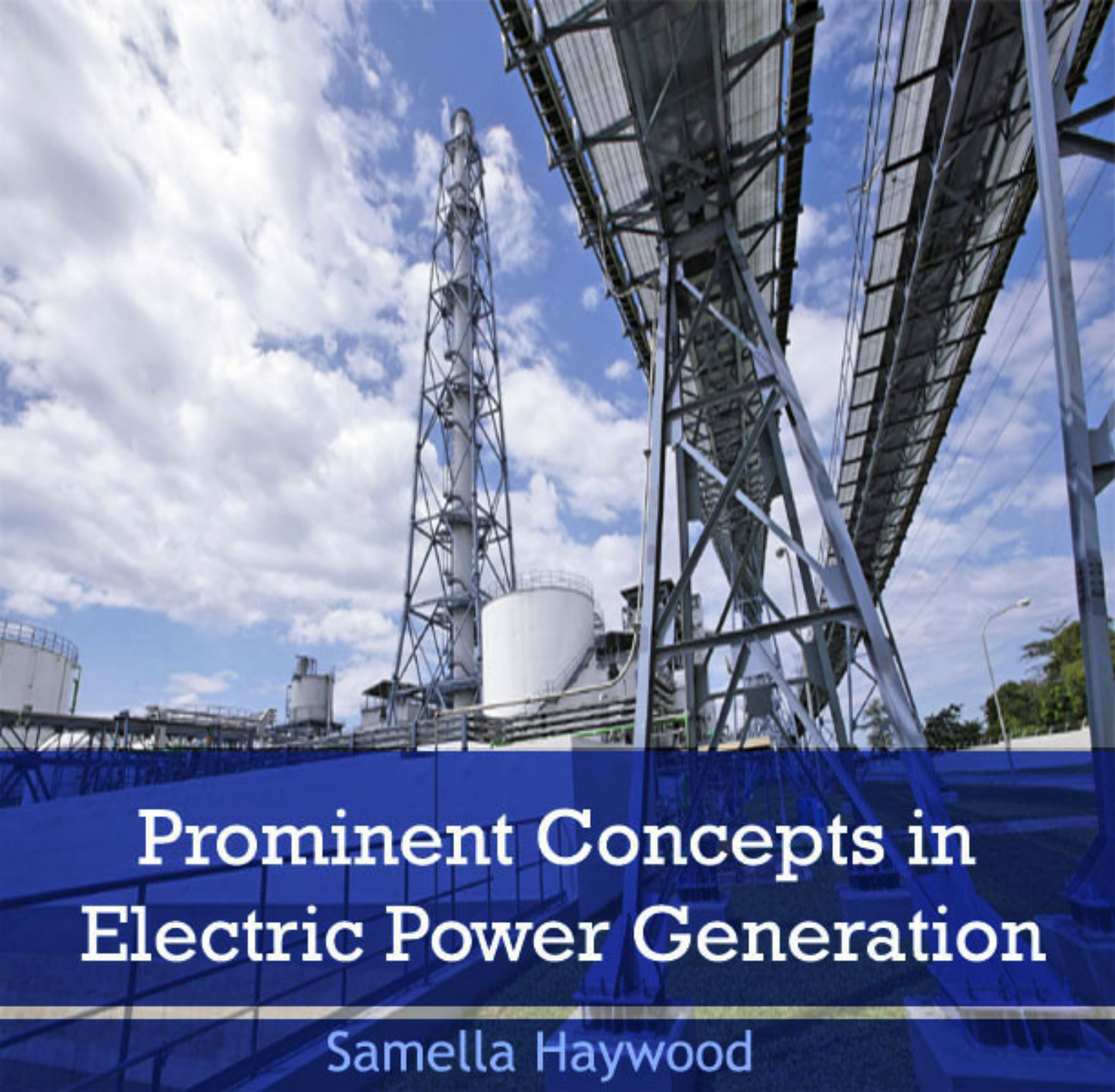

Prominent Concepts in Electric Power Generation

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Chapter 1

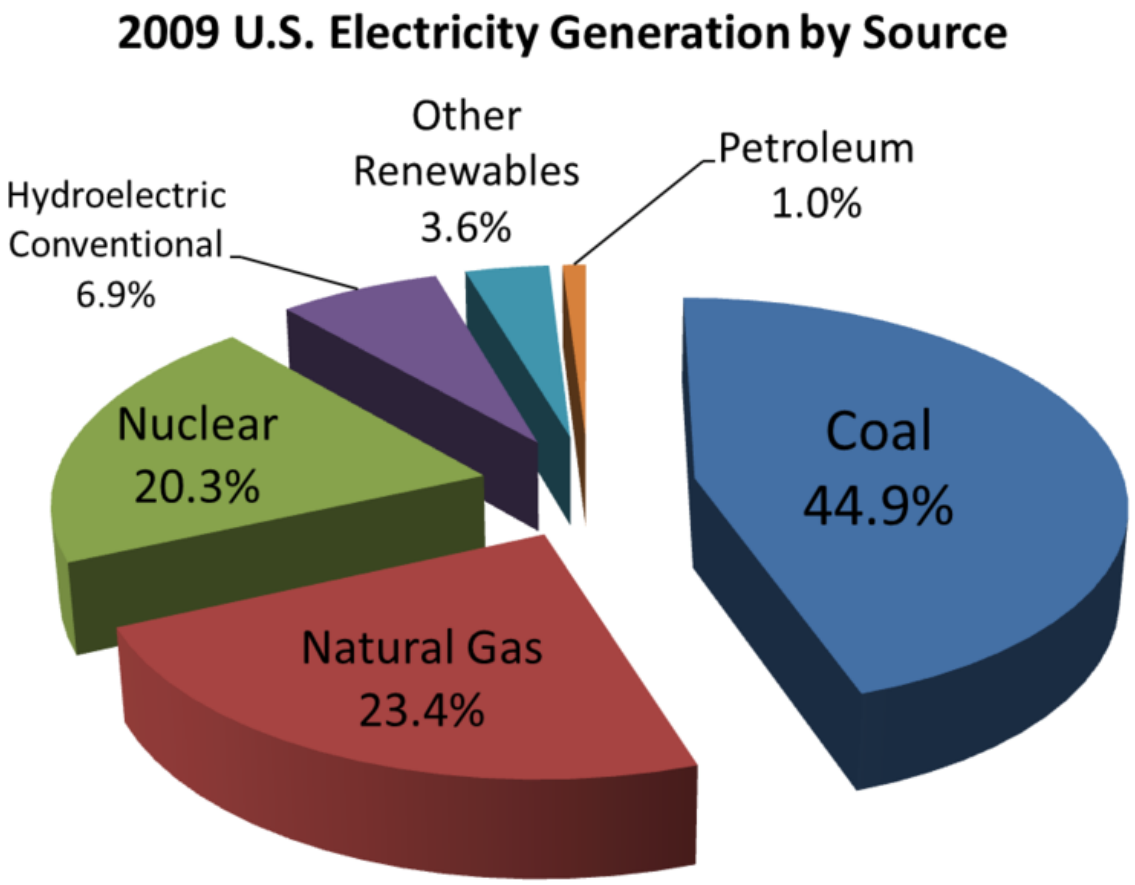
Electricity Generation

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

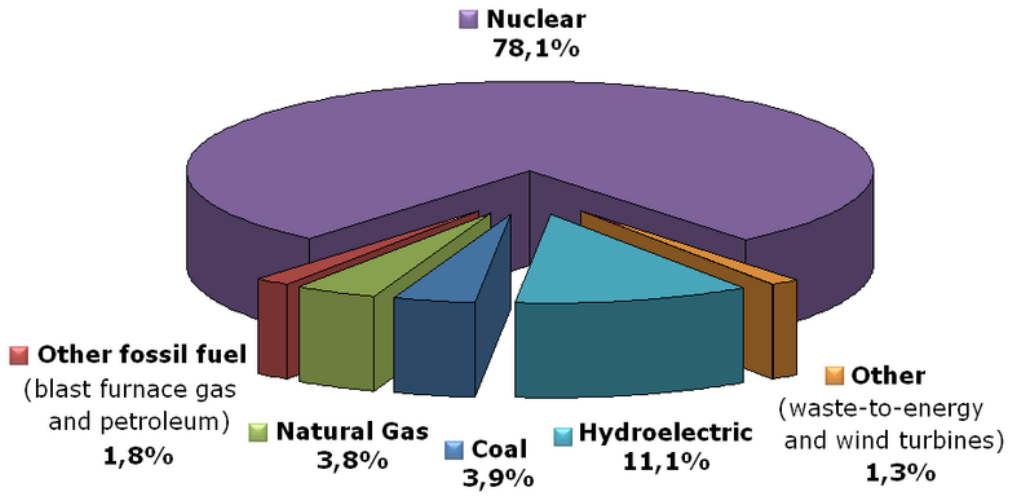
The fundamental principles of electricity generation were discovered during the 1820s and early 1830s by the British scientist Michael Faraday. His basic method is still used today: electricity is generated by the movement of a loop of wire, or disc of copper between the poles of a magnet.

