
Electric Power
Infrastructure
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Overhead Lines

Overhead lines on Swiss Federal Railways

The overhead lines in China

Overhead lines or **overhead wires** are used to transmit electrical energy to trams, trolleybuses or trains at a distance from the energy supply point. These overhead lines are known variously as

- **Overhead contact system** (**OCS**)—Europe, except UK and Spain
- **Overhead line equipment** (**OLE** or **OHLE**)—UK
- **Overhead equipment** (**OHE**) — UK, India, Pakistan and Malaysia
- **Overhead wiring** (**OHW**)—Australia
- **Catenary**—United States, India, UK, Singapore (North East MRT Line) , Canada and Spain.

Overhead line is designed on the principle of one or more overhead wires or rails (particularly in tunnels) situated over rail tracks, raised to a high electrical potential by connection to feeder stations at regular intervals. The feeder stations are usually fed from a high-voltage electrical grid.

Overview

Electric trains that collect their current from an overhead line system use a device such as a pantograph, bow collector, or trolley pole. The device presses against the underside of the lowest wire of an overhead line system, the **contact wire**. The current collectors are electrically conductive and allow current to flow through to the train or tram and back to the feeder station through the steel wheels on one or both running rails. Non-electric trains (such as diesels) may pass along these tracks without affecting the overhead line, although there may be difficulties with overhead clearance. Alternative electrical power transmission schemes for trains include third rail, Aesthetic Power Supply, batteries, and electromagnetic induction.

Construction

Linemen on a maintenance of way vehicle repairing overhead lines

To achieve good high-speed current collection, it is necessary to keep the contact wire geometry within defined limits. This is usually achieved by supporting the contact wire from above by a second wire known as the **messenger wire** (US & Canada) or **catenary** (UK). This wire approximates the natural path of a wire strung between two points, a catenary curve, thus the use of *catenary* to describe this wire or sometimes the whole system. This wire is attached to the contact wire at regular intervals by vertical wires known as **droppers** or **drop wires**. The messenger wire is supported regularly at structures, by a pulley, link, or clamp. The whole system is then subjected to a mechanical tension.

As the contact wire makes contact with the pantograph, the carbon surface of the insert on top of the pantograph is worn down. Going around a curve, the "straight" wire between supports will cause the contact wire to cross over the whole surface of the pantograph as the train travels around the curve, causing an even wear and avoiding any notches. On straight track, the contact wire is zigzagged slightly to the left and right of centre at each successive support so that the pantograph wears evenly.

The zigzagging of the overhead line is not required for trams using trolley poles or for trolleybuses.

Depot areas tend to have only a single wire and are known as **simple equipment**. When overhead line systems were first conceived, good current collection was possible only at low speeds, using a single wire. To enable higher speeds, two additional types of equipment were developed:

- **Stitched equipment** uses an additional wire at each support structure, terminated on either side of the messenger wire.
- **Compound equipment** uses a second support wire, known as the **auxiliary**, between the messenger wire and the contact wire. Droppers support the auxiliary from the messenger wire, and additional droppers support the contact wire from the auxiliary. The auxiliary wire can be constructed of a more conductive but less wear-resistant metal, increasing the efficiency of power transmission.

Dropper wires traditionally only provide physical support of the contact wire, and do not join the catenary and contact wires electrically. Contemporary systems use current-carrying droppers, which eliminate the need for separate wires.

The present transmission system originated about 100 years ago. A simpler system was proposed in the 1970s by the Pirelli Construction Co consisting of a single wire embedded at each support for 2.5 metres (8 ft 2 in) of its length in a clipped extruded aluminum beam with the wire contact face exposed. With a somewhat higher tension than used before clipping the beam yielded a deflected profile for the wire which could be easily handled at 250 miles per hour (400 km/h) by a pneumatic servo pantograph with only 3 G accelerations. This cut about 40% from the total track overhead equipment cost but required a pantograph development period which was not accepted by British Rail.

For tramways there is often just a simple contact wire and no messenger wire.

In situations where there is limited clearance to accommodate wire suspensions systems such as in tunnels, the overhead wire may be replaced by rigid overhead rail. This was done when the overhead line had to be raised in the Simplon Tunnel to accommodate taller rail vehicles.

Parallel overhead lines

An electrical circuit requires at least two conductors. Trams and railways use the overhead line as one side of the circuit and the steel rails as the other side of the circuit. For a trolleybus there are no rails to send the return current along—the vehicles use rubber tyres and the normal road surface. Trolleybuses use a second parallel overhead line for the return, and two trolley-poles, one contacting each overhead wire. The circuit is completed by using both wires.

Germany

A twisting pylon of a single phase AC 110 kV power line near Bartholomä in Germany. Lines of this type are used in Germany to supply electric railways with single phase AC at 16+⅔ Hz

In Germany there are special overhead power lines for single phase AC traction current with a frequency of 16⅔ hertz. All operate at a voltage of 110 kV (the voltage of the railway overhead lines is 15 kV) and have four conductor cables for two circuits. As a rule at traction current lines, a single-level arrangement of conductor cables is used.

A traction current pylon is a type of electricity pylon with at least one electric circuit for traction current. For traction current lines with four circuits (eight conductor cables) usually two-level arrangements of conductors are used, in which one pylon crossbar carries four conductor cables. For traction current lines used to supply high-speed rail tracks, three-level arrangements of conductors are employed; thereby four conductor cables are mounted on the lowest crossbar, and two on the upper crossbars. The three-level arrangement is also used for traction current lines with six electric circuits (12 conductor cables).

There are other overhead line pylons with crossbars for 110 kV traction voltage. For example the power supplies of rapid transit railways. Additionally there are pylons that transmit both electric power for railway traction current as well as three-phase alternating current for the public power grid.

Tensioning

Line tensioning

Catenary wires are kept at a mechanical tension because the pantograph causes oscillations in the wire and the wave must travel faster than the train to avoid producing standing waves that would cause the wires to break. Tensioning the line makes waves travel faster.

For medium and high speeds, the wires are generally tensioned by means of weights or occasionally by hydraulic tensioners. Either method is known as **auto-tensioning** (**AT**), or **constant tension** and ensures that the tension in the equipment is virtually independent of temperature. Tensions are typically between 9 and 20 kN (2,000 and 4,500 lbf) per

wire. Where weights are used, they slide up and down on a rod or tube attached to the mast, to stop the weights from swaying.

For low speeds and in tunnels where temperatures are constant, **fixed termination** (**FT**) equipment may be used, with the wires terminated directly on structures at each end of the overhead line. Here the tension is generally about 10 kN (2,200 lbf). This type of equipment will sag on hot days and hog on cold days.

Where AT is used, there is a limit to the continuous length of overhead line which may be installed. This is due to the change in the position of the weights with temperature as the overhead line expands and contracts. This movement is proportional to the **tension length**, i.e. the distance between anchors. This leads to the concept of maximum tension length. For most 25 kV OHL equipment in the UK, the maximum tension length is 1970 m.

An additional issue with AT equipment is that, if balance weights are attached to both ends, the whole tension length will be free to move along track. To rectify this issue, a **midpoint anchor** (**MPA**), close to the centre of the tension length, restricts movement of the messenger wire by anchoring it; the contact wire and its suspension hangers can move only within the constraints of the MPA. MPAs are sometimes fixed to low bridges; otherwise, they are anchored to the typical vertical catenary poles or portal catenary supports. Therefore, a tension length can be seen as a fixed centre point, with the two half tension lengths expanding and contracting with temperature.

Most overhead systems include a brake to stop the wires from unravelling completely should a wire break or tension be lost for any other reason. German systems usually use a single large tensioning pulley with a toothed rim, mounted on an arm hinged to the mast. Normally the downward pull of the weights, and the reactive upward pull of the tensioned wires, lifts the pulley so its teeth are well clear of a stop on the mast. The pulley can turn freely while the weights move up or down as the wires contract or expand. If a wire breaks or tension is otherwise lost, the pulley falls back toward the mast, and one of its teeth will jam against the stop. This stops further rotation, limits the damage, and keeps the undamaged part of the wire intact until it can be repaired. Other systems use various other braking mechanisms, usually with multiple smaller pulleys in a block and tackle arrangement.

Breaks

Section Break

A section insulator installed at a section break in Amtrak's 12 kV catenary.

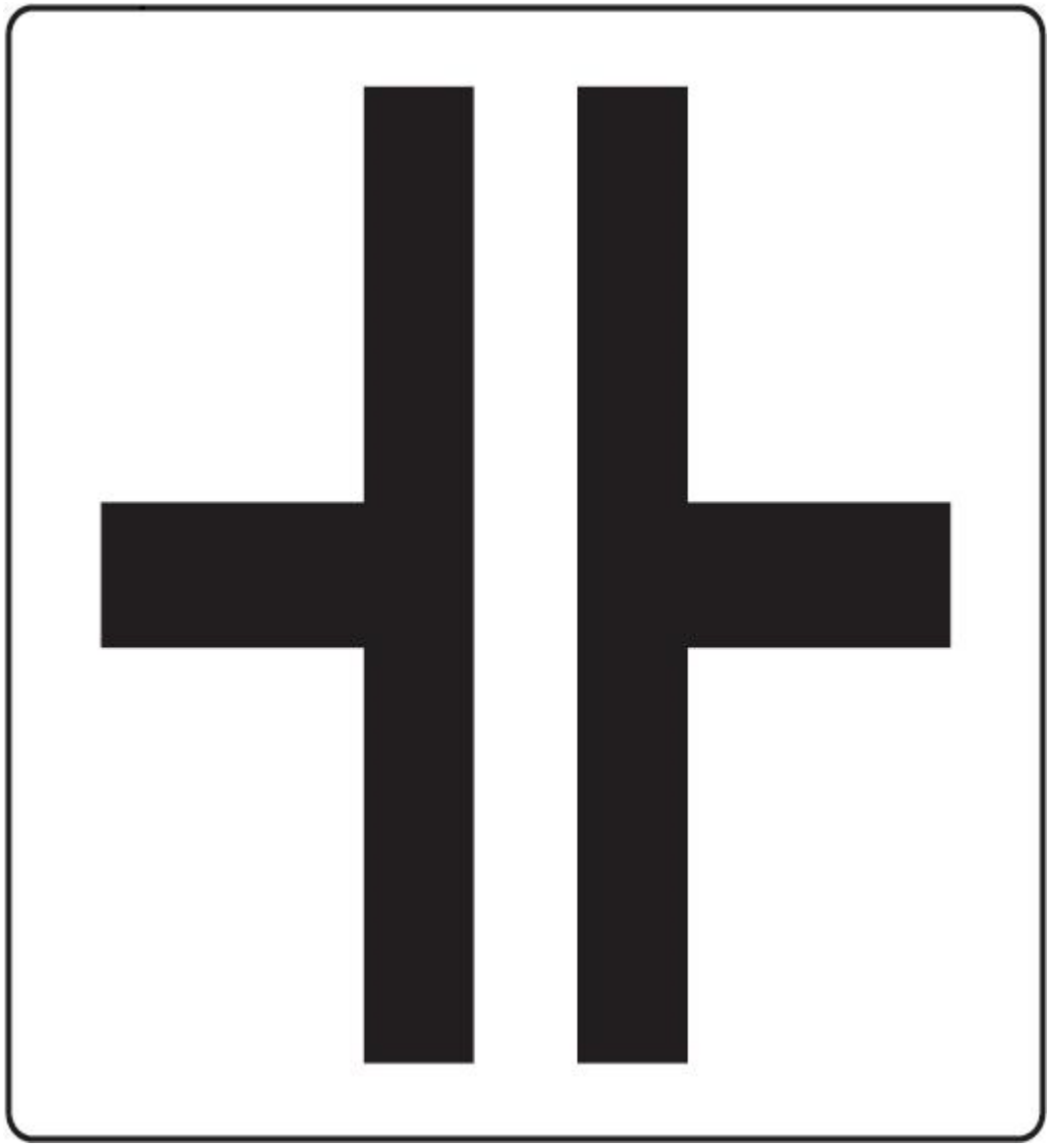
To allow maintenance to sections of the overhead line without having to turn off the entire system, the overhead line system is broken into electrically separated portions known as **sections**. Sections often correspond with tension lengths as described above. The transition from section to section is known as a **section break** and is set up so that the locomotive's pantograph is in continuous contact with the wire.

