossil fuel power plants, using discounted cash flows. In general large fossil plants are attractive due to their low initial capital costs—typically around £750–£1000 per kilowatt electrical compared to perhaps £1500 per kilowatt for onshore wind.