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

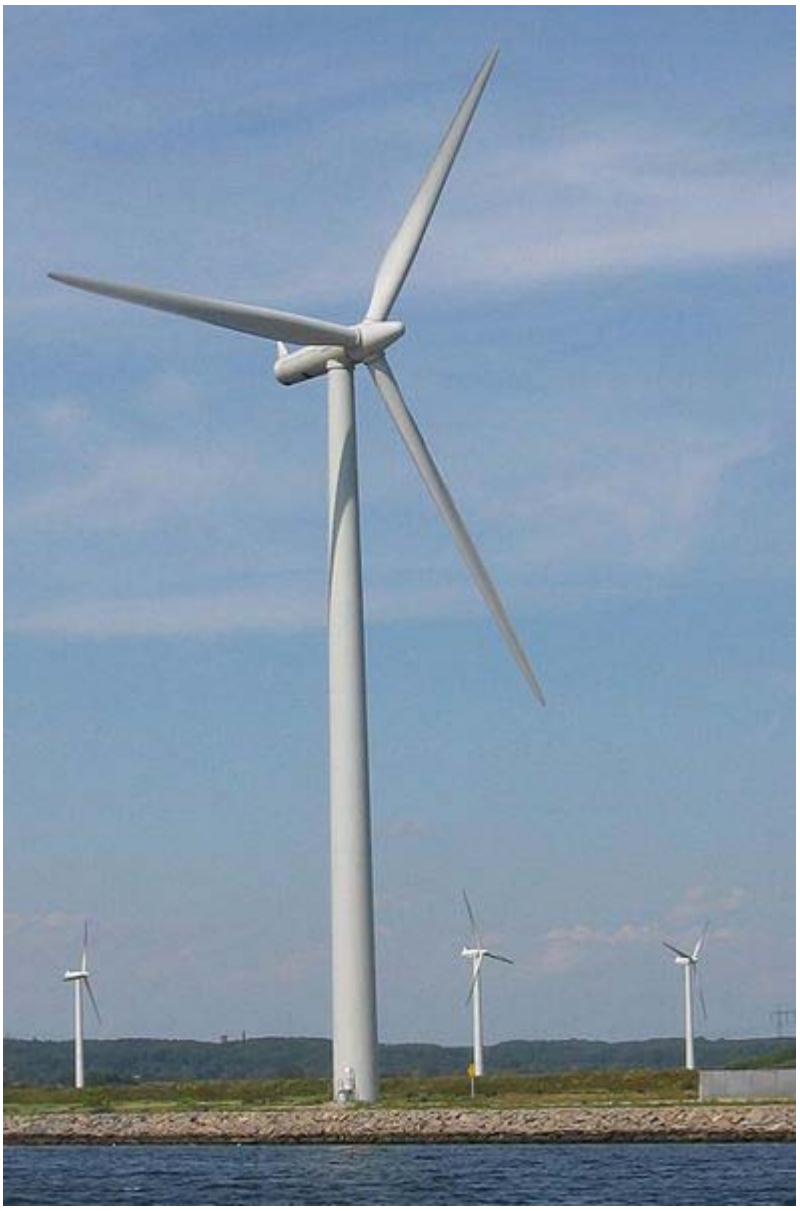
Small electricity generators are often powered by reciprocating engines burning diesel, biogas or natural gas. Diesel engines are often used for back up generation, usually at low voltages. However most large power grids also use diesel generators, originally provided as emergency back up for a specific 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.

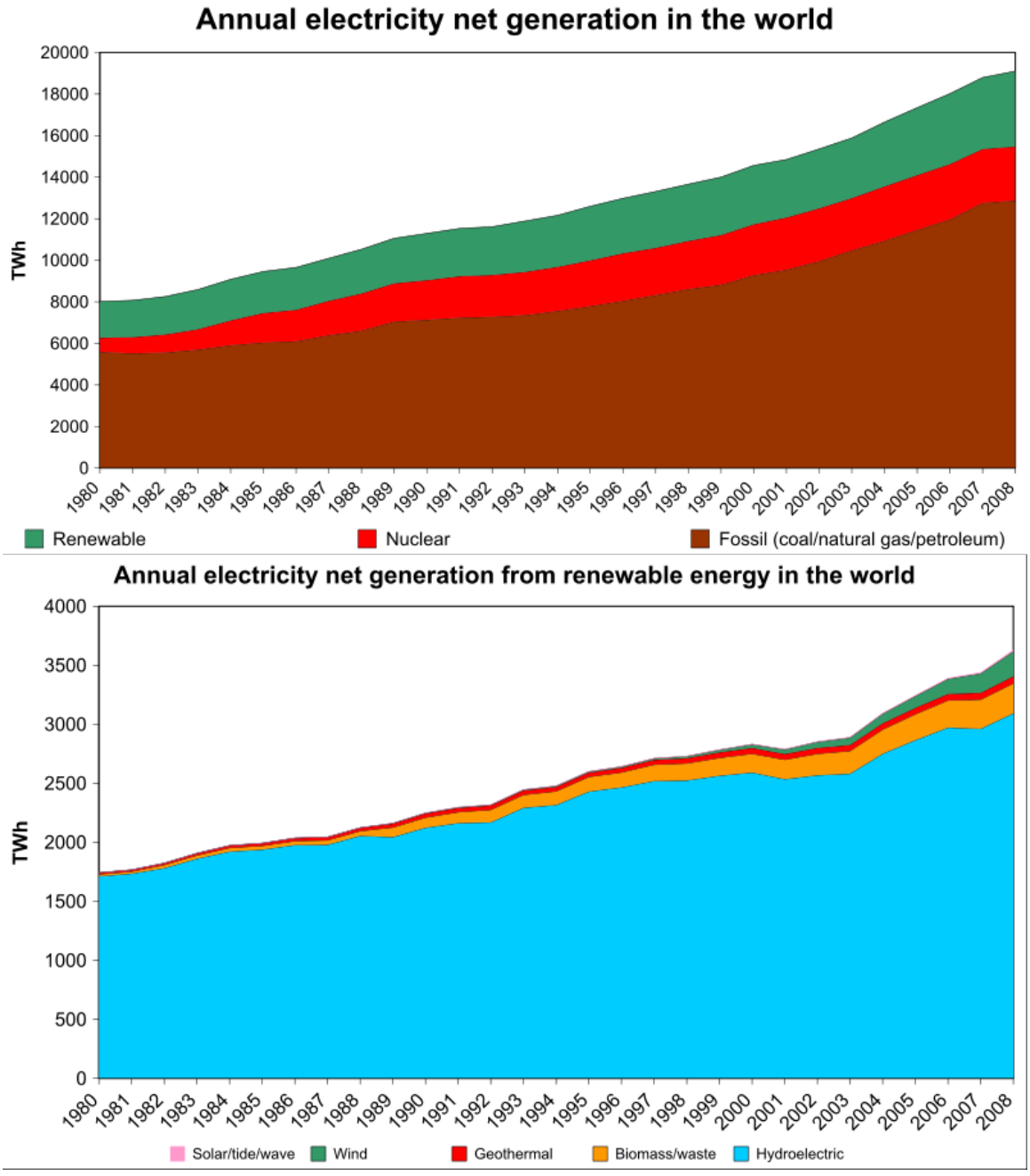
Various other technologies have been studied and developed for power generation. Solid-state generation (without moving parts) is of particular interest in portable applications. This area is largely dominated by thermoelectric (TE) devices, though thermionic (TI) and thermophotovoltaic (TPV) systems 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, ...)

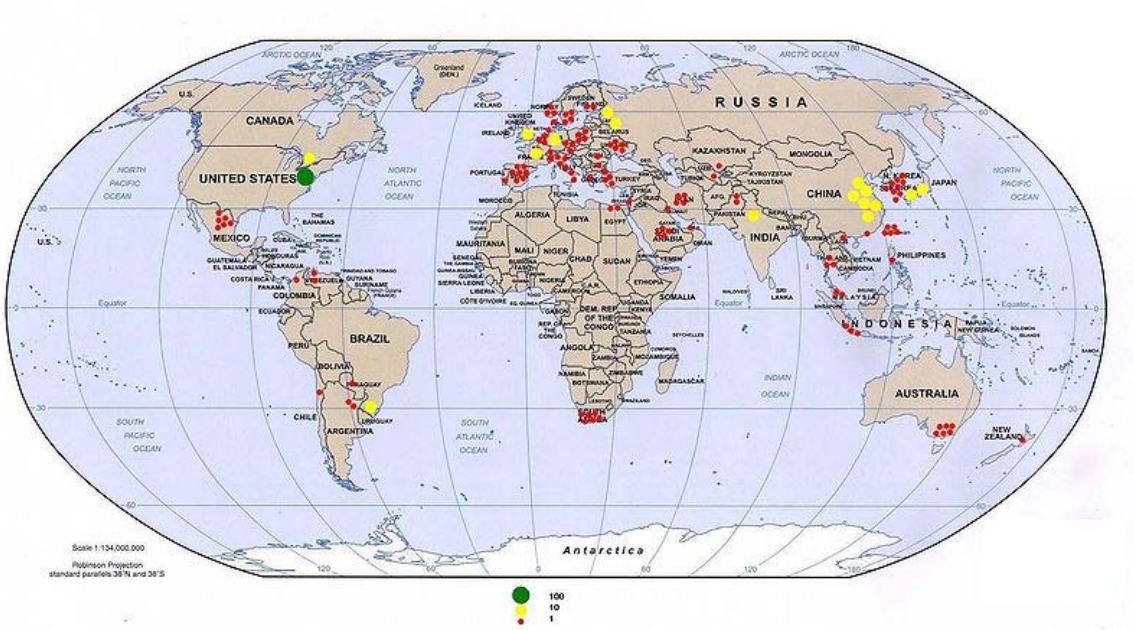
Electrochemical electricity generation is also important in portable and mobile applications. Currently, most electrochemical power comes from closed electrochemical cells ("batteries"), which are arguably utilized more as storage systems than generation systems, but open electrochemical systems, known 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



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.

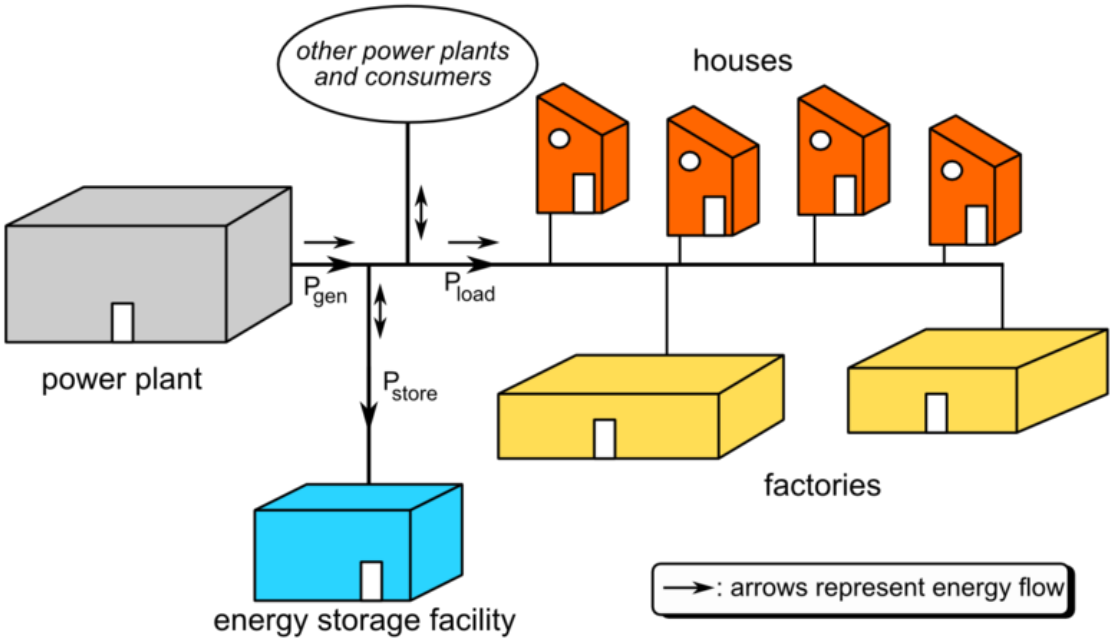
In the United States, fossil fuel combustion for electric power generation is responsible for 65% of all emissions of sulfur dioxide, the main component of acid rain. Electricity generation is the fourth highest combined source of NOx, carbon monoxide, and particulate matter in the US.