For bow collectors and pantographs, this is done by having two contact wires run next to each other over a length about four wire supports: a new one dropping down and the old one rising up until the pantograph smoothly transfers from one to the next. The two wires never touch (although the bow collector/pantograph is briefly in contact with both wires). In normal service, the two sections are electrically connected (to different substations if at or near the halfway mark between them) but this can be broken for servicing.

On overhead wires designed for trolley poles this is done by having a neutral section between the wires, requiring an insulator. The driver of the tram or trolleybus must turn off the power when the trolley pole passes through, to prevent arc damage to the insulator.

Pantograph equipped locomotives may never run through a section break when one side is de-energized. Of course the locomotive would then become trapped, but as it passes the section break, the pantograph will briefly short the two catenary lines together. If the opposite line is de-energized, this voltage transient may trip supply breakers. If the line is under maintenance, personnel injury may occur as the catenary is suddenly energized. Even if the catenary is properly grounded, the arc generated across the pantograph will likely cause damage to the pantograph, the catenary insulator, or both.

Phase Break



Neutral Section Indication Board used on railways in the UK

Sometimes on a larger electrified railway, tramway or trolleybus system, it is necessary to power different areas of track from different power grids, the synchronisation of the phases of which cannot be guaranteed. (Sometimes the sections are powered with

different voltages or frequencies.) There may be mechanisms for having the grids synchronised on a normal basis but events may cause desynchronisation. This is no problem for DC systems but, for AC systems, it is highly undesirable to connect two unsynchronised grids. A normal section break is insufficient to guard against this, since the pantograph briefly connects both sections.

Instead, a **phase break** or neutral section is used. This consists of two section breaks back-to-back so that there is a short section of overhead line that belongs to neither grid. If the two grids are synchronized, this stretch of line is energized (by either supply) and trains run through it normally. If the two supplies are not synchronized, the short isolating section is disconnected from the supplies, leaving it electrically dead, ensuring that the two grids cannot be connected to each other.

The sudden loss of power over the phase break would jar the train if the locomotive was at full throttle, so special signals are set up to warn the crew. When synchronization is lost and the phase break is deenergized, the train's operator must put the controller (throttle) into neutral and coast through an isolated phase break section.

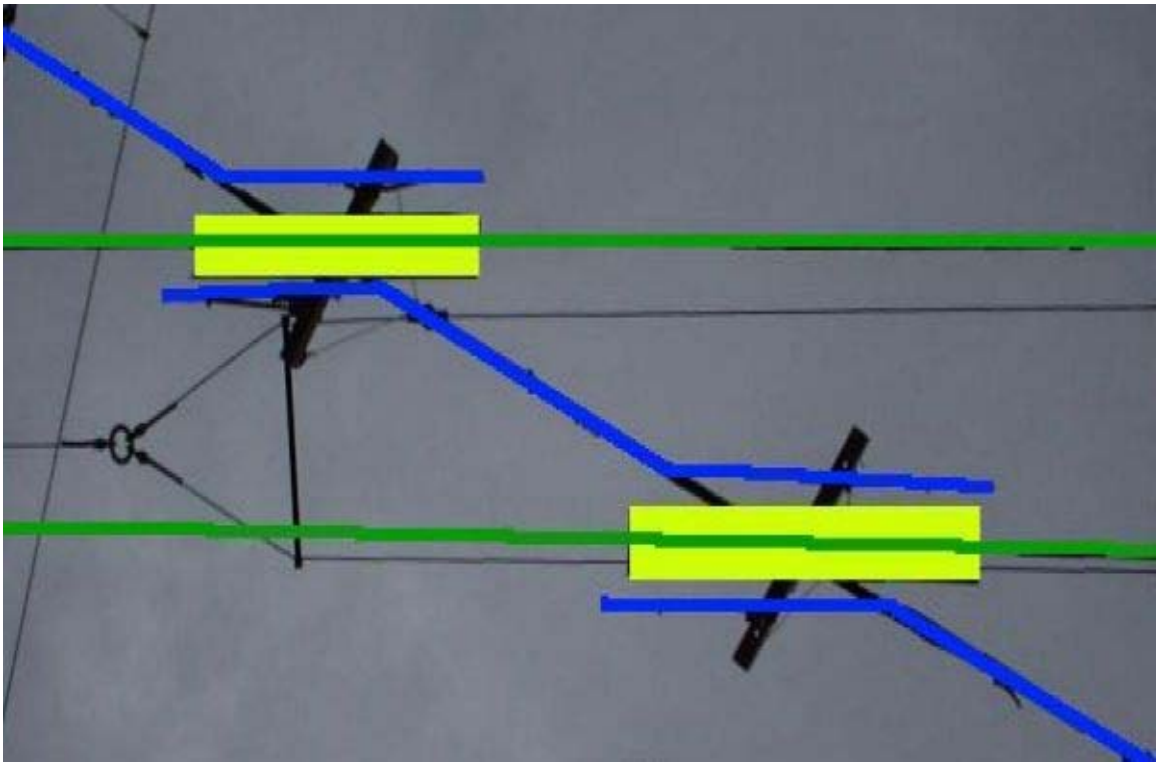
On the Pennsylvania Railroad, phase breaks were indicated by a position light signal face with all eight radial positions filled by lenses and no center light. When the phase break was active (that is when the catenary sections were out of phase), all lights were lit. The position light signal aspect was originally devised by the Pennsylvania Railroad but was continued by its successor Amtrak and has been adopted by Metro North. Metal signs were also hung from the catenary supports with the letters *PB* created by a pattern of drilled holes.

Transnet Freight Rail in South Africa has permanent magnets between the rails at both sides of the neutral section where two phases are separated. These are detected by equipment on the locomotive, which disconnect and reconnect power from the pantographs.

Dead Section

A special category of phase break was also developed in American practice, primarily by the Pennsylvania Railroad. Since its traction power network was centrally supplied, and only segmented by abnormal conditions, phase breaks were normally not active. Phase breaks which were always activated came to be known as *Dead Sections*. They often were to separate boundaries between power systems (for example, the Hell's Gate Bridge boundary between Amtrak and Metro North's electrification systems), which would never be in-phase. Since a dead section is, by definition, always dead, no special signal aspect was developed to warn engineers of its presence. A simple metal sign with *DS* in drilled-hole letters was hung from the catenary supports.

Crossings



An annotated version of the above.
tram conductor
trolley bus wires
insulated trough

Trams draw their power from a single overhead wire at about 500 to 750 V, while trolleybuses draw their power from two overhead wires at a similar voltage. Because of that, at least one of the trolleybus wires must be insulated from tram wires. This is usually solved by the trolleybus wires running continuously through the crossing, with the tram conductors a few centimetres lower. Close to the junction on each side, the wire merges into a solid bar running parallel to the trolleybus wires for about half a metre. Another bar similarly angled at its ends is hung between the trolleybus wires. This is electrically connected above to the tram wire. The tram's pantograph bridges the gap between the different conductors, providing it with a continuous pickup.

Where the tram wire crosses, the trolleybus wires are protected by an inverted trough of insulating material extending 20 or 30 mm below.

Until 1946, there was a level crossing in Stockholm, Sweden between the railway south of Stockholm Central Station and a tramway line. The tramway operated on 600-700 V DC and the railway on 15 kV AC. Some crossings between tramway/light rail and railways are still extant in Germany. In Zürich, Switzerland the VBZ trolleybus line 32 has a level crossing with the 1,200 V DC railway to mount Uetliberg; at many places in

the town, trolleybus lines cross the tramway. In the Swiss village of Suhr, the WSB tramway operating at 1,200 V DC crosses the SBB line at 15 kV AC. In some cities, trolleybuses and trams have shared the same positive (feed) wire. In such cases, a normal trolleybus frog can be used.

Another system that has been used is to coincide section breaks with the crossing point so that the crossing is electrically dead.

Australia

Many cities had trams and trolleybuses both using trolley pole current collection. They used insulated crossovers which required tram drivers to put the controller into neutral and coast through. Trolleybus drivers had to either lift off the accelerator or switch to auxiliary power.

In Melbourne, Victoria, tram drivers put the controller into neutral and coast through section insulators, indicated by insulator markings between the rails.

Melbourne has four level crossings between electrified suburban railways and tram lines. They have complex switching arrangements to separate the 1,500 V DC overhead of the railway and the 650 V DC of the trams, called an overhead square. Proposals have been put forward which would see these crossings grade separated or the tram routes diverted.

Queensland uses 25 kV AC overhead traction with booster transformers in the Brisbane suburban area and auto transformers elsewhere.

Western Australia (Perth city) uses 25 kV AC overhead traction with booster transformers.

Greece

In Athens, there are two crossings between tram and trolleybus wires, at Vas. Amalias Avenue and Vas. Olgas Avenue, and at Ardittou Street and Athanasiou Diakou Street. They use the above-mentioned solution.

From the opening of the tram system in the summer of 2004, trams and trolleybuses in the direction of Pagrati shared the same exclusive lane, about 400m long, on the far right side of Vas. Olgas Avenue, with tram and trolleybus wires side-by-side above a narrow lane of road. The trolleybus wires were on the far right of the lane, away from the trams' (very wide) pantographs. Trolleybus drivers were required to drive very slowly because the trolley poles were extended to their limits. A change of route for trolleybuses was implemented in mid-2005, ending this arrangement.

Italy

In Milan, most of the city's tram lines cross its circular trolleybus line once or twice, so crossings between overhead tram and trolleybus wires are quite commonplace. Trolleybus and tram wires run parallel in some streets, like viale Stelvio and viale Tibaldi.

Multiple overhead lines

Two overhead conductor rails for the same track. Left, 1,200 V DC for the Uetliberg railway (the pantograph is mounted asymmetrically to collect current from this rail); right, 15 kV AC for the Sihltal railway

There are and were some railways that used two or three overhead lines, usually to carry three-phase current to the trains. Nowadays, three-phase AC current is used only on the Gornergrat Railway and Jungfraujoch Railway in Switzerland, the Petit train de la Rhune in France, and the Corcovado Rack Railway in Brazil; until 1976, it was widely used in Italy. On these railways, the two conductors of the overhead lines are used for two different phases of the three-phase AC, while the rail was used for the third phase. The neutral was not used.

Some three-phase AC railways used three overhead wires. These were an experimental railway line of Siemens in Berlin-Lichtenberg in 1898 (length: 1.8 kilometres), the military railway between Marienfelde and Zossen between 1901 and 1904 (length: 23.4

kilometres) and an 800-metre-long section of a coal railway near Cologne, between 1940 and 1949.

On DC systems, bipolar overhead lines were sometimes used to avoid galvanic corrosion of metallic parts near the railway, such as on the Chemin de fer de la Mure.

All systems of multiple overhead lines have the disadvantage of high risk of short circuits at switches and therefore tend to be impractical in use, especially when high voltages are used or when trains run through the points at high speed.

The Sihltal Zürich Uetliberg Bahn is the result of a merge of two railways with different electification. To be able to use different electic systems on shared tracks one of the railways (Sihltalbahn) has overhead wire right above the train, and the other line (Uetlibergbahn) has overhead wire a bit off to one side.

Overhead catenary

Overhead feeding rail on the RER Line C trenches and tunnels in central Paris

Compound catenary equipment of JR West

Overhead lines now mean that historic images are no longer recreatable on many lines, such as in this recreation of a 1960s scene of a steam express in Berwick-upon-Tweed, United Kingdom.

A catenary is a system of overhead wires used to supply electricity to a locomotive, streetcar, or light rail vehicle which is equipped with a pantograph.

Unlike simple overhead wires, in which the uninsulated wire or cable is attached by clamps to closely spaced crosswires, themselves supported by line poles, catenary systems use at least two wires. One wire, called the catenary or messenger wire, is hung at a specific tension between line structures. A second wire is held in tension by the messenger wire, and is attached to it at frequent intervals by clamps and connecting wires. The second wire is straight and level, parallel to the rail tracks, suspended over it as the roadway of a suspension bridge is over water.

Simple wire installations are common in light rail applications, especially on city streets, while more expensive catenery systems are especially suited to high-speed operations.

The Northeast Corridor in the United States features electrified catenary over a 600-mile or 1000 km distance between Boston, Massachusetts and Washington, D.C., providing power for Amtrak's high-speed Acela Express and other trains. Several commuter rail agencies, including MARC, SEPTA, NJ Transit, Metro-North utilize the catenary to provide local service along the Northeast Corridor.