Water Consumption

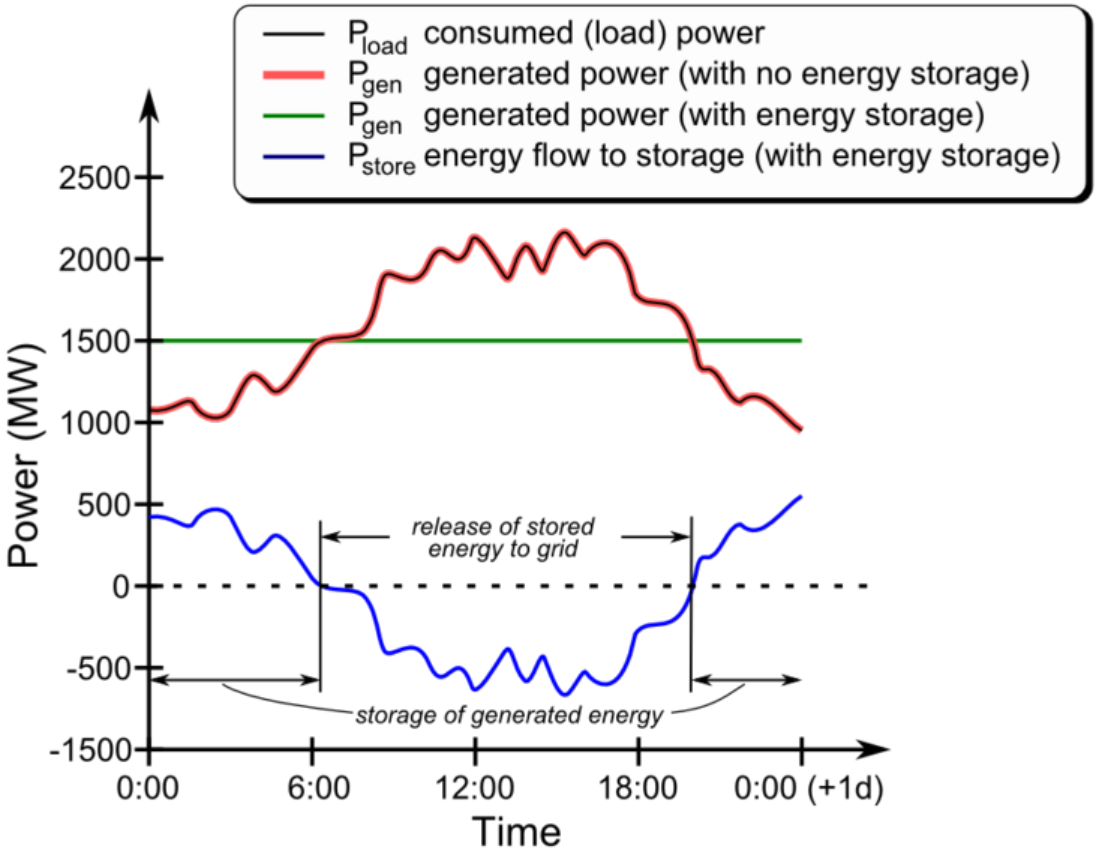
Most large scale conventional electricity-only fossil fueled power stations consume considerable amounts of water for cooling purposes and boiler water make up - 1 L/kWh for once through (e.g. river cooling), and 1.7 L/kWh for cooling tower cooling. Water abstraction for cooling water accounts for about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

Chapter 2

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 3

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.

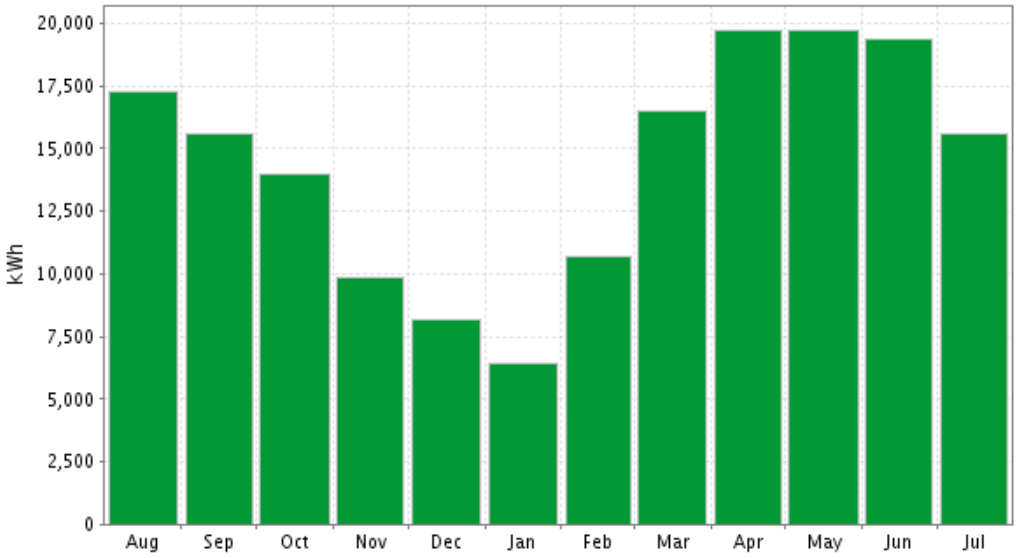
Terminology

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



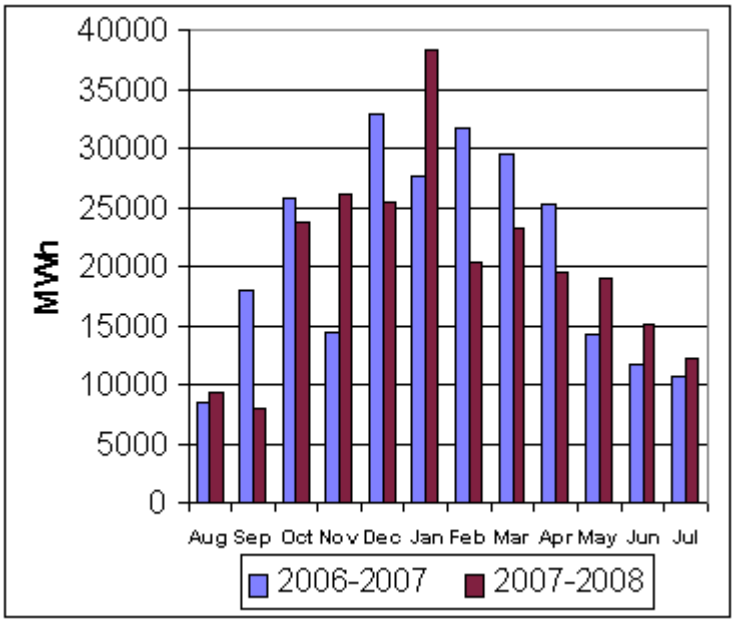
Seasonal variation of the output of the solar panels at AT&T park in San Francisco.

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.

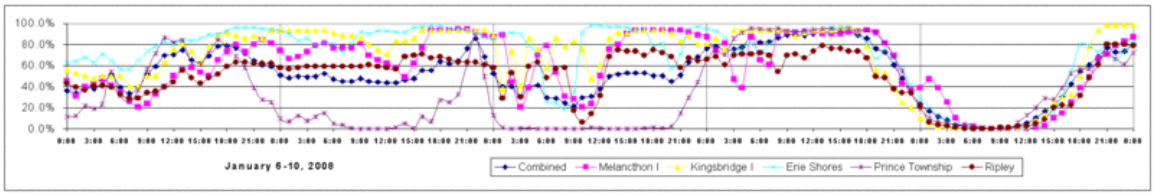
- **Intermittence:** A single wind turbine is highly intermittent. Theoretical arguments often claim that a large wind farm spread over a geographically diverse area will as a whole rarely stop producing power altogether, however this is in contradiction to the observed variability in total power output 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

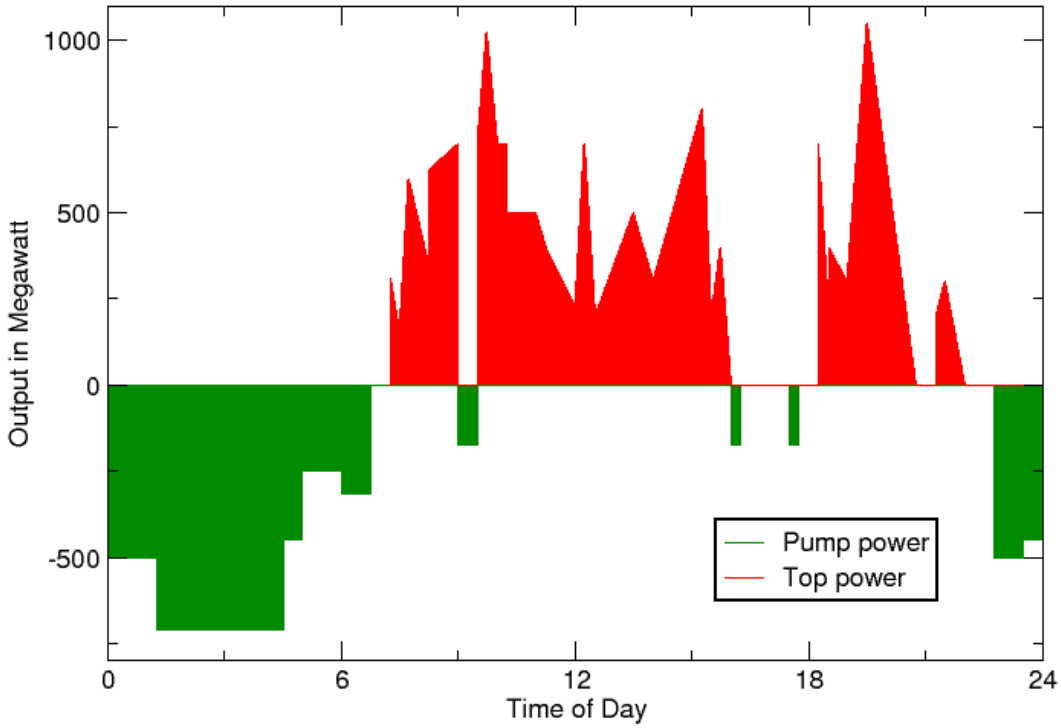
A November 2006 analysis found that "wind power may be able to cover more than 50% of the Danish electricity consumption in 2025" under conditions of high oil prices and higher costs for CO_2 allowances. Denmark's two grids (covering West Denmark and East Denmark separately) each incorporate high-capacity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