In Cleveland, Ohio the interurban/light rail lines use overhead wires, and the heavy rail line also uses overhead wires, instead of a third rail. This was due to a city ordinance intended to limit air pollution from the large number of steam trains passing through the Cleveland between the east coast and Chicago. Trains switched from steam to **overhead catenary** electric locomotives at the Collinwood Rail Yards about 10 miles (16 km) east of Downtown Cleveland and similarly at Linndale on the west side. When Cleveland constructed its rapid transit (heavy rail) line between the airport, Downtown Cleveland and beyond it employed similar overhead catenary technologies that the railroads used, and were able to utilize railroad electrification equipment left over after railroads switched from steam to diesel locomotives. Consequently, light and heavy rail public transit systems share trackage for about 3 miles (4.8 km) along the Cleveland Hopkins International Airport Red (heavy rail) line, Blue and Green interurban/light rail lines between Cleveland Union Terminal and just past East 55th Street station, where the heavy- and light-rail line tracks separate.

The Blue Line, running through suburbs northeast of Boston, Massachusetts, uses overhead power lines.

Height

The height of overhead wiring can create hazards at level crossings, where it may be struck by road vehicles. The wiring in most countries is too low to allow double stack container trains. The Channel Tunnel has an extended height overhead line to accommodate double-height car and truck transporters. India is proposing a network of freight only lines, which would almost certainly be electrified with extra height wiring and pantographs that can reach it.

Technical advances lower running costs

The introduction of supercapacitors has promised to drop electrical running costs for trains powered by overhead lines or third rails. Kinetic braking energy is reclaimed by storing electrical energy in supercapacitors onboard the vehicle. This stored energy is used when accelerating the train, when high current is needed. The supplementing supercapacitors reduce current drawn through the electrical supply during acceleration and puts less strain on the distribution system.

Later developments locate banks of supercapacitors at track side. All trains on the system can then use the stored energy in the supercapacitors to supplement the energy drawn through a third rail or overhead wires. Trackside location reduces vehicle weight and creates more onboard space. However, such locations would require additional equipment to charge the supercapacitors from the overhead line voltage and to generate supplementary power at the voltage and frequency of the overhead line from the stored energy.

Claimed energy reduction is around 30%. Electric railway systems can be more competitive and a real economical alternative to automobiles.

The technology can be used equally well for diesel electric locomotives, where 25% to 40% reduction in energy consumption is claimed, however only onboard location of supercapacitor banks is feasible. (This technology equally applies to road vehicles that use electric motors for propulsion, such as hybrid cars and buses.) Any electrical equipment that requires regular braking can reduce operating costs using supercapacitors. Reduced operating costs of elevators on underground railways would be a great benefit to operators and adding to their economic competitiveness.

An additional benefit is that emissions from generating plants and diesel-electric locomotives will be decreased.

Since 2003, the Mannheim Stadtbahn in Germany has operated a light-rail vehicle using electric double-layer supercapacitors to store braking energy.

A number of companies are developing electric double-layer supercapacitor technology. Siemens AG is developing mobile energy storage based on double-layer supercapacitors called Sibac Energy Storage Sitras SES, are developing stationary trackside version. The company Cegelec is also developing an electric double-layer capacitor-based energy storage system.

History

In 1881 the first tram with overhead lines was presented by Werner von Siemens on the International Electric Exposition in Paris 1881 but the installation was removed after that event. In October 1883, the first permanent tram service with overhead lines was started on Mödling and Hinterbrühl Tram in Austria. These trams had bipolar overhead lines,

consisting of two U-pipes, in which the pantographs hung and ran like shuttles. In April to June 1882, Siemens had tested a similar system on his Electromote, an early percursor of the trolleybuses.

Much simpler and more functional was an overhead wire in combination with a pantograph borne by the vehicle and pressed at the line from below. This system, for rail traffic with a unipolar line, was invented by Frank J. Sprague in 1888. Since 1889, it was used at the Richmond Union Passenger Railway in Richmond, Virginia. That was the onset of worldwide use of electric traction.

Chapter 2

Stobie Pole and Stockbridge Damper

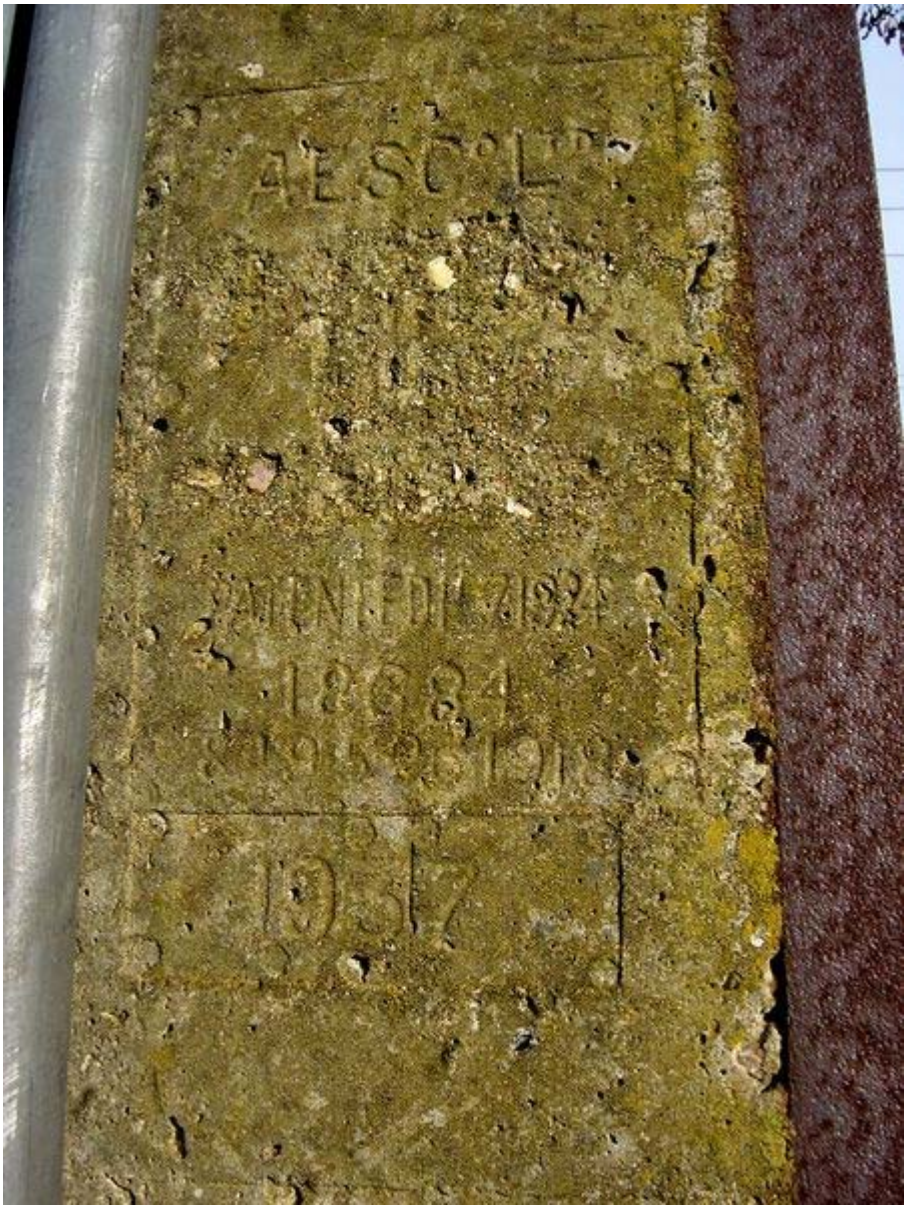
Stobie pole

Stobie pole in a southern suburb of Adelaide.

A **Stobie pole** is a power line pole made of two steel joists held apart by a slab of concrete in the middle. It was invented by Adelaide Electricity Supply Company design engineer James Cyril Stobie (1895–1953). Stobie used materials easily at hand due to the shortage of timber caused by the arid and treeless nature of much of South Australia. In 1924 the pole was patented, Stobie describing his invention as

"an improved pole adopted to be used for very many purposes, but particularly for carrying electric cables, telegraph wires... [it] consists of two flanged beams of iron or steel, preferably rolled steel joist of '**H**' or of channel sections, placed one beside the other with their flanges inward and preferably at a very slight angle one with the other and held together by means of tie bolts, the space between them being filled with cement concrete."

Stobie and John Brookman were so confident of the new pole that they formed 'The Stobie Pole Syndicate' for the purpose of patenting the design and then selling the patent or manufacturing rights. The Hume Pipe Company became their first agents and, while there were numerous international enquiries, South Australia has remained, virtually, the only place where they are used. Stobie poles are reasonably common in Broken Hill, New South Wales.



1937 imprint

The first poles were erected in South Terrace, Adelaide in 1924, and were then used extensively in building the electricity transmission and distribution infrastructure throughout the state. The Stobie pole was central to the speedy expansion of Adelaide Electricity Supply Company's supply. It was cheap and simple to produce, had a uniform appearance, saved an enormous amount of timber from being cut down, had a long life expectancy and, at the time, was seen as more environmentally sensitive.

The poles carry voltages from 415 to 275,000 volts and come in various sizes from 9 to 35 metres in length. The expected service life of a Stobie pole is predicted to be in excess of 80 years. It is now commonly regarded as a South Australian icon. ETSA Utilities manufactures Stobie poles at a plant in Angle Park, South Australia.

Its modern construction is a composite of two steel beams connected intermittently by bolts to manage compressive buckling, with the gap between the beams filled with concrete. The bolts transfer the shear, with an equal number of bolts above and below ground. The poles are tapered from ground level to the top and the toe. This construction uses the tensile properties of the steel, giving the poles excellent properties in bending. Small holes through the concrete enable easy attachment of modular cross-arms, insulators and other hardware. The poles are fireproof, rotproof, and termiteproof. They are also "car proof", causing enormous amounts of damage to vehicles when collided with.

Attempts have been made to beautify their appearance through Stobie pole gardens and Stobie pole art projects. Renowned artist Clifton Pugh painted Adam and Eve in the Garden of Eden on a Stobie pole in 1984, but was subsequently asked to "cover up" the genitals on his painting.

Stockbridge damper

Stockbridge dampers on an overhead power line

A **Stockbridge damper** is a tuned mass damper used to suppress wind-induced vibrations on taut cables, such as overhead power lines. The dumbbell-shaped device consists of two masses at the ends of a short length of cable or flexible rod, which is clamped at its middle to the main cable. The damper is designed to dissipate the energy of oscillations in the main cable to an acceptable level. Its distinctive shape gives it the nickname "**dog-bone damper**".

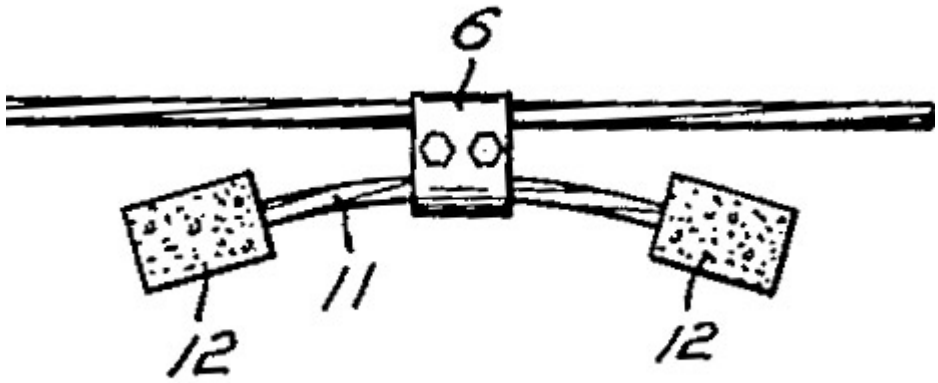
Wind-induced oscillation

Wind can generate three major modes of oscillation in suspended cables:

- gallop has an amplitude measured in metres and a frequency range of 0.08 to 3 Hz;
- aeolian vibration (sometimes termed flutter) has an amplitude of millimetres to centimetres and a frequency of 3 to 150 Hz;
- wake-induced vibration has an amplitude of centimetres and a frequency of 0.15 to 10 Hz

The Stockbridge damper targets oscillations due to aeolian vibration; it is less effective outside this amplitude and frequency range. Aeolian vibration occurs in the vertical plane and is caused by alternating shedding of vortices on the leeward side of the cable. A steady but moderate wind can induce a standing wave pattern on the line consisting of several wavelengths per span. Aeolian vibration causes damaging stress fatigue to the cable and represents the principal cause of failure of conductor strands. The ends of a power line span, where it is clamped to the transmission towers, are at most risk. The effect becomes more pronounced with increased cable tension, as its natural self-damping is reduced.