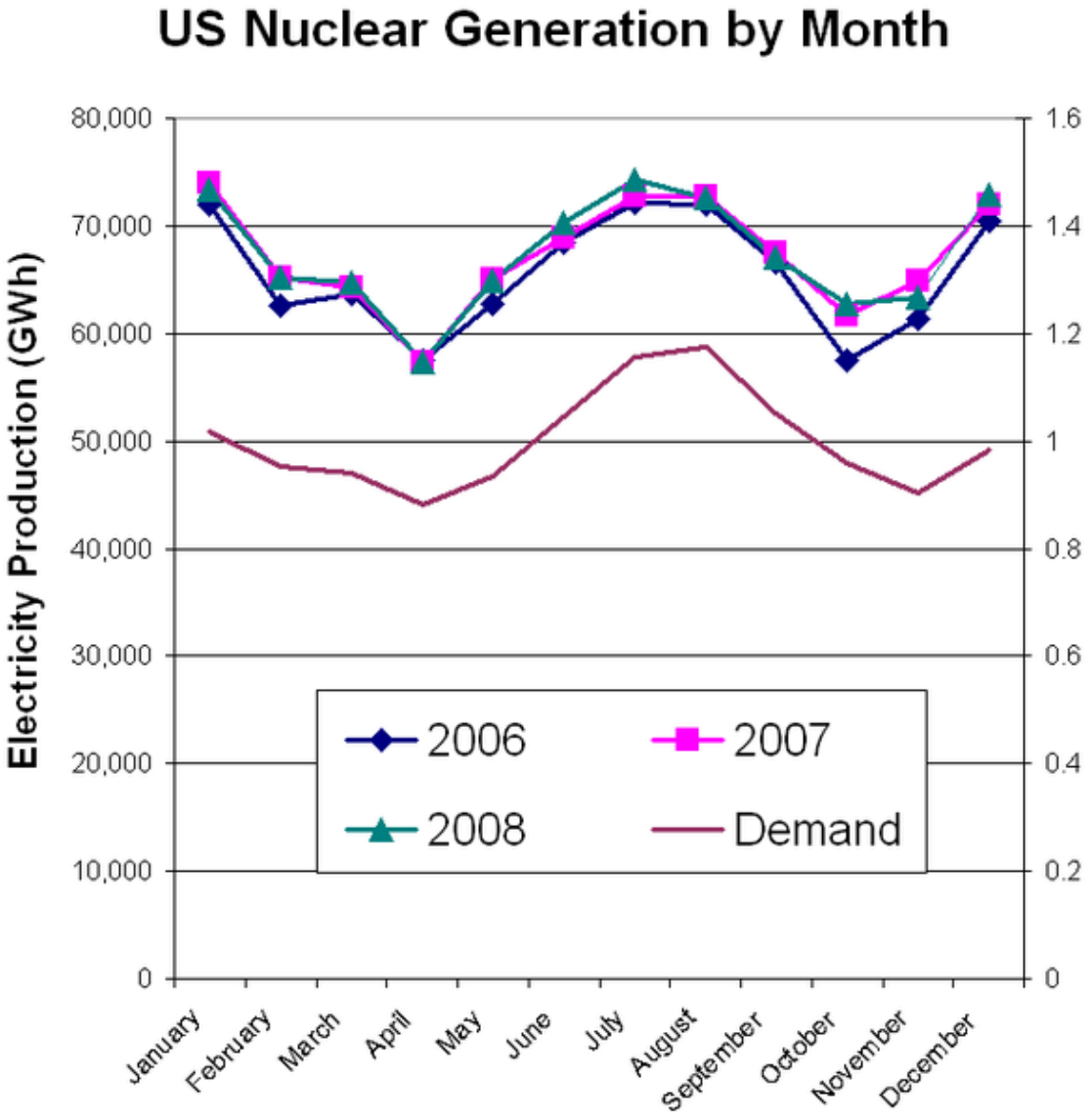
- **Capacity factor**: Base load coal plant 70–90%

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 4

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 5

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 6

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 7

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 8

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.

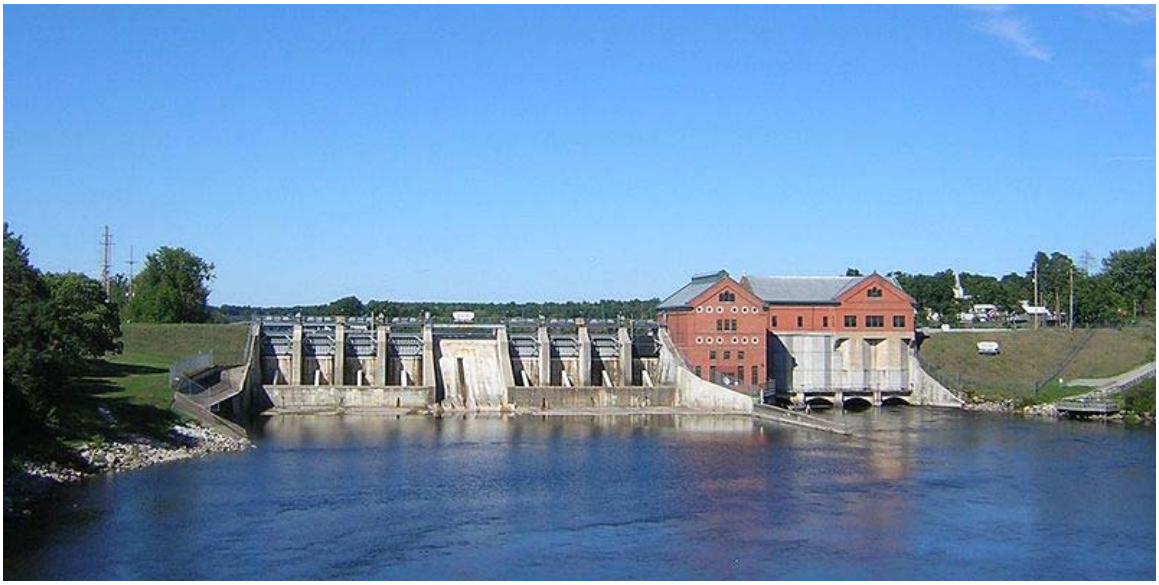
Where economically and environmentally possible, electric companies prefer to use cooling water from the ocean, or a lake or river, or a cooling pond, instead of a cooling tower. This type of cooling can save the cost of a cooling tower and may have lower energy costs for pumping cooling water through 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

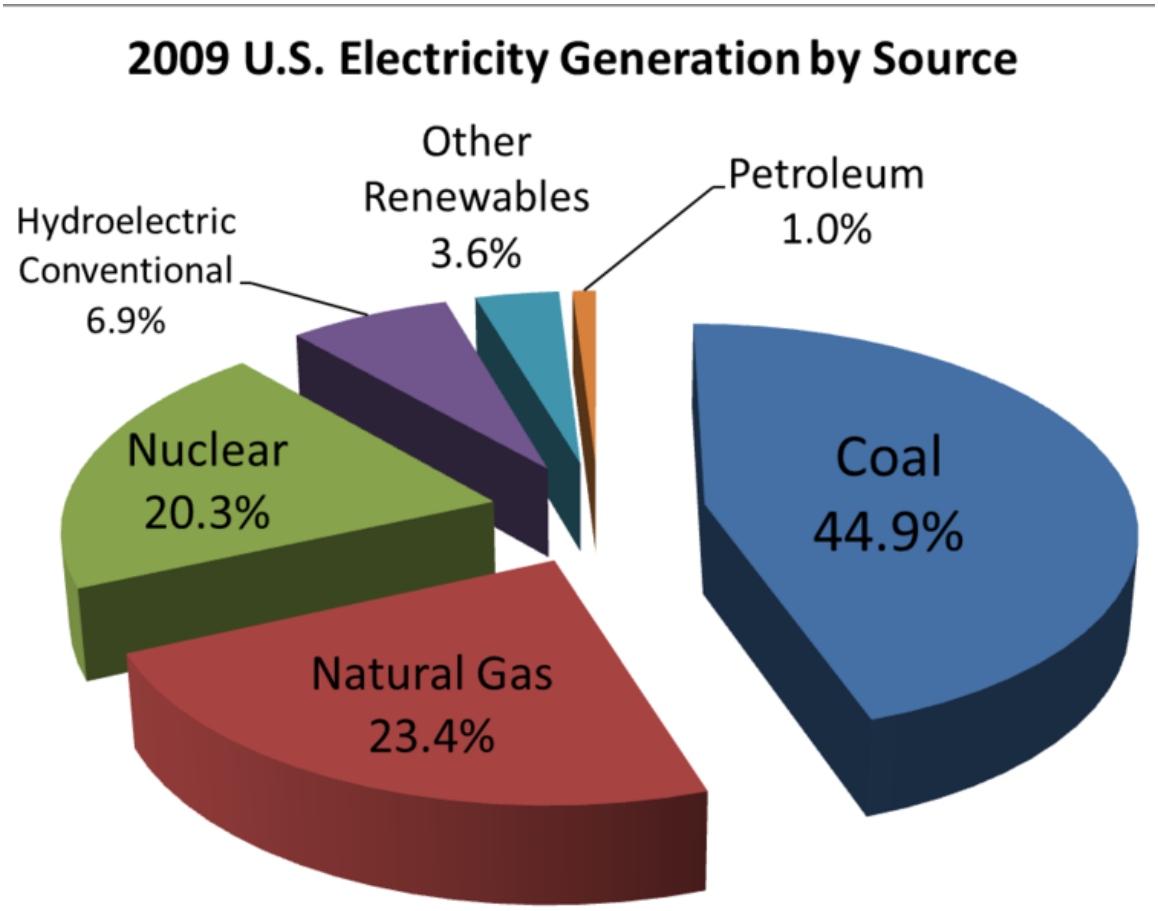
The **power station operator** has several duties in the electrical generating facility. Operators are responsible for the safety of the work crews that frequently do repairs on the mechanical and electrical equipment. They maintain the equipment with periodic inspections and log temperatures, pressures 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 9

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

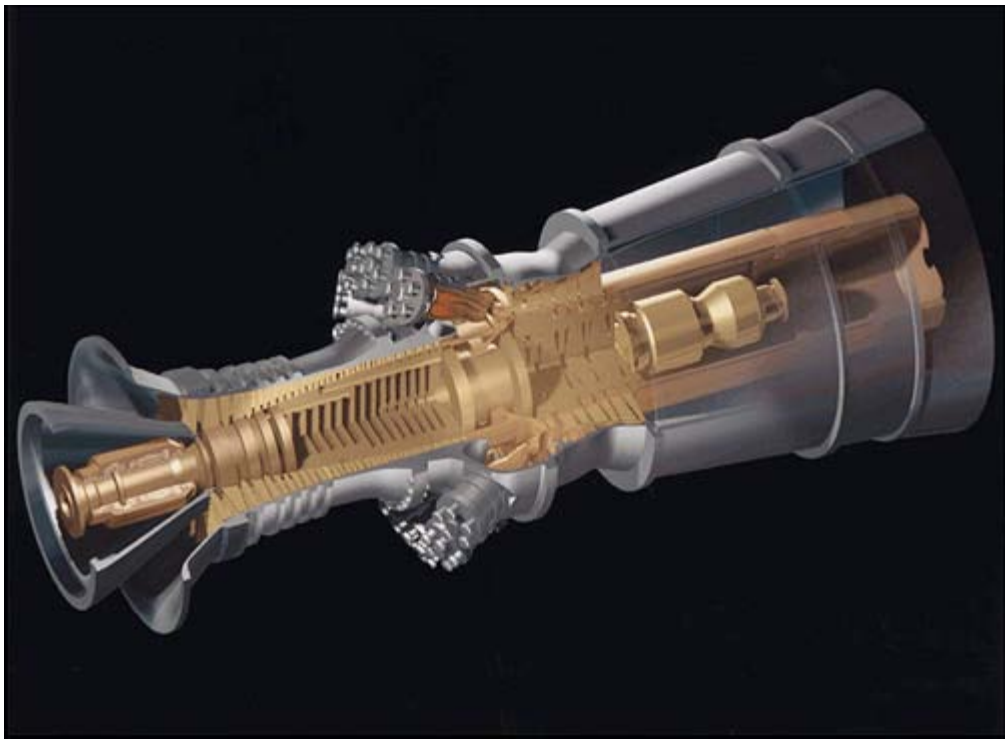
preheats the coal to drive off excess moisture content. A 500 MWe plant may have six such pulverizers, five of which can supply coal to the furnace at 250 tons per hour under full load.

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.

Chapter 10

Transmission Tower

A delta pylon carrying a 400kV power line towards Madrid.

A **transmission tower** (colloquially termed an **electricity pylon** in the United Kingdom and parts of Europe, an **ironman** in Australia, and a **hydro tower** in parts of Canada) is a tall structure, usually a steel lattice tower, used to support an overhead power line. They are used in high-voltage AC and DC systems, and come in a wide variety of shapes and sizes. Typical height ranges from 15 to 55 metres (49 to 180 ft), although heights in excess of 300 metres (980 ft) exist. In addition to steel, other materials may be used, including concrete and wood.

Four major functions of transmission towers are in use: suspension towers, terminal towers, tension towers, and transposition towers. Some transmission towers combine these basic functions. Transmission towers and their overhead power lines are often considered to be a form of visual pollution. Methods to reduce the visual impact include undergrounding.

Naming

"Transmission tower" is the name for the structure used in the industry in the United Kingdom, United States, and other English-speaking countries. The term "pylon" comes from the basic shape of the structure, an obelisk-like structure which tapers toward the top, and is mostly used in the United Kingdom and parts of Europe in everyday colloquial speech. This term is rarely, if ever, used in the United States, as the word "pylon" is commonly used for a multitude of other things, mostly for traffic cones. In Canada, the term "hydro tower" comes from the name of local hydroelectric power utility companies.

High voltage AC transmission towers

The two main pylons of "Elbe Crossing 2", acrossing the German river Elbe

Three-phase electric power systems are used for high and extra-high voltage AC transmission lines (50 kV and above). The towers must be designed to carry three (or multiples of three) conductors. The towers are usually steel lattices or trusses (wooden structures are used in Canada, Germany, and Scandinavia in some cases) and the insulators are either glass or porcelain discs or composite insulators using silicone rubber or EPDM rubber material assembled in strings or long rods whose lengths are dependent on the line voltage and environmental conditions.

Typically, one or two ground wires are placed on top to intercept lightning and harmlessly divert it to ground.

In some countries, towers for high and extra-high voltage are usually designed to carry two or more electric circuits. For double circuit lines in Germany, the "Danube" towers or, more rarely, the "fir tree" towers are usually used. If a line is constructed using towers designed to carry several circuits, it is not necessary to install all the circuits at the time of construction.

Some high voltage circuits are often erected on the same tower as 110 kV lines. Paralleling circuits of 380 kV, 220 kV and 110 kV-lines on the same towers is common. Sometimes, especially with 110 kV circuits, a parallel circuit carries traction lines for railway electrification.

High voltage DC transmission towers

HVDC distance tower near the terminus of the Nelson River Bipole adjacent to Dorsey Converter Station near Rosser, Manitoba, Canada — August 2005

High-voltage direct current (HVDC) transmission lines are either monopolar or bipolar systems. With bipolar systems a conductor arrangement with one conductor on each side of the tower is used. For single-pole HVDC transmission with ground return, towers with only one conductor can be used. In many cases, however, the towers are designed for later conversion to a two-pole system. In these cases, conductors are installed on both sides of the tower for mechanical reasons. Until the second pole is needed, it is either grounded, or joined in parallel with the pole in use. In the latter case the line from the converter station to the earthing (grounding) electrode is built as underground cable.

Railway traction line towers

Tension tower with phase transposition of a powerline for single phase AC traction current (110 kV, 16.67 Hz) near Bartholomä, Germany

Towers used for single phase AC railway traction lines are similar in construction to those towers used for 110 kV-three phase lines. Steel tube or concrete poles are also often used for these lines. However, railway traction current systems are two-pole AC systems, so traction lines are designed for two conductors (or multiples of two, usually four, eight, or twelve). As a rule, the towers of railway traction lines carry two electric circuits, so they have four conductors. These are usually arranged on one level, whereby each circuit occupies one half of the crossarm. For four traction circuits the arrangement of the conductors is in two-levels and for six electric circuits the arrangement of the conductors is in three levels.

With limited space conditions, it is possible to arrange the conductors of one traction circuit in two levels. Running a traction power line parallel to a high voltage transmission line for three-phase AC on a separate crossarm of the same tower is possible. If traction lines are led parallel to 380 kV-lines, the insulation must be designed for 220 kV, because in the event of a fault, dangerous overvoltages to the three-phase alternating current line can occur. Traction lines are usually equipped with one earth conductor. In Austria, on some traction circuits, two earth conductors are used.

Assembly

Before transmission towers are even erected, prototype towers are tested at tower testing stations. There are a variety of ways they can then be assembled and erected:

- They can be assembled horizontally on the ground and erected by push-pull cable. This method is rarely used, however, because of the large assembly area needed.
- They can be assembled vertically (in their final upright position). Very tall towers, such as the Yangtze River Crossing, were assembled in this way.
- A jin-pole crane can be used to assemble lattice towers. This is also used for utility poles.
- Helicopters can serve as aerial cranes for their assembly in areas with limited accessibility. Towers can also be assembled elsewhere and flown to their place on the transmission right-of-way.

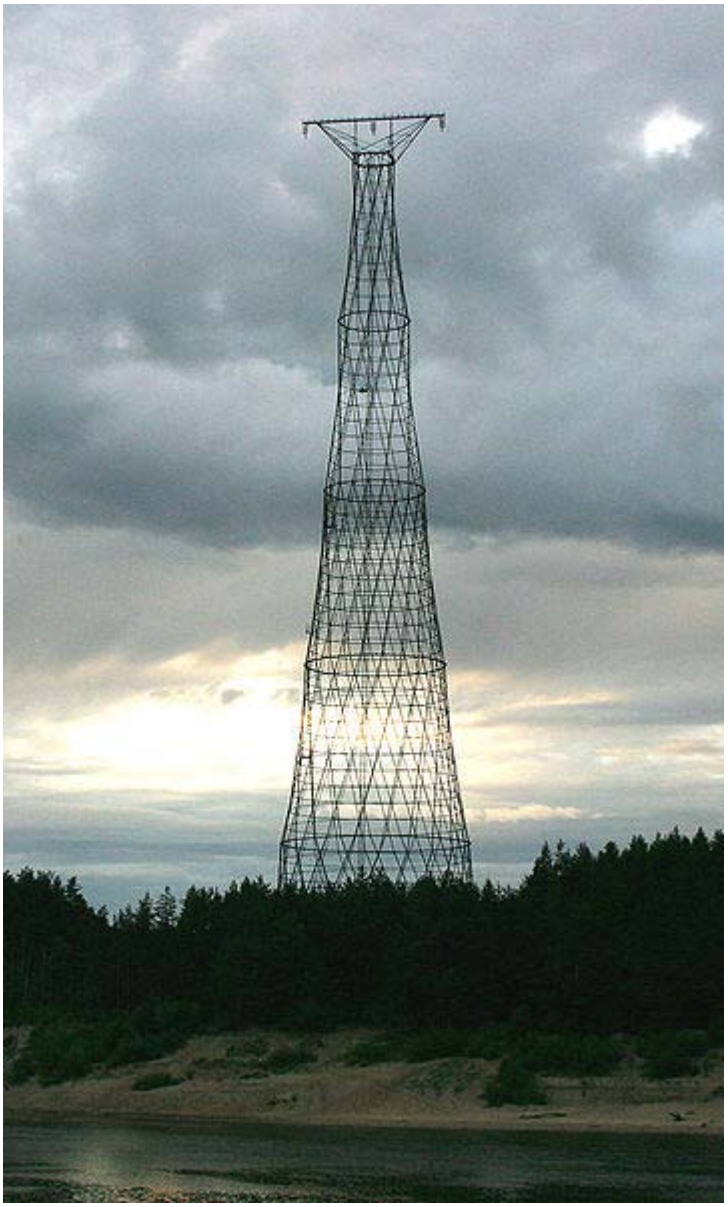
Sign markings

A typical tower identification tag

Electricity pylons often have an identification number or code placed on the pole in the form of a sign, an identification plate, painted numbers, or anything else the electric company chooses. These tags are usually marked with the names of the line (either the terminal points of the line or the internal designation of the power company) and the tower number. This makes identifying the location of a fault to the power company that owns the tower easier.