Description



Stockbridge's original concrete block design

The Stockbridge damper was invented in the 1920s by George H. Stockbridge, who was at the time working as an engineer for Southern California Edison. Stockbridge obtained US patent 1675391 on 3 July 1928 for a "vibration damper". His patent described three means of damping vibrations on lines: a sack of metal punchings tied to the line; a short length of cable clamped parallel to the main cable; and a short (30 in, 75 cm) cable with a concrete mass fixed at each end. It would be this last device that developed into the widely used Stockbridge damper.

Vibrations in the main cable were passed down through the clamp and into the shorter damper, or "messenger", cable. This would flex and cause the symmetrically-placed concrete blocks at its ends to oscillate. Careful choice of the mass of the blocks, and the stiffness and length of the damper cable would match the mechanical impedance of the damper to that of the line, and greatly attenuate oscillation of the main cable. Since Stockbridge dampers were economical, effective and very easy to fit, they soon became installed on overhead lines as a matter of routine design. Live-line working using hot stick tools meant it was even possible to retrofit dampers to lines while they were still energised.

Modern designs

A modern design with metal weights

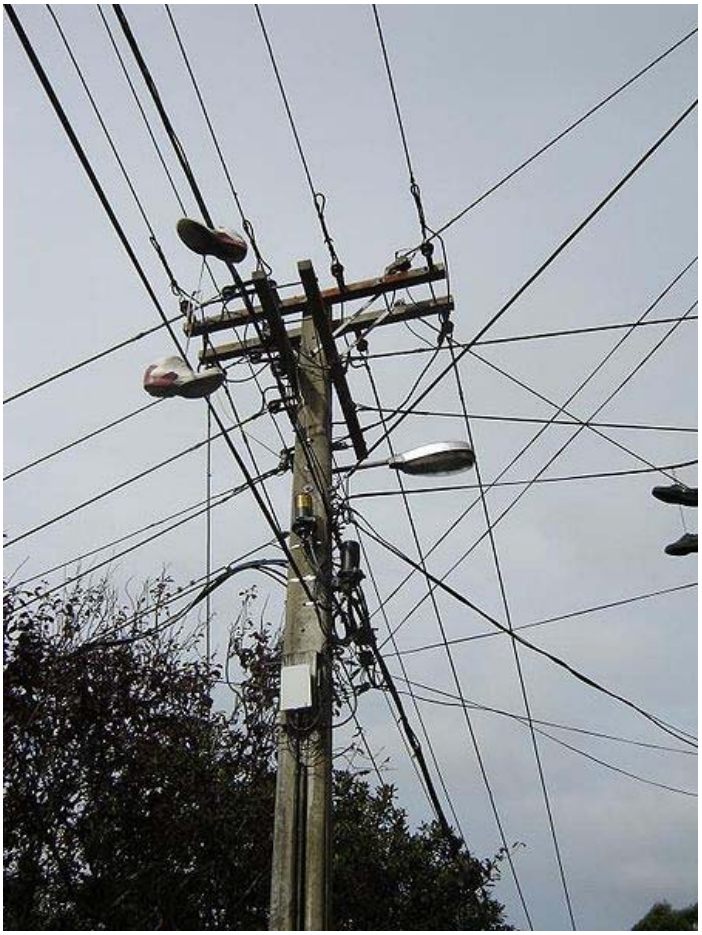
Modern designs use metal bell-shaped weights rather than Stockbridge's concrete blocks. The bell is hollow and the damper cable is fixed internally to the distal end, which permits relative motion between the cable and damping weights. To provide for greater freedom of motion, the weights may be partially slotted in the vertical plane, allowing the cable to travel outside the confines of the bell. In some installations, the weights are unequal, allowing damping over a greater frequency range. More complex designs use weights with asymmetric mass distribution, which enables the damper to oscillate in several different frequency modes.

The most vulnerable section of the cable is where it is clamped to the end of an insulator string and so dampers are typically installed at the nearest anti-nodes (points of maximum oscillation) either side of the clamp. There are thus normally two dampers per span, though more can be installed if necessary on longer spans.

Overhead transmission lines form a catenary for which vibration is predominately in the vertical plane. When more than one plane of vibration is anticipated, Stockbridge dampers may be mounted at right angles to each other. This is common when the cable runs in a vertical or off-horizontal plane, for example in cable-stayed bridges or radio mast guy-wires.

Chapter 3

Utility Pole



Utility pole supporting wires for electrical power distribution, coaxial cable for Cable TV, and telephone cable. Two pairs of shoes can be seen hanging from the wires (center-left, far right).

A **utility pole** is a pole used to support overhead power lines and various other public utilities, such as cable, fibre optic cable, and related equipment such as transformers and street lights. It can be referred to as a **telephone pole**, **power pole**, **hydro pole**, **telegraph pole**, or **telegraph post**, depending on its application. A stobie pole is a multi-purpose pole made of two steel joists held apart by a slab of concrete in the middle, generally found in South Australia. Electrical cable is routed overhead as an inexpensive way to keep it insulated from the ground and out of the way of people and vehicles. Utility poles can be made of wood, metal, concrete, or composites like fibreglass. They are used for lower voltage power transmission; higher voltage transmission lines are carried on steel transmission towers or pylons.

Utility poles were first used in the mid-19th century with telegraph systems, starting with Samuel Morse who attempted to bury a line between Baltimore and Washington, D.C., but moved it aboveground when this system proved faulty.

Use

Utility poles are commonly used to carry two types of electric power lines: distribution lines (or "feeders") and **subtransmission** lines. Distribution lines carry power from local substations to customers. They generally carry voltages from 4.6 to 33 kilovolts (kV) for distances up to thirty miles, and include transformers to step the voltage down from the primary voltage of the lines to the lower secondary voltage used by the customer. A service drop carries this lower voltage to the customer's premises. Subtransmission lines carry higher voltage power from regional substations to local substations. They usually carry 46 kV, 69 kV, or 115 kV for distances up to 60 miles. 230kV lines are often supported on H-shaped towers made with two or three poles. Transmission lines carrying voltages of above 230kV are usually not supported by poles, but by metal pylons (known as transmission towers in the United States).

For economic or practical reasons, such as to save space in urban areas, a distribution line is often carried on the same poles as a subtransmission line but mounted under the higher voltage lines; a practice called "underbuild". Telecommunication cables are usually carried on the same poles that support power lines; poles shared in this fashion are known as joint use poles. However, they may also have their own dedicated poles.

Description

The standard utility pole in the United States is about 40 ft (12 m) long and is buried about 6 ft (2 m) in the ground. However, poles can reach heights of 120 ft (37 m) or more to satisfy clearance requirements. They are typically spaced about 125 ft (38 m) apart in urban areas, or about 300 ft (91 m) in rural areas, but distances vary widely based on terrain. Joint use poles are usually owned by one utility, which leases space on it for other cables. In the United States, the National Electrical Safety Code, published by the Institute of Electrical and Electronics Engineers (IEEE), sets the standards for construction and maintenance of utility poles and their equipment.

Pole materials

Steel utility pole in Darwin, Australia.

Most utility poles are made of wood, pressure-treated with some type of preservative for protection against rot, fungi and insects. Southern yellow pine is the most widely used species in the United States; however, many species of long straight trees are used to make utility poles, including Douglas-fir, Jack pine, lodgepole pine, western red cedar and Pacific silver fir. Traditionally the preservative used was creosote, but due to environmental concerns, alternatives such as pentachlorophenol, copper naphthenate and borates are becoming widespread in the U.S. For over 100 years, the American Wood Protection Association (AWPA) has developed the standards for preserving wood utility poles. Despite the preservatives, wood poles decay and have a life of approximately 25 to

50 years depending on climate and soil conditions, therefore requiring regular inspection and remedial preservative treatments.

Other common utility pole materials are steel and concrete, with composites (such as fibreglass) also becoming more prevalent. One particular patented utility pole variant used in Australia is the Stobie pole, made up of two vertical steel posts with a slab of concrete between them.

Power distribution wires and equipment

On poles carrying both, the electric power distribution lines and associated equipment are mounted at the top of the pole above the communication cables, for safety. The vertical space on the pole reserved for this equipment is called the *supply space*. The wires themselves are usually uninsulated, and supported by insulators, commonly mounted on a horizontal crossarm. Power is transmitted using the three-phase system, with three wires, or phases, labeled "A", "B", and "C". Subtransmission lines comprise only these 3 wires, plus sometimes an overhead ground wire (OGW), also called a "static line" or a "neutral", suspended above them. The OGW acts like a lightning rod, providing a low resistance path to ground thus protecting the phase conductors from atmospheric static discharges.

A joint use utility pole in China.

Distribution lines use two systems, either grounded-wye ("Y" on electrical schematics) or delta (Greek letter Delta, "Δ", on electrical schematics). A delta system requires only a conductor for each of the three phases. A grounded-wye system requires a fourth conductor, the neutral, whose source is the center of the "Y" and is grounded. However, "spur lines" branching off the main line to provide power to side streets often carry only one or two phase wires, plus the neutral. A wide range of standard distribution voltages are used, from 2,400 V to 34,500 V. On poles near a service drop, there is a cylindrical pole-mounted step-down transformer to provide the required mains voltage, usually 240/120 V split-phase for residential and light commercial service in the US. The transformer's primary is connected to the distribution line through protective devices called fused cutouts. In the event of an overload, the fuse melts and the device pivots

open to provide a visual indication of the problem. They can also be opened manually by linemen using a long insulated rod called a hot stick to disconnect the transformer from the line.

Single-phase distribution transformer with center-tapped secondary for "split-phase" service. Note use of a grounded conductor as one leg of the primary feeder.

The pole may be grounded with a heavy bare copper wire running down the pole, attached to the metal pin supporting each insulator, and at the bottom connected to a metal rod driven into the ground. Some countries ground every pole while others only ground every fifth pole and any pole with a transformer on it. This provides a path for leakage currents across the surface of the insulators to get to ground, preventing the current from flowing through the wooden pole which could cause a fire or shock hazard.

It provides similar protection in case of flashovers and lightning strikes. A surge arrester (also called a lightning arrester) may also be installed between the line (ahead of the cutout) and the ground wire for lightning protection. The purpose of the device is to conduct extremely high voltages present on the line directly to ground.

If non-insulated conductors touch due to wind or fallen trees, the resultant sparks can start bushfires. To reduce this problem, aerial bundled conductors are being introduced.

Communication cables

The communications cables are attached below the electric power lines, in a space about the pole designated the *communications space*. The communications space is separated from the lowest electrical conductor by the *communication worker safety zone*, which provides room for workers to maneuver safely while servicing the communication cables, avoiding contact with the power lines. The most common communication cables found on utility poles are copper or fibre optic cable (FOC) for telephone lines and coaxial cables for cable television (CATV). Coaxial or optical fibre cables linking computer networks are also increasingly found on poles in urban areas. The cable linking the telephone exchange to local customers is a thick cable lashed to a thin supporting cable, containing hundreds of twisted pair subscriber lines. Each twisted pair line provides a single telephone circuit or local loop to a customer. There may also be fibre optic cables interconnecting telephone exchanges. Like electrical distribution lines, communication cables connect to service drops when used to provide local service.

Other equipment

Utility poles may also carry other equipment such as street lights, supports for traffic lights and overhead electric trolley wires, and cellular network antennas. They can also carry fixtures and decorations specific for certain holidays or events specific to the city they are located in.

Streetlights and holiday fixtures are powered directly from secondary distribution.

Access

In some countries, such as the United Kingdom, utility poles have sets of brackets arranged in a standard pattern up the pole to act as hand and foot holds so that maintenance and repair workers, known as linemen, can climb the pole to work on the lines. In the United States, such steps have been determined a public hazard and are no longer allowed on new poles. Linemen may use climbing spikes called gaffs to ascend wood poles without steps on them. In the UK, boots fitted with steel loops that go around the pole (known as “Scandinavian Climbers”) are also used for climbing poles. In the USA, linemen use bucket trucks for the vast majority of poles that are accessible by vehicle.