Transmission towers, much like other steel lattice towers including broadcasting or cellphone towers, are marked with signs which discourage public access due to the danger of the high voltage. Often this is accomplished with a sign warning of the high voltage; other times the entire access point to the transmission corridor is marked with a sign. Some countries require that lattice steel towers be equipped with a barbed wire barrier approximately 3 metres (9.8 ft) above ground in order to deter unauthorized climbing. Such barriers can often be found on towers close to roads or other areas with easy public access, even where there is not a legal requirement. In the United Kingdom, all such towers are fitted with barbed wire.

Special designs



Hyperboloid pylon in the suburb of Nizhniy Novgorod, Russia.

Sometimes (in particular on steel lattice towers for the highest voltage levels) transmitting plants are installed, and antennas mounted on the top above or below the overhead ground wire. Usually these installations are for mobile phone services or the operating radio of the power supply firm, but occasionally also for other radio services, like directional radio. Thus transmitting antennas for low-power FM radio and television transmitters were already installed on pylons. On the Elbe Crossing 1 tower, there is a radar facility belonging to the Hamburg water and navigation office.

One of the Pylons of Cádiz, Spain

For crossing broad valleys, a large distance between the conductors must be maintained to avoid short-circuits caused by conductor cables colliding during storms. To achieve this, sometimes a separate mast or tower is used for each conductor. For crossing wide rivers and straits with flat coastlines, very tall towers must be built due to the necessity of a large height clearance for navigation. Such towers and the conductors they carry must be equipped with flight safety lamps and reflectors.

Two well-known wide river crossings are the Elbe Crossing 1 and Elbe Crossing 2. The latter has the tallest overhead line masts in Europe, at 227 metres (745 ft) tall. In Spain, the overhead line crossing pylons in the Spanish bay of Cádiz have a particularly interesting construction. The main crossing towers are 158 metres (518 ft) tall with one

crossarm atop a frustum framework construction. The longest overhead line spans are the crossing of the Norwegian Sognefjord (4,597 metres (15,082 ft) between two masts) and the Ameralik span in Greenland (5,376 metres (17,638 ft)). In Germany, the overhead line of the EnBW AG crossing of the Eyachtal has the longest span in the country at 1,444 metres (4,738 ft).

In order to drop overhead lines into steep, deep valleys, inclined towers are occasionally used. These are utilized at the Hoover Dam, located in the United States, to descend the cliff walls of the Black Canyon of the Colorado. In Switzerland, a NOK pylon inclined around 20 degrees to the vertical is located near Sargans, St. Gallens. Highly sloping masts are used on two 380 kV pylons in Switzerland, the top 32 meters of one of them being bent by 18 degrees to the vertical.

Power station chimneys are sometimes equipped with crossbars for fixing conductors of the outgoing lines. Because of possible problems with corrosion by the flue gases, such constructions are very rare.

A new type of pylon will be used in the Netherlands starting in 2010. The pylons were designed as a minimalist structure by Dutch architects Zwarts and Jansma. The use of physical laws for the design made a reduction of the magnetic field possible. Also, the visual impact on the surrounding landscape is reduced.

Tower functions

Three-phase alternating current transmission towers over water, near Darwin, Northern Territory, Australia

Tower structures can be classified by the way in which they support the line conductors. Suspension structures support the conductor vertically using suspension insulators. . Strain structures resist net tension in the conductors and the conductors attach to the structure through strain insulators. Dead-end structures support the full weight of the conductor and also all the tension in it, and also use strain insulators.

Where the conductors are straight, a tangent tower is used. Angle towers are used where a line must change direction.

Structures are classified as tangent suspension, angle suspension, tangent strain, angle strain, tangent dead-end and angle dead-end.

Cross arms and conductor arrangement

Generally three conductors are required per AC 3-phase circuit, although single-phase and DC circuits are also carried on towers. Conductors may be arranged in one plane, or by use of several cross-arms may be arranged in a roughly symmetrical, triangulated pattern to balance the impedances of all three phases. If more than one circuit is required to be carried and the width of the line right-of-way does not permit multiple towers to be used, two or three circuits can be carried on the same tower using several levels of cross-arms. Often multiple circuits are the same voltage, but mixed voltages can be found on some structures.

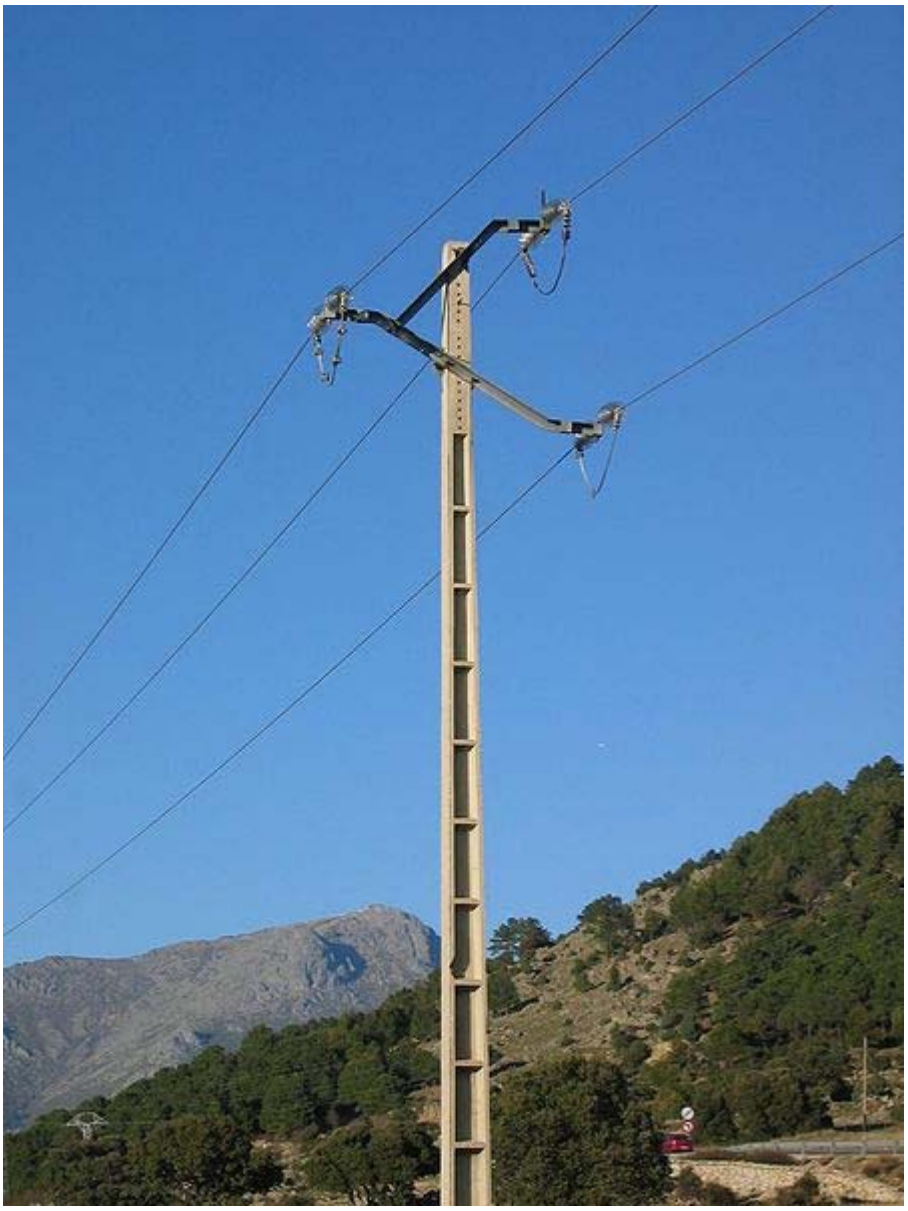
Tower designs

Wood

Wooden pylon from Finland

Because of the limited height of available trees the maximum height of wooden pylons is limited (approximately 30 metres). In Germany wood pylons are used as a rule only for lines with voltages up to approximately 30 kV. In the United States wood poles are used to construct H-frame or K-frame stuctures for voltages up to 345 kV; these can be less costly than steel structures and take advantage of the surge voltage insulating properties of wood.

Concrete



A reinforced concrete pole in Spain

Because of its durability and ease of manufacturing and installation, many utilities in recent years prefer the use of concrete and steel tube pylons over wood and lattice steel pylons for new power lines and pylon replacements.

Concrete pylons are used in Germany normally only for lines with operating voltages below 30kV. In exceptional cases concrete pylons are used also for 110kV-lines, as well as for the public grid or for the railway traction current grid. In Switzerland, concrete pylons with heights of up to 59.5 metres (world's tallest pylon of prefabricated concrete at Littau) are used for 380kV-overhead lines. Concrete poles are also used in Canada.

Concrete pylons, which are not prefabricated, are also used for constructions taller than 60 metres. One example is a 66 metres tall pylon of a 380 kV powerline near Reutter West Power Plant in Berlin. Such pylons look like industrial chimneys and some of these structures are also used as chimneys. In China some tall pylons of powerline crossings of wide rivers were built of concrete. The tallest of these pylons belong to the Yangtze Powerline crossing at Nanjing with a height of 257 metres.

Steel tube pylon near Madrid, Spain

Tubular steel monopole

Poles made of tubular steel generally are assembled at the factory and placed on the right-of-way afterward. Because of its durability and ease of manufacturing and installation, many utilities in recent years prefer the use of steel tube and concrete pylons over wood and lattice steel pylons for new power lines and pylon replacements.