Dead-end poles

Example of dead-end riser poles

The poles at the end of a straight section of utility line, where the line ends or angles off in another direction, are called *dead-end* poles in the United States. Elsewhere they may be referred to as anchor or termination poles. These must carry the lateral tension of the long straight sections of wire. They are usually made with heavier construction. The power lines are attached to the pole by horizontal strain insulators, either placed on crossarms (which are either doubled, tripled, or replaced with a steel crossarm, to provide more resistance to the tension forces) or attached directly to the pole itself.

Dead-end and other poles that support lateral loads have guy-wires to support them. The guys always have strain insulators inserted in their length to prevent any high voltages caused by electrical faults from reaching the lower portion of the cable that is accessible by the public. In populated areas, guy wires are often encased in a yellow plastic or wood tube reflector attached to their lower end, so that they can be seen more easily, reducing the chance of people and animals walking into them or vehicles crashing into them. Another means of providing support for lateral loads is a 'push brace' pole, a second shorter pole that is attached to the side of the first and runs at an angle to the ground. If there is no space for a lateral support, a stronger pole, e.g. a construction of concrete or iron is used.

History

In 1844, the United States Congress granted Samuel Morse $30,000 to build a 40-mile telegraph line between Baltimore, Maryland and Washington, D.C.. Morse began by having a lead-sheathed cable made. After laying seven miles underground, he tested it. He found so many faults with this system that he dug up his cable, stripped off its sheath, bought poles and strung his wires overhead. On February 7, 1844, Morse inserted the following advertisement in the Washington newspaper: "Sealed proposals will be received by the undersigned for furnishing 700 straight and sound chestnut posts with the bark on and of the following dimensions to wit: 'Each post must not be less than eight inches in diameter at the butt and tapering to five or six inches at the top. Six hundred and eighty of said posts to be 24 feet in length, and 20 of them 30 feet in length.' One of the early Bell System lines was the Washington DC-Norfolk line which was for the most part, square sawn tapered poles of yellow pine probably treated to refusal with creosote. Some of these were still in service after 80 years.

However, in Eastern Europe, Russia, and third world countries, there are still many utility poles carrying bare wires mounted on insulators not only along railway lines, but also along roads and sometimes even in urban areas. Errant traffic being uncommon on railways, their poles are usually less tall. In the United States electricity is predominately carried on unshielded aluminum conductors wound around a solid steel core and affixed to rated insulators made from glass, ceramic, or poly. Telephone, CATV and Fiber Optic cables are generally attached directly to the pole without insulators.

In the United Kingdom, much of the rural electricity distribution system is carried on wood poles. These normally carry electricity at 11 or 33 kV (three phases) from 132 kV substations supplied from pylons to distribution substations or pole-mounted transformers. The conductors on these are bare metal connected to the posts by insulators. Wood poles can also be used for low voltage distribution to customers.

Poles in Ottawa, Canada.

Today, utility poles may hold much more than the uninsulated copper wire that they originally supported. Thicker cables holding many twisted pair, coaxial cable, or even fibre-optic, may be carried. Simple analogue repeaters or other outside plant equipment have long been mounted against poles, and often new digital equipment for multiplexing/demultiplexing or digital repeaters may now be seen. In many places, as seen in the illustration, providers of electricity, television, telephone, street light, traffic signal and other services share poles, either in joint ownership or by renting space to each other. In the United States, ANSI standard 05.1.2008 governs wood pole sizes and strength loading. Utilities that fall under the Rural Electrification Act must also follow the guidelines set forth in RUS Bulletin 1724E-150 (from the US Department of Agriculture) for pole strength and loading.

Steel utility poles are becoming more prevalent in the United States thanks to improvements in engineering and corrosion prevention coupled with lowered production costs. However, premature failure due to corrosion is a concern when compared to wood. The National Association of Corrosion Engineers or NACE is developing inspection, maintenance, and prevention procedures similar to those used on wood utility poles to identify and prevent decay.

Markings

Pole brandings

Markings on a BT post.

British Telecom posts are usually marked with the following information:

- 'BT' - to mark it as a British Telecom UK Post
- a horizontal line marking 3 metres from the bottom of the post
- the pole length and size (e.g. 9L implies a 9 metres long, light post)
- the year of treatment and therefore generally the year of installation (e.g. the pole was treated in 2003 in the picture)
- the batch and type of wood used

Brandings on a pole in Salisbury, Maryland, United States.

The date on the pole is applied by the manufacturer and refers to the date the pole was "preserved" (treated to withstand the elements).

In the United States, utility poles are marked with information concerning the manufacturer, pole height, ANSI strength class, wood species, original preservative, and year manufactured (vintage) in accordance with ANSI standard O5.1.2008; this is called branding, as it is usually burned into the surface. Although the position of the brand is determined by ANSI specification, it is essentially just below "eye level" after installation. A general rule of thumb for understanding a pole's brand is the manufacturer's name or logo at the top with a 2-digit date beneath (sometimes preceded by a month).

Below the date is a 2-character wood species abbreviation and 1 to 3 character preservative. Some wood species may be: "SP" for southern pine, "WC" for western cedar, and "DF" for Douglas fir; common preservative abbreviations are "C" for creosote, "P" for pentachlorophenol, and "SK" for chromated copper arsenate (originally referred to Salts type K). The next line of the brand is usually the pole's ANSI Class, used to determine maximum load; this number ranges from 10 to H6 with a smaller number meaning higher strength. The pole's height (from butt to top) in 5 foot increments is usually to the right of the class separated by a hyphen, although it is not uncommon for

older brands to have the height on a separate line. The pole brand is sometimes an aluminum tag nailed in place.

Before the practice of branding, many utilities would set a 2- to 4-digit date nail into the pole upon installation. The use of date nails went out of favor during WWII due to war shortages, but is still used by a few utilities. These nails are considered valuable to collectors, with older dates being more valuable, and unique markings such as the utilities' name also increasing the value. However, regardless of the value to collectors, all attachments on a utility pole are the property of the utility company, and unauthorized removal is a felony.

Coordinates on pole labels

The tags on a subtransmission pole located in Crisfield, Maryland, United States. The faded tag says "733".

A practice in some areas is to place poles on coordinates upon a grid. The pole at right is located in a rural area of the state of Maryland in the United States. The lower two tags

are the "X" and "Y" coordinates along said grid. Just as in a coordinate plane used in geometry, X increases as one travels east and Y increases as one travels north. The upper two tags are specific to the subtransmission section of the pole; the first refers to the route number, the second to the specific pole along the route.

However, not all power lines follow the road. In the British region of East Anglia, EDF Energy Networks often add the Ordnance Survey Grid Reference coordinates of the pole or substation to the name sign.

In some areas, utility pole name plates may provide valuable coordinate information; a poor man's GPS.

Pole route

An image of a traditional telegraph pole with spars, insulators and open wires on a now decommissioned Railway Pole Route, Eccles Road, Norfolk, United Kingdom.

A **pole route** (or **pole line** in the USA) is a telephone link or electrical power line between two or more locations by way of multiple uninsulated wires suspended between wooden utility poles. This method of link is common especially in rural areas where burying the cables would be expensive. Another situation in which pole routes were extensively used were on the railways to link signal boxes. Traditionally, prior to around

1965, pole routes were built with open wires along non-electrical operated railways; this necessitated insulation when the wire passed over the pole, thus preventing the signal from becoming attenuated. At electrical operated railways, pole routes were usually not built as too much jamming from the overhead wire would occur. To do this, cables were separated using spars with insulators spaced along them; in general four insulators were used per spar. Only one such pole route still exists on the UK rail network, in the highlands of Scotland. There was also a long section in place between Wymondham, Norfolk and Brandon in Suffolk, United Kingdom; however, this was de-wired and removed during March 2009.

Visual pollution

Utility poles and related structures are regarded by some to be a form of visual pollution. This is combated in several places by placing lines underground; however, burial of power lines is considerably more expensive, and so it is not common.

Chapter 4

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.

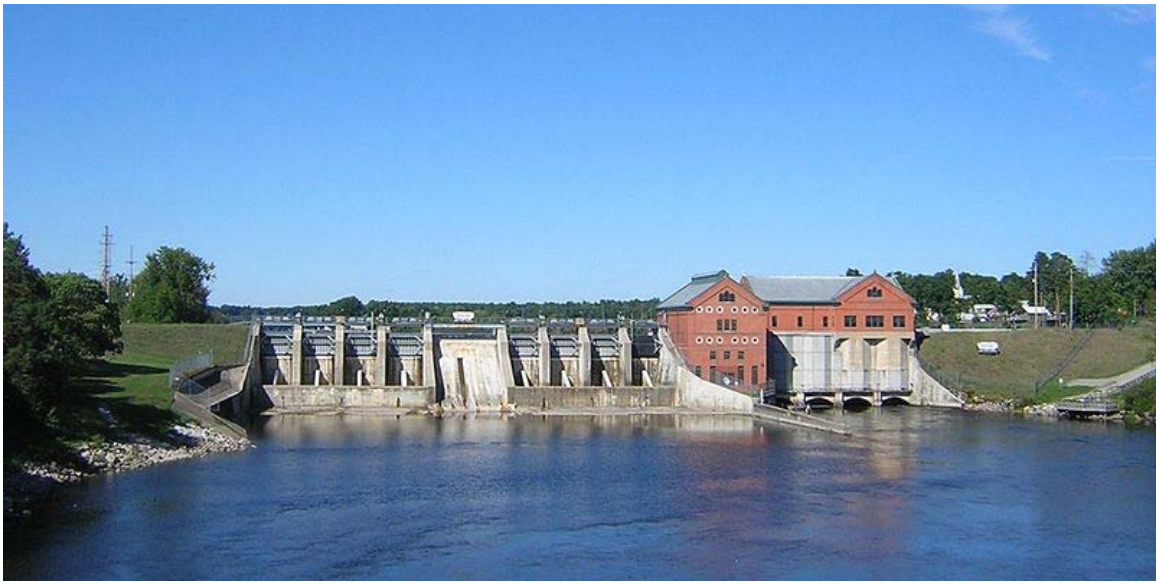
Where economically and environmentally possible, electric companies prefer to use cooling water from the ocean, or a lake or river, or a cooling pond, instead of a cooling tower. This type of cooling can save the cost of a cooling tower and may have lower energy costs for pumping cooling water through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

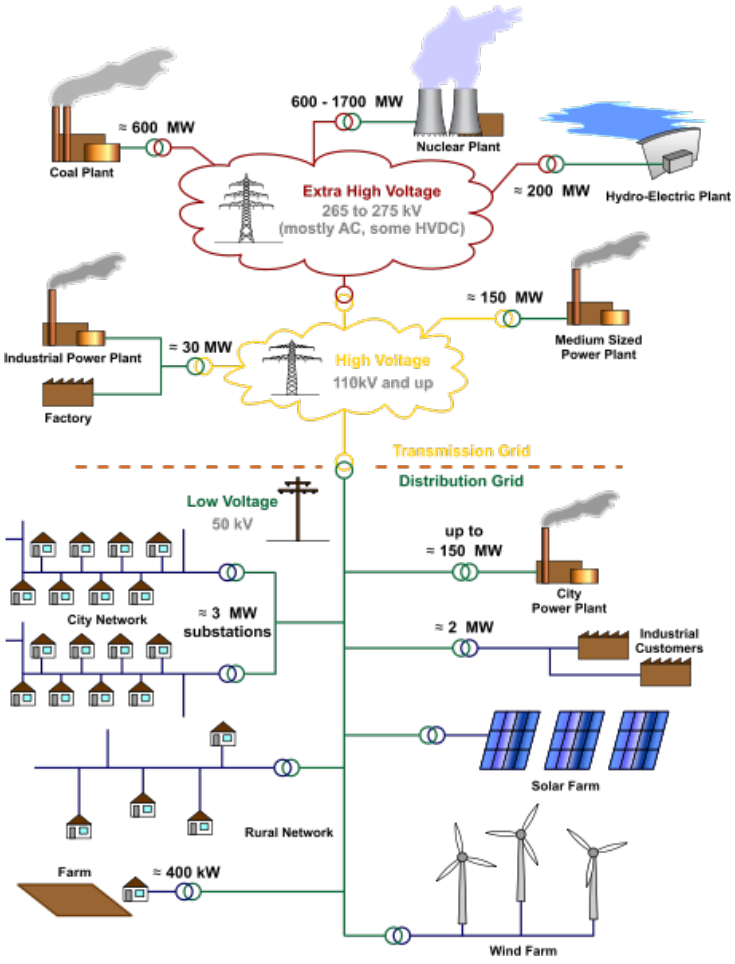
In some cases operators deliberately produce less power for economic reasons. The cost of fuel to run a load following power plant may be relatively high, and the cost of fuel to run a peaking power plant is even higher—they have relatively high marginal costs. Operators keep them turned off ("operational 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 5

Electrical Grid



General layout of electricity networks. Voltages and depictions of electrical lines are typical for Germany and other European systems.

An **electrical grid** is an interconnected network for delivering electricity from suppliers to consumers.

Overview

When referring to the power industry, *grid* is a term used for an electricity network which may support all or some of the following four distinct operations:

1. Electricity generation
2. Electric power transmission
3. Electricity distribution
4. Electricity control

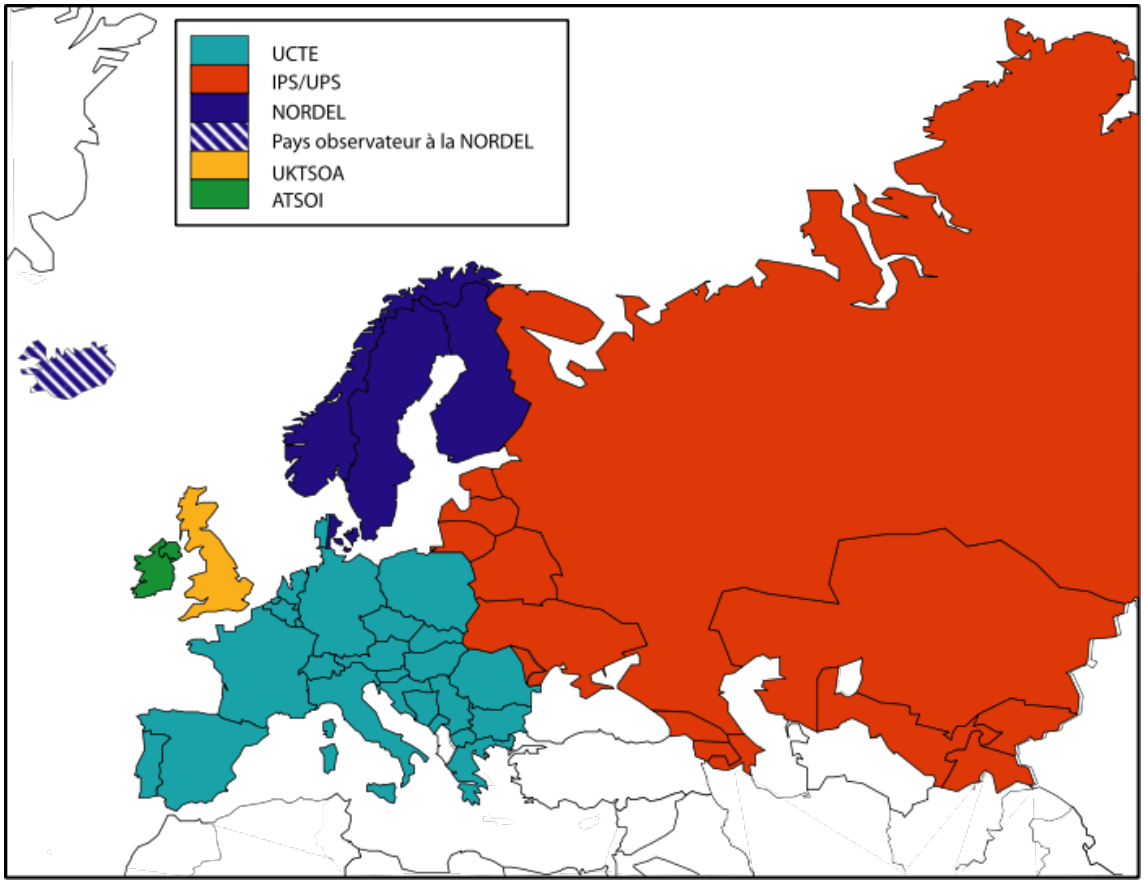
The sense of grid is as a network, and should not be taken to imply a particular physical layout, or breadth. *Grid* may be used to refer to an entire continent's electrical network, a regional transmission network or may be used to describe a subnetwork such as a local utility's transmission grid or distribution grid.

Electricity in a remote location might be provided by a simple distribution grid linking a central generator to homes. The traditional paradigm for moving electricity around in developed countries is more complex. Generating plants are usually located near a source of water, and away from heavily populated areas. They are usually quite large in order to take advantage of the economies of scale. The electric power which is generated is stepped up to a higher voltage—at which it connects to the transmission network. The transmission network will move (wheel) the power long distances—often across state lines, and sometimes across international boundaries—until it reaches its wholesale customer (usually the company that owns the local distribution network). Upon arrival at the substation, the power will be stepped down in voltage—from a transmission level voltage to a distribution level voltage. As it exits the substation, it enters the distribution wiring. Finally, upon arrival at the service location, the power is stepped down again from the distribution voltage to the required service voltage(s).

This traditional centralized model along with its distinctions are breaking down with the introduction of new technologies. For example, the characteristics of power generation can in some new grids be entirely opposite of those listed above. Generation can occur at low levels in dispersed locations, in highly populated areas, and not outside the distribution grids. Such characteristics could be attractive for some locales, and can be implemented if the grid uses a combination of new design options such as net metering, electric cars as a temporary energy source, or distributed generation.

Features

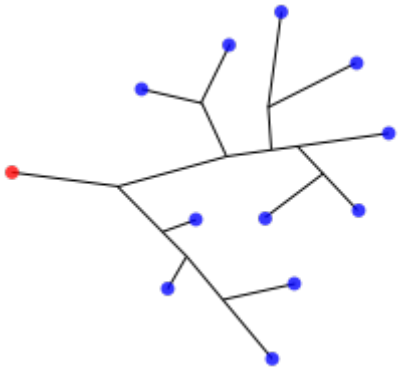
Structure of distribution grids



The wide area synchronous grids of Europe. Most are members of the European Transmission System Operators association.

The structure, or "topology" of a grid can vary considerably. The physical layout is often forced by what land is available and its geology. The logical topology can vary depending on the constraints of budget, requirements for system reliability, and the load and generation characteristics.

The cheapest and simplest topology for a distribution or transmission grid is a *radial* structure. This is a *tree* shape where power from a large supply radiates out into progressively lower voltage lines until the destination homes and businesses are reached.



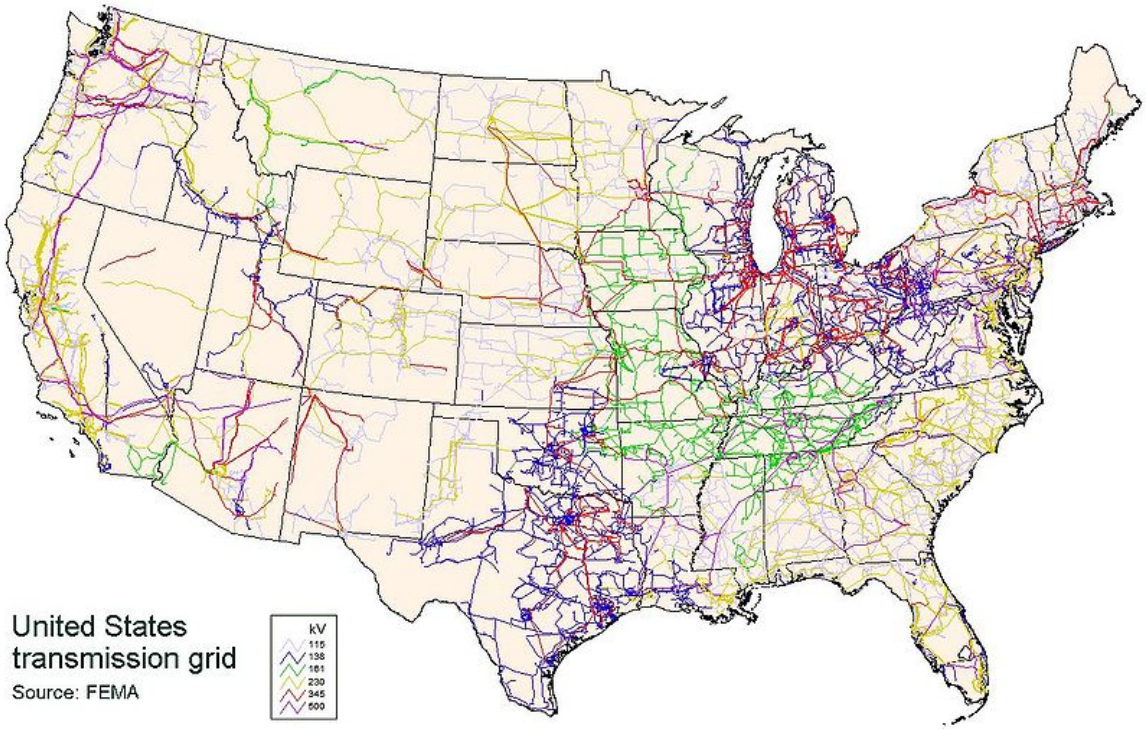
Classic North American electricity distribution grids were simple "radial" trees, sending power from a source (red dot representing power generation or a substation) to delivery points (blue dots representing homes, businesses, or other subnetworks).

Most transmission grids require the reliability that more complex *mesh networks* provide. If one were to imagine running redundant lines between limbs/branches of a tree that could be turned in case any particular limb of the tree were severed, then this image approximates how a mesh system operates. The expense of mesh topologies restrict their application to transmission and medium voltage distribution grids. Redundancy allows line failures to occur and power is simply rerouted while workmen repair the damaged and deactivated line.

Other topologies used are *looped* systems found in Europe and *tied ring* networks.

In cities and towns of North America, the grid tends to follow the classic "radially fed" design. A substation receives its power from the transmission network, the power is stepped down with a transformer and sent to a bus from which feeders fan out in all directions across the countryside. These feeders carry three-phase power, and tend to follow the major streets near the substation. As the distance from the substation grows, the fanout continues as smaller laterals spread out to cover areas missed by the feeders. This tree-like structure grows outward from the substation, but for reliability reasons, usually contains at least one unused backup connection to a nearby substation. This connection can be enabled in case of an emergency, so that a portion of a substation's service territory can be alternatively fed by another substation.

Geography of transmission networks



The Continental U.S. power transmission grid consists of about 300,000 km of lines operated by approximately 500 companies.