In Germany steel tube pylons are also established predominantly for medium voltage lines, in addition, for high voltage transmission lines or two electric circuits for operating voltages by up to 110 kV. In France steel tube pylons are used frequently also for pylons by 380 kV lines in the USA also for 500 kV lines.

Lattice steel

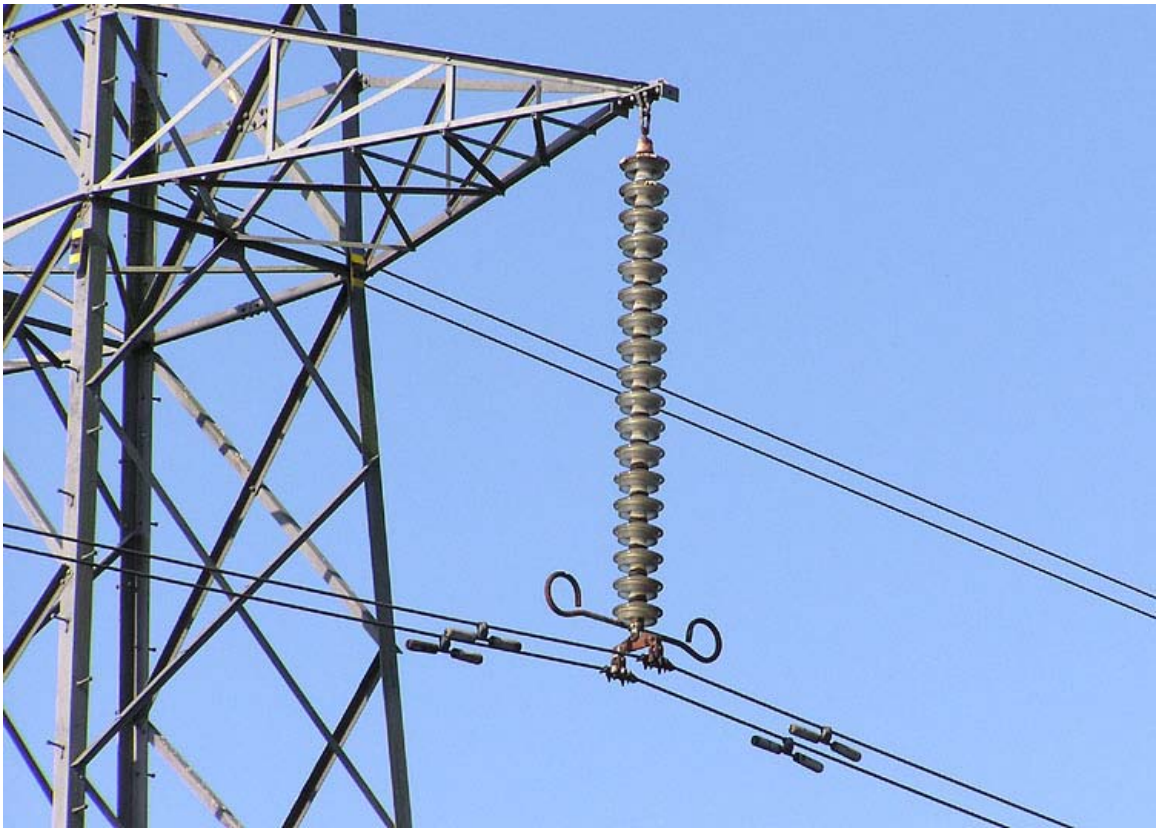
A lattice steel tower is a steel framework construction. Lattice steel towers are used for power lines of all voltages, and are the most common type for high-voltage transmission lines.

A lattice tower is usually assembled at the location where it is to be erected. This makes very tall towers possible (up to 100 metres—in special cases even higher, as in the Elbe crossing 1 and Elbe crossing 2). Assembly of lattice steel towers can be done using a crane. Lattice steel towers are generally made of angle-profiled steel beams (L- or T-beams). For very tall towers, trusses are often used.

Aluminum

Where towers must be placed in inaccessible terrain by helicopters, the extra material cost of aluminum towers will be offset by lower installation cost. Design of aluminum lattice towers is similar to that for steel, but must take into account alumunim's lower Young's modulus.

Notable pylons



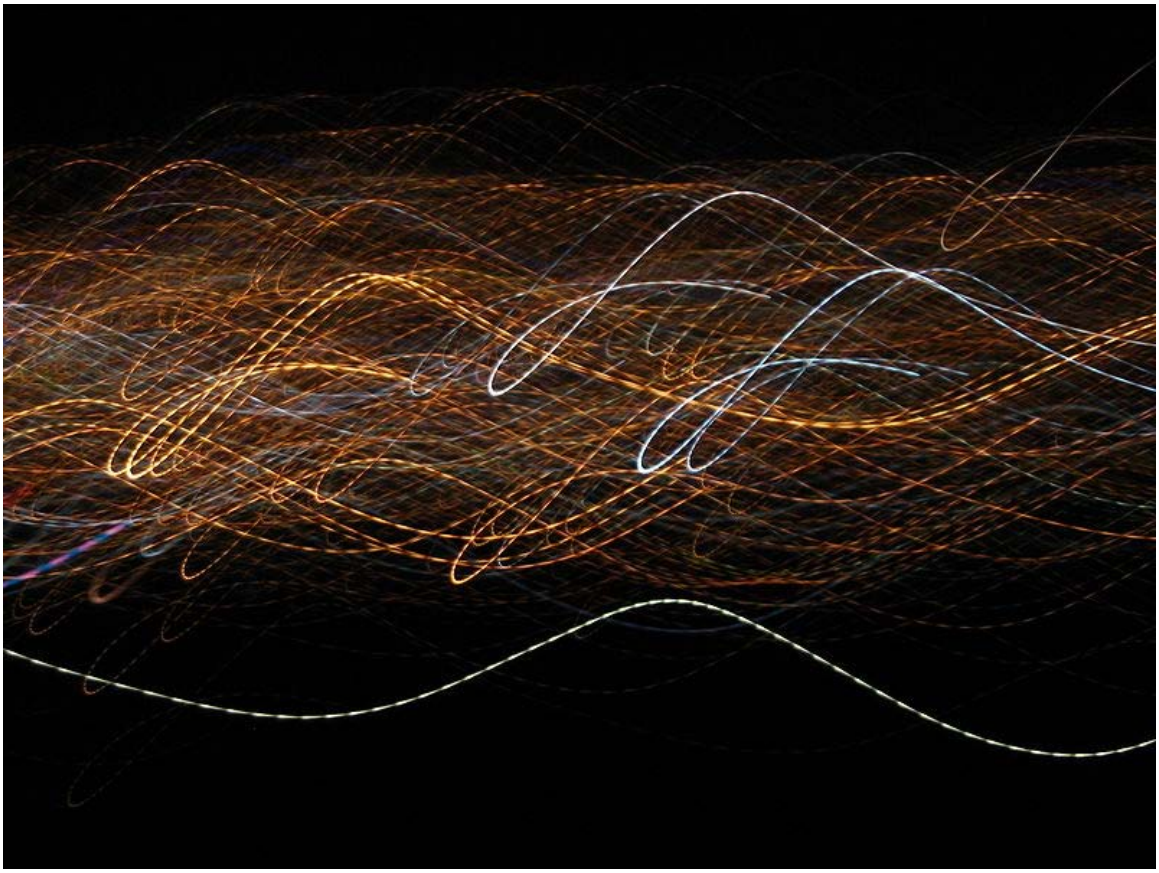
Detail of the insulators (the vertical string of discs) and conductor vibration dampers (the weights attached directly to the conductors) on a 275,000 volt suspension tower near Thornbury, South Gloucestershire, England, United Kingdom

A tubular pylon, or *muguet* (lily) pylon, of an Hydro-Québec TransÉnergie line in Gatineau, Quebec, Canada. The tubular monopolar towers are used in urban settings for high-voltage lines, from 110 to 315 kV, and are considered more aesthetically pleasing.

Pylon decorated with balls in Ruhr Park, Bochum, Germany

Chapter 11

AC Power

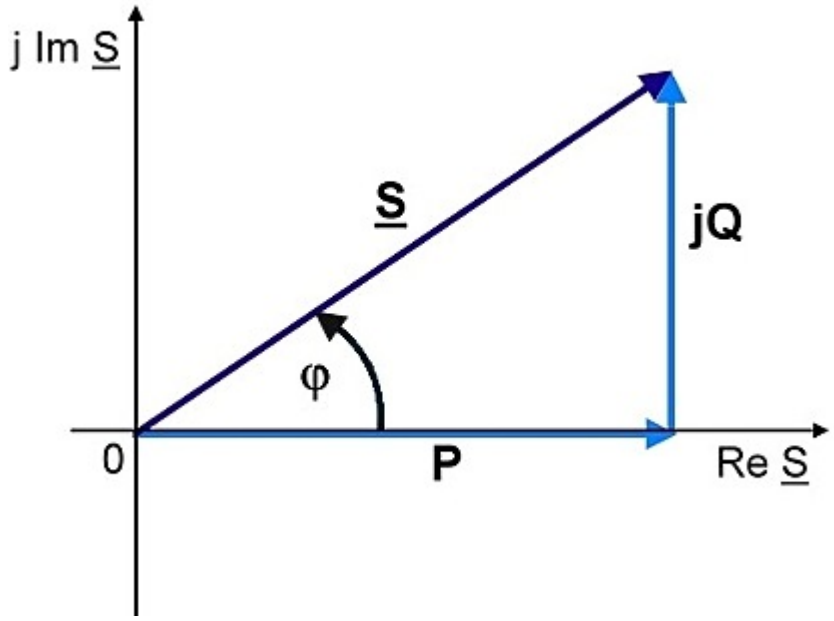


Usually hidden from the unaided eye, the blinking of (non-incandescent) lighting powered by AC mains is revealed in this motion-blurred long exposure of city lights. Light is emitted twice each cycle.

Power in an electric circuit is the rate of flow of energy past a given point of the circuit. In alternating current circuits, energy storage elements such as inductance and capacitance may result in periodic reversals of the direction of energy flow. The portion of power that, averaged over a complete cycle of the AC waveform, results in net transfer

of energy in one direction is known as real power. The portion of power due to stored energy, which returns to the source in each cycle, is known as reactive power.