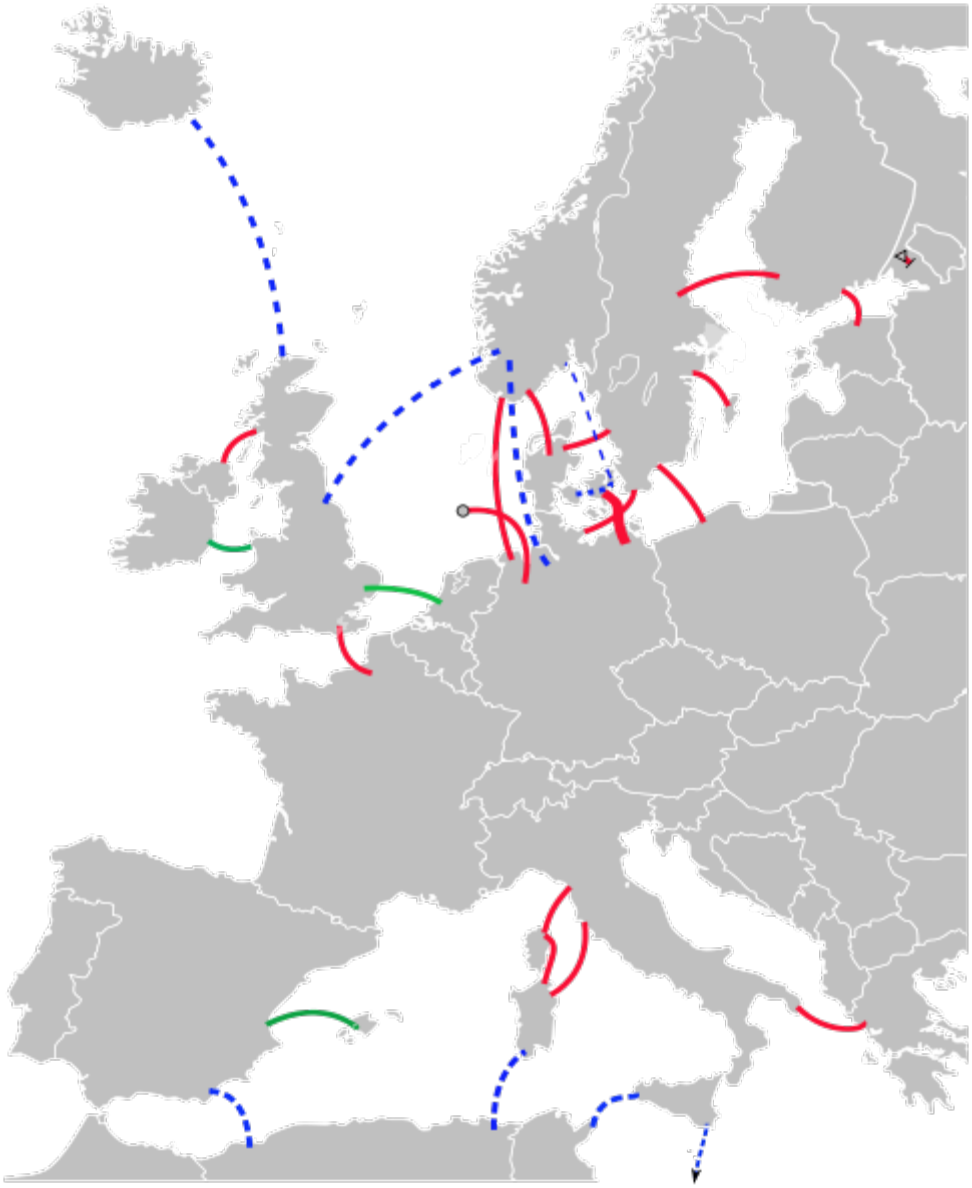
Transmission networks are more complex with redundant pathways.

A wide area synchronous grid or "interconnection" is a group of distribution areas all operating with alternating current (AC) frequencies synchronized (so that peaks occur at the same time). This allows transmission of AC power throughout the area, connecting a large number of electricity generators and consumers and potentially enabling more efficient electricity markets and redundant generation. Interconnection maps are shown of North America (right) and Europe (below left).

Electricity generation and consumption must be balanced across the entire grid, because energy is consumed almost immediately after it is produced. A large failure in one part of the grid - unless quickly compensated for - can cause current to re-route itself to flow from the remaining generators to consumers over transmission lines of insufficient capacity, causing further failures. One downside to a widely connected grid is thus the possibility of cascading failure and widespread power outage. A central authority is usually designated to facilitate communication and develop protocols to maintain a stable grid. For example, the North American Electric Reliability Corporation gained binding powers in the United States in 2006, and has advisory powers in the applicable parts of Canada and Mexico. The U.S. government has also designated National Interest Electric Transmission Corridors, where it believes transmission bottlenecks have developed.

Some areas, for example rural communities in Alaska, do not operate on a large grid, relying instead on local diesel generators.

High-voltage direct current lines or variable frequency transformers can be used to connect two alternating current interconnection networks which are not synchronized with each other. This provides the benefit of interconnection without the need to synchronize an even wider area. For example, compare the wide area synchronous grid map of Europe (below left) with the map of HVDC lines (below right).



High-voltage direct current interconnections in western Europe - red are existing links, green are under construction, and blue are proposed. Many of these transfer power from renewable sources such as hydro and wind.

Redundancy and defining "grid"

A town is only said to have achieved grid connection when it is connected to several redundant sources, generally involving long-distance transmission.

This redundancy is limited. Existing national or regional grids simply provide the interconnection of facilities to utilize whatever redundancy is available. The exact stage of development at which the supply structure becomes a *grid* is arbitrary. Similarly, the term *national grid* is something of an anachronism in many parts of the world, as transmission cables now frequently cross national boundaries. The terms *distribution grid* for local connections and *transmission grid* for long-distance transmissions are therefore preferred, but *national grid* is often still used for the overall structure...

Distributed generation

Utilities are under pressure to evolve their classic topologies to accommodate distributed generation. As generation becomes more common from rooftop solar and wind generators, the differences between distribution and transmission grids will continue to blur.

Modern trends

Deregulation

The three components of a complete grid: generation, transmission, and distribution of electrical power, can all be found in most large utilities. A utility can be completely self-sufficient, but finds it advantageous to have the opportunity to buy and sell power to and from neighboring utilities. This improves their reliability, and that of their neighbors. Utilities are often awarded a "monopoly" status (at least at the distribution level) simply because it doesn't make sense to have competing utilities installing their hardware in the same location as another utility. The idea of a monopoly becomes less compelling as one considers the generation of electrical power. Wildly varying costs for the production of electricity, and the opportunity to encourage free market competition spurs many legislatures to move towards deregulation of the electric utilities (also known as "liberalization" in some parts of the world.) The idea of de-regulation usually involves the separation of the generation, transmission, and distribution operations into separate financial entities. Generation assets in particular can often be sold-off in piecemeal fashion to the highest bidders. With the aging infrastructure present at many utilities, and the pressure to de-regulate, there are numerous opportunities to re-engineer the system.

Transitioning utilities from regulated monopolies to a deregulated market has run into a number of challenges such as those surfaced by the California electricity crisis.

Demand response

Demand response is a grid management technique where retail or wholesale customers are requested either electronically or manually to reduce their load. Currently, transmission grid operators use demand response to request load reduction from major energy users such as industrial plants.

Distributed generation

With everything interconnected, and open competition occurring in a free market economy, it starts to make sense to allow and even encourage distributed generation (DG). Smaller generators, usually not owned by the utility, can be brought on-line to help supply the need for power. The smaller generation facility might be a home-owner with excess power from their solar panel or wind turbine. It might be a small office with a diesel generator. These resources can be brought on-line either at the utility's behest, or by owner of the generation in an effort to sell electricity. Many small generators are allowed to sell electricity back to the grid for the same price they would pay to buy it.

Smart grid

Numerous efforts are underway to develop a "smart grid". In the U.S., the Energy Policy Act of 2005 and Title XIII of the Energy Independence and Security Act of 2007. are providing funding to encourage smart grid development. The hope is to enable utilities to better predict their needs, and in some cases involve consumers in some form of time-of-use based tariff. Funds have also been allocated to develop more robust energy control technologies.

Micro grid

Decentralization of the power transmission distribution system is vital to the success and reliability of this system. Currently the system is reliant upon relatively few generation stations. This makes current systems susceptible to impact from failures not within said area. Micro grids would have local power generation, and allow smaller grid areas to be separated from the rest of the grid if a failure were to occur. Furthermore, micro grid systems could help power each other if needed. Generation within a micro grid could be a downsized industrial generator or several smaller systems such as photo-voltaic systems, or wind generation. When combined with Smart Grid technology, electricity could be better controlled and distributed, and more efficient.

Super grid

Various planned and proposed systems to dramatically increase transmission capacity are known as super, or mega grids. The promised benefits include enabling the renewable energy industry to sell electricity to distant markets, the ability to increase usage of intermittent energy sources by balancing them across vast geological regions, and the removal of congestion that prevents electricity markets from flourishing. Local

opposition to siting new lines and the significant cost of these projects are major obstacles to super grids.

Chapter 6

Hydroelectricity

The Gordon Dam in Tasmania is a large hydro facility, with an installed capacity of 430 MW.

Hydroelectricity is the term referring to electricity generated by hydropower; the production of electrical power through the use of the gravitational force of falling or flowing water. It is the most widely used form of renewable energy. Once a hydroelectric complex is constructed, the project produces no direct waste, and has a considerably lower output level of the greenhouse gas carbon dioxide (CO_2) than fossil fuel powered energy plants. Worldwide, an installed capacity of 777 GWe supplied 2998 TWh of hydroelectricity in 2006. This was approximately 20% of the world's electricity, and accounted for about 88% of electricity from renewable sources.

History

Hydropower has been used since ancient times to grind flour and perform other tasks. In the mid-1770s, French engineer Bernard Forest de Bélidor published *Architecture Hydraulique* which described vertical- and horizontal-axis hydraulic machines. By the late 19th century, the electrical generator was developed and could now be coupled with hydraulics. The growing demand for the Industrial Revolution would drive development as well. In 1878 the world's first house to be powered with hydroelectricity was Cragside in Northumberland, England. The old Schoelkopf Power Station No. 1 near Niagara Falls in the U.S. side began to produce electricity in 1881. The first Edison hydroelectric power plant, the Vulcan Street Plant, began operating September 30, 1882, in Appleton, Wisconsin, with an output of about 12.5 kilowatts. By 1886 there were 45 hydroelectric power plants in the U.S. and Canada. By 1889 there were 200 in the U.S. alone.

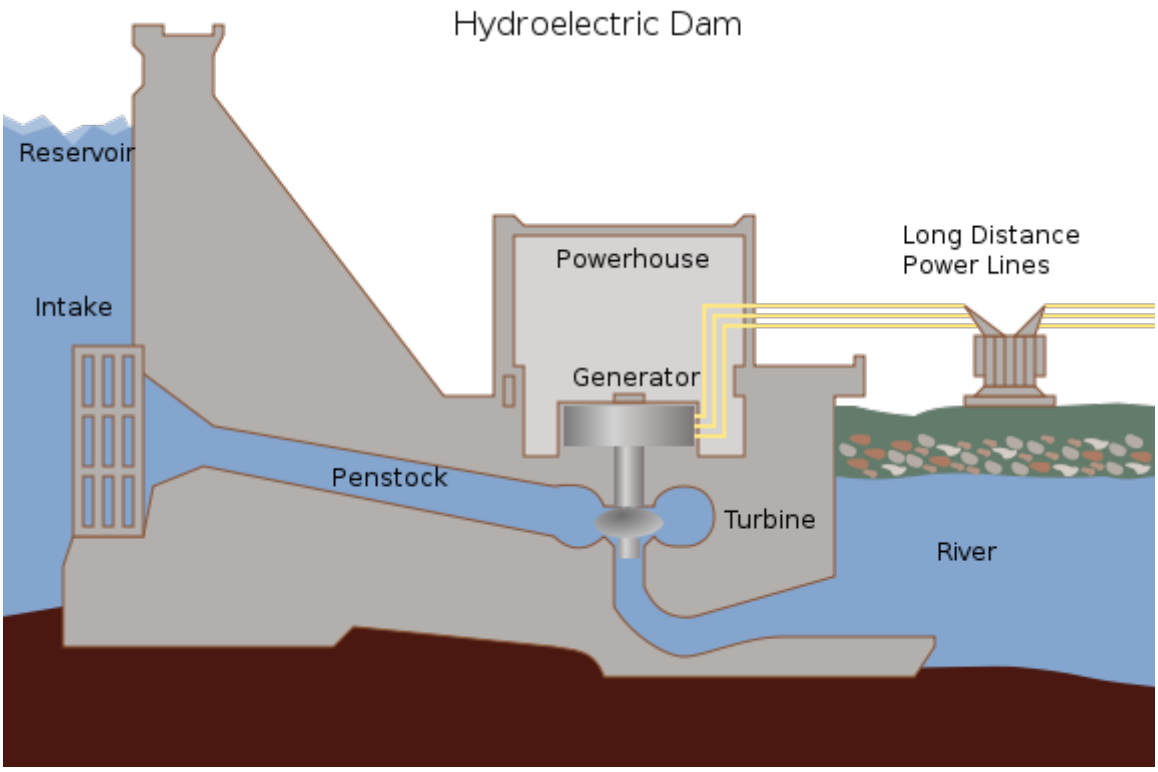
At the beginning of the 20th century, many small hydroelectric power plants were being constructed by commercial companies in mountains near metropolitan areas. Grenoble, France held the International Exhibition of Hydropower and Tourism with over one million visitors. By 1920 as 40% of the power produced in the United States was hydroelectric, the Federal Power Act was enacted into law. The Act created the Federal Power Commission to regulate hydroelectric power plants on federal land and water. As the power plants became larger, their associated dams developed additional purposes to include flood control, irrigation and navigation. Federal funding became necessary for large-scale development and federally owned corporations, such as the Tennessee Valley Authority (1933) and the Bonneville Power Administration (1937) were created. Additionally, the Bureau of Reclamation which had began a series of western U.S. irrigation projects in the early 20th century was now constructing large hydroelectric projects such as the 1928 Hoover Dam. The U.S. Army Corps of Engineers was also involved in hydroelectric development, completing the Bonneville Dam in 1937 and being recognized by the Flood Control Act of 1936 as the premier federal flood control agency.