Real, reactive, and apparent power



The apparent power is the vector sum of real and reactive power.
Real power (P)
Reactive power (Q)
Complex power (S)
Apparent Power (|S|)
Phase of Current (φ)

In a simple alternating current (AC) circuit consisting of a source and a linear load, both the current and voltage are sinusoidal. If the load is purely resistive, the two quantities reverse their polarity at the same time. At every instant the product of voltage and current is positive, indicating that the direction of energy flow does not reverse. In this case, only real power is transferred.

If the load is purely reactive, then the voltage and current are 90 degrees out of phase. For half of each cycle, the product of voltage and current is positive, but on the other half of the cycle, the product is negative, indicating that on average, exactly as much energy flows toward the load as flows back. There is no net energy flow over one cycle. In this case, only reactive energy flows—there is no net transfer of energy to the load.

Practical loads have resistance, inductance, and capacitance, so both real and reactive power will flow to real loads. Power engineers measure apparent power as the vector sum of real and reactive power. Apparent power is the product of the **root-mean-square** of voltage and current.

Engineers care about apparent power, because even though the current associated with reactive power does no work at the load, it heats the wires, wasting energy. Conductors, transformers and generators must be sized to carry the total current, not just the current that does useful work.

Another consequence is that adding the apparent power for two loads will not accurately give the total apparent power unless they have the same displacement between current and voltage (the same power factor).

If a capacitor and an inductor are placed in parallel, then the currents flowing through the inductor and the capacitor tend to cancel rather than add. Conventionally, capacitors are considered to generate reactive power and inductors to consume it. This is the fundamental mechanism for controlling the power factor in electric power transmission; capacitors (or inductors) are inserted in a circuit to partially cancel reactive power 'consumed' by the load.

Engineers use the following terms to describe energy flow in a system (and assign each of them a different unit to differentiate between them):

- **Real power** (*P*) or **active power** : watt [W]
- **Reactive power** (*Q*): volt-ampere reactive [Var]
- **Complex power** (*S*): volt-ampere [VA]
- **Apparent Power** (|*S*|), that is, the absolute value of complex power *S*: volt-ampere [VA]
- **Phase of Current** (φ), the angle of difference (in degrees) between voltage and current; Current lagging Voltage (Quadrant I Vector), Current leading voltage (Quadrant IV Vector)

In the diagram, *P* is the real power, *Q* is the reactive power (in this case positive), *S* is the complex power and the length of *S* is the apparent power.

Reactive power does not transfer energy, so it is represented as the imaginary axis of the vector diagram. Real power moves energy, so it is the real axis.

The unit for all forms of power is the watt (symbol: W), but this unit is generally reserved for real power. Apparent power is conventionally expressed in volt-amperes (VA) since it is the product of rms voltage and rms current. The unit for reactive power is expressed as var, which stands for volt-amperes reactive. Since reactive power transfers no net energy to the load, it is sometimes called "wattless" power. It does, however, serve an important function in electrical grids and its lack has been cited as a significant factor in the Northeast Blackout of 2003.

Understanding the relationship between these three quantities lies at the heart of understanding power engineering. The mathematical relationship among them can be represented by vectors or expressed using complex numbers, $S=P+jQ$(where j is the imaginary unit).

Power factor

The ratio between real power and apparent power in a circuit is called the power factor. It's a practical measure of the efficiency of a power distribution system. For two systems transmitting the same amount of real power, the system with the lower power factor will have higher circulating currents due to energy that returns to the source from energy storage in the load. These higher currents produce higher losses and reduce overall transmission efficiency. A lower power factor circuit will have a higher apparent power and higher losses for the same amount of real power.

The power factor is one when the voltage and current are in phase. It is zero when the current leads or lags the voltage by 90 degrees. Power factors are usually stated as "leading" or "lagging" to show the sign of the phase angle, where leading indicates a negative sign.

Purely capacitive circuits cause reactive power with the current waveform leading the voltage wave by 90 degrees, while purely inductive circuits cause reactive power with the current waveform lagging the voltage waveform by 90 degrees. The result of this is that capacitive and inductive circuit elements tend to cancel each other out.

Where the waveforms are purely sinusoidal, the power factor is the cosine of the phase angle (φ) between the current and voltage sinusoid waveforms. Equipment data sheets and nameplates often will abbreviate power factor as "cosφ" for this reason.

Example: The real power is 700 W and the phase angle between voltage and current is 45.6°. The power factor is cos(45.6°) = 0.700. The apparent power is then: 700 W / cos(45.6°) = 1000 VA.

Reactive power

Reactive power flow on the alternating current transmission system is needed to support the transfer of real power over the network. In alternating current circuits energy is stored temporarily in inductive and capacitive elements, which can result in the periodic reversal of the direction of energy flow. The portion of power flow remaining after being averaged over a complete AC waveform is the real power, which is energy that can be used to do work (for example overcome friction in a motor, or heat an element). On the other hand the portion of power flow that is temporarily stored in the form of electric or magnetic fields, due to inductive and capacitive network elements, and returned to source is known as the reactive power.

AC connected devices that store energy in the form of a magnetic field include inductive devices called reactors, which consist of a large coil of wire. When a voltage is initially placed across the coil a magnetic field builds up, and it takes a period of time for the current to reach full value. This causes the current to lag the voltage in phase, and hence these devices are said to absorb reactive power.

A capacitor is an AC device that stores energy in the form of an electric field. When current is driven through the capacitor, it takes a period of time for charge to build up to produce the full voltage difference. On an AC network the voltage across a capacitor is always changing – the capacitor will oppose this change causing the voltage to lag behind the current. In other words the current leads the voltage in phase, and hence these devices are said to generate reactive power.

Energy stored in capacitive or inductive elements of the network give rise to reactive power flow. Reactive power flow strongly influences the voltage levels across the network. Voltage levels and reactive power flow must be carefully controlled to allow a power system to be operated within acceptable limits.

Reactive power control

Transmission connected generators are generally required to support reactive power flow. For example on the Great Britain transmission system generators are required by the Grid Code Requirements to supply their rated power between the limits of 0.85 power factor lagging and 0.95 power factor leading at the designated terminals. The system operator will perform switching actions to maintain a secure and economical voltage profile while maintaining a reactive power balance equation:

Generator_MVARs + System_gain + Shunt_capacitors = MVAR_Demand + Reactive_losses + Shunt_reactors

The ‘System gain’ is an important source of reactive power in the above power balance equation, which is generated by the network itself. By making decisive switching actions in the early morning before the demand increases, the system gain can be maximized early on, helping to secure the system for the whole day.

To balance the equation some pre-fault reactive generator use will be required. Other sources of reactive power that will also be used include shunt capacitors, shunt reactors, Static VAR Compensators and voltage control circuits.

Unbalanced polyphase systems

While real power and reactive power are well defined in any system, the definition of apparent power for unbalanced polyphase systems is considered to be one of the most controversial topics in power engineering. Originally, apparent power arose merely as a figure of merit. Major delineations of the concept are attributed to Stanley's *Phenomena of Retardation in the Induction Coil* (1888) and Steinmetz's *Theoretical Elements of Engineering* (1915). However, with the development of three phase power distribution, it became clear that the definition of apparent power and the power factor could not be applied to unbalanced polyphase systems. In 1920, a "Special Joint Committee of the AIEE and the National Electric Light Association" met to resolve the issue. They considered two definitions:

- $$pf = \frac{Pa + Pb + Pc}{|Sa| + |Sb| + |Sc|}$$

that is, the quotient of the sums of the real powers for each phase over the sum of the apparent power for each phase.

- $$pf = \frac{Pa + Pb + Pc}{|Pa + Pb + Pc + j(Qa + Qb + Qc)|}$$

that is, the quotient of the sums of the real powers for each phase over the magnitude of the sum of the complex powers for each phase.

The 1920 committee found no consensus and the topic continued to dominate discussions. In 1930 another committee formed and once again failed to resolve the question. The transcripts of their discussions are the lengthiest and most controversial ever published by the AIEE (Emanuel, 1993). Further resolution of this debate did not come until the late 1990s.

Basic calculations using real numbers

A perfect resistor stores no energy, so current and voltage are in phase. Therefore there is no reactive power and $P = S$. Therefore for a perfect resistor

$$P = S = V_{\mathrm{RMS}} I_{\mathrm{RMS}} = I_{\mathrm{RMS}}^2 R = \frac{V_{\mathrm{RMS}}^2}{R}$$

For a perfect capacitor or inductor there is no net power transfer, so all power is reactive. Therefore for a perfect capacitor or inductor:

$$P = 0$$

$$Q = |S| = V_{\mathrm{RMS}} I_{\mathrm{RMS}} = I_{\mathrm{RMS}}^2 |X| = \frac{V_{\mathrm{RMS}}^2}{|X|}$$

Where X is the reactance of the capacitor or inductor.

If X is defined as being positive for an inductor and negative for a capacitor then we can remove the modulus signs from Q and X and get

$$Q = I_{\mathrm{RMS}}^2 X = \frac{V_{\mathrm{RMS}}^2}{X}$$

Multiple frequency systems

Since an RMS value can be calculated for any waveform, apparent power can be calculated from this.

For real power it would at first appear that we would have to calculate loads of product terms and average all of them. However if we look at one of these product terms in more detail we come to a very interesting result.

$$A\cos(\omega_1 t + k_1)\cos(\omega_2 t + k_2)$$
$$= \frac{A}{2}\cos((\omega_1 t + k_1) + (\omega_2 t + k_2)) + \frac{A}{2}\cos((\omega_1 t + k_1) - (\omega_2 t + k_2))$$
$$= \frac{A}{2}\cos((\omega_1 + \omega_2)t + k_1 + k_2) + \frac{A}{2}\cos((\omega_1 - \omega_2)t + k_1 - k_2)$$

however the time average of a function of the form $\cos(\omega t+k)$ is zero provided that ω is nonzero. Therefore the only product terms that have a nonzero average are those where the frequency of voltage and current match. In other words it is possible to calculate real (average) power by simply treating each frequency separately and adding up the answers.

Furthermore, if we assume the voltage of the mains supply is a single frequency (which it usually is), this shows that harmonic currents are a bad thing. They will increase the rms current (since there will be non-zero terms added) and therefore apparent power, but they will have no effect on the real power transferred. Hence, harmonic currents will reduce the power factor.

Harmonic currents can be reduced by a filter placed at the input of the device. Typically this will consist of either just a capacitor (relying on parasitic resistance and inductance in the supply) or a capacitor-inductor network. An active power factor correction circuit at the input would generally reduce the harmonic currents further and maintain the power factor closer to unity.