Hydroelectric power plants continued to become larger throughout the 20th century. Hydropower was referred to as *white coal* for its power and plenty. Hoover Dam's initial 1,345 MW power plant was the world's largest hydroelectric power plant in 1936; it was eclipsed by the 6809 MW Grand Coulee Dam in 1942. The Itaipu Dam opened in 1984 in South America as the largest, producing 14,000 MW but was surpassed in 2008 by the Three Gorges Dam in China at 22,500 MW. Hydroelectricity would eventually supply

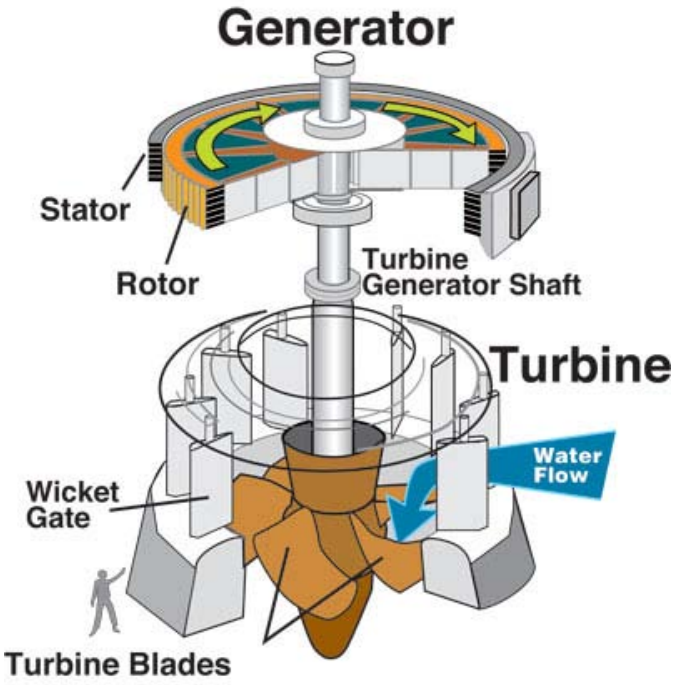
some countries, including Norway, Democratic Republic of the Congo, Paraguay and Brazil, with over 85% of their electricity. The United States currently has over 2,000 hydroelectric power plants which supply 49% of its renewable electricity.

Generating methods

Turbine row at Los Nihuiles Power Station in Mendoza, Argentina



Cross section of a conventional hydroelectric dam.



A typical turbine and generator

Conventional (dams)

Most hydroelectric power comes from the potential energy of dammed water driving a water turbine and generator. The power extracted from the water depends on the volume and on the difference in height between the source and the water's outflow. This height difference is called the head. The amount of potential energy in water is proportional to the head. A large pipe (the "penstock") delivers water to the turbine.

Pumped-storage

This method produces electricity to supply high peak demands by moving water between reservoirs at different elevations. At times of low electrical demand, excess generation capacity is used to pump water into the higher reservoir. When there is higher demand, water is released back into the lower reservoir through a turbine. Pumped-storage schemes currently provide the most commercially important means of large-scale grid energy storage and improve the daily capacity factor of the generation system.

Run-of-the-river

Run-of-the-river hydroelectric stations are those with small or no reservoir capacity, so that the water coming from upstream must be used for generation at that moment, or must be allowed to bypass the dam.

Tide

A tidal power plant makes use of the daily rise and fall of ocean water due to tides; such sources are highly predictable, and if conditions permit construction of reservoirs, can also be dispatchable to generate power during high demand periods. Less common types of hydro schemes use water's kinetic energy or undammed sources such as undershot waterwheels.

Underground

An underground power station makes use of a large natural height difference between two waterways, such as a waterfall or mountain lake. An underground tunnel is constructed to take water from the high reservoir to the generating hall built in an underground cavern near the lowest point of the water tunnel and a horizontal tailrace taking water away to the lower outlet waterway.

Sizes and capacities of hydroelectric facilities

Large and specialized industrial facilities

The Three Gorges Dam is the largest operating hydroelectric power station, at 22,500 MW.

Although no official definition exists for the capacity range of large hydroelectric power stations, facilities from over a few hundred megawatts to more than 10 GW are generally considered large hydroelectric facilities. Currently, only three facilities over 10 GW (10,000 MW) are in operation worldwide; Three Gorges Dam at 22.5 GW, Itaipu Dam at 14 GW, and Guri Dam at 10.2 GW. Large-scale hydroelectric power stations are more commonly seen as the largest power producing facilities in the world, with some hydroelectric facilities capable of generating more than double the installed capacities of the current largest nuclear power stations.

While many hydroelectric projects supply public electricity networks, some are created to serve specific industrial enterprises. Dedicated hydroelectric projects are often built to provide the substantial amounts of electricity needed for aluminium electrolytic plants, for example. The Grand Coulee Dam switched to support Alcoa aluminium in Bellingham, Washington, United States for American World War II airplanes before it was allowed to provide irrigation and power to citizens (in addition to aluminium power) after the war. In Suriname, the Brokopondo Reservoir was constructed to provide electricity for the Alcoa aluminium industry. New Zealand's Manapouri Power Station was constructed to supply electricity to the aluminium smelter at Tiwai Point.

The construction of these large hydroelectric facilities, and their changes on the environment, are also often on grand scales, creating as much damage to the environment

as at helps it by being a renewable resource. Many specialized organizations, such as the International Hydropower Association, look into these matters on a global scale.

Small

Small hydro is the development of hydroelectric power on a scale serving a small community or industrial plant. The definition of a small hydro project varies but a generating capacity of up to 10 megawatts (MW) is generally accepted as the upper limit of what can be termed small hydro. This may be stretched to 25 MW and 30 MW in Canada and the United States. Small-scale hydroelectricity production grew by 28% during 2008 from 2005, raising the total world small-hydro capacity to 85 GW. Over 70% of this was in China (65 GW), followed by Japan (3.5 GW), the United States (3 GW), and India (2 GW).

Small hydro plants may be connected to conventional electrical distribution networks as a source of low-cost renewable energy. Alternatively, small hydro projects may be built in isolated areas that would be uneconomic to serve from a network, or in areas where there is no national electrical distribution network. Since small hydro projects usually have minimal reservoirs and civil construction work, they are seen as having a relatively low environmental impact compared to large hydro. This decreased environmental impact depends strongly on the balance between stream flow and power production.

Micro

A micro-hydro facility in Vietnam

Micro hydro is a term used for hydroelectric power installations that typically produce up to 100 KW of power. These installations can provide power to an isolated home or small community, or are sometimes connected to electric power networks. There are many of these installations around the world, particularly in developing nations as they can provide an economical source of energy without purchase of fuel. Micro hydro systems complement photovoltaic solar energy systems because in many areas, water flow, and thus available hydro power, is highest in the winter when solar energy is at a minimum.

Pico

Pico hydro is a term used for hydroelectric power generation of under 5 KW. It is useful in small, remote communities that require only a small amount of electricity. For example, to power one or two fluorescent light bulbs and a TV or radio for a few homes. Even smaller turbines of 200-300W may power a single home in a developing country with a drop of only 1 m (3 ft). Pico-hydro setups typically are run-of-the-river, meaning that dams are not used, but rather pipes divert some of the flow, drop this down a gradient, and through the turbine before returning it to the stream.

Calculating the amount of available power

A simple formula for approximating electric power production at a hydroelectric plant is: $P = \rho hrgk$, where

- P is Power in watts,
- ρ is the density of water (~1000 kg/m^3),
- h is height in meters,
- r is flow rate in cubic meters per second,
- g is acceleration due to gravity of 9.8 m/s^2,
- k is a coefficient of efficiency ranging from 0 to 1. Efficiency is often higher (that is, closer to 1) with larger and more modern turbines.

Annual electric energy production depends on the available water supply. In some installations the water flow rate can vary by a factor of 10:1 over the course of a year.

Advantages and disadvantages of hydroelectricity

Advantages

The Ffestiniog Power Station can generate 360 MW of electricity within 60 seconds of the demand arising.

Economics

The major advantage of hydroelectricity is elimination of the cost of fuel. The cost of operating a hydroelectric plant is nearly immune to increases in the cost of fossil fuels such as oil, natural gas or coal, and no imports are needed.

Hydroelectric plants have long economic lives, with some plants still in service after 50-100 years. Operating labor cost is also usually low, as plants are automated and have few personnel on site during normal operation.

Where a dam serves multiple purposes, a hydroelectric plant may be added with relatively low construction cost, providing a useful revenue stream to offset the costs of dam operation. It has been calculated that the sale of electricity from the Three Gorges Dam will cover the construction costs after 5 to 8 years of full generation.

CO_2 emissions

Since hydroelectric dams do not burn fossil fuels, they do not directly produce carbon dioxide. While some carbon dioxide is produced during manufacture and construction of

the project, this is a tiny fraction of the operating emissions of equivalent fossil-fuel electricity generation. One measurement of greenhouse gas related and other externality comparison between energy sources can be found in the ExternE project by the Paul Scherrer Institut and the University of Stuttgart which was funded by the European Commission. According to that study, hydroelectricity produces the least amount of greenhouse gases and externality of any energy source. Coming in second place was wind, third was nuclear energy, and fourth was solar photovoltaic. The extremely positive greenhouse gas impact of hydroelectricity is found especially in temperate climates. The above study was for local energy in Europe; presumably similar conditions prevail in North America and Northern Asia, which all see a regular, natural freeze/thaw cycle (with associated seasonal plant decay and regrowth).

Other uses of the reservoir

Reservoirs created by hydroelectric schemes often provide facilities for water sports, and become tourist attractions themselves. In some countries, aquaculture in reservoirs is common. Multi-use dams installed for irrigation support agriculture with a relatively constant water supply. Large hydro dams can control floods, which would otherwise affect people living downstream of the project.

Disadvantages

Ecosystem damage and loss of land

Hydroelectric power stations that use dams would submerge large areas of land due to the requirement of a reservoir.

Large reservoirs required for the operation of hydroelectric power stations result in submersion of extensive areas upstream of the dams, destroying biologically rich and productive lowland and riverine valley forests, marshland and grasslands. The loss of land is often exacerbated by the fact that reservoirs cause habitat fragmentation of surrounding areas.

Hydroelectric projects can be disruptive to surrounding aquatic ecosystems both upstream and downstream of the plant site. For instance, studies have shown that dams along the Atlantic and Pacific coasts of North America have reduced salmon populations by preventing access to spawning grounds upstream, even though most dams in salmon habitat have fish ladders installed. Salmon spawn are also harmed on their migration to sea when they must pass through turbines. This has led to some areas transporting smolt downstream by barge during parts of the year. In some cases dams, such as the Marmot Dam, have been demolished due to the high impact on fish. Turbine and power-plant designs that are easier on aquatic life are an active area of research. Mitigation measures

such as fish ladders may be required at new projects or as a condition of re-licensing of existing projects.

Generation of hydroelectric power changes the downstream river environment. Water exiting a turbine usually contains very little suspended sediment, which can lead to scouring of river beds and loss of riverbanks. Since turbine gates are often opened intermittently, rapid or even daily fluctuations in river flow are observed. For example, in the Grand Canyon, the daily cyclic flow variation caused by Glen Canyon Dam was found to be contributing to erosion of sand bars. Dissolved oxygen content of the water may change from pre-construction conditions. Depending on the location, water exiting from turbines is typically much warmer than the pre-dam water, which can change aquatic faunal populations, including endangered species, and prevent natural freezing processes from occurring. Some hydroelectric projects also use canals to divert a river at a shallower gradient to increase the head of the scheme. In some cases, the entire river may be diverted leaving a dry riverbed. Examples include the Tekapo and Pukaki Rivers in New Zealand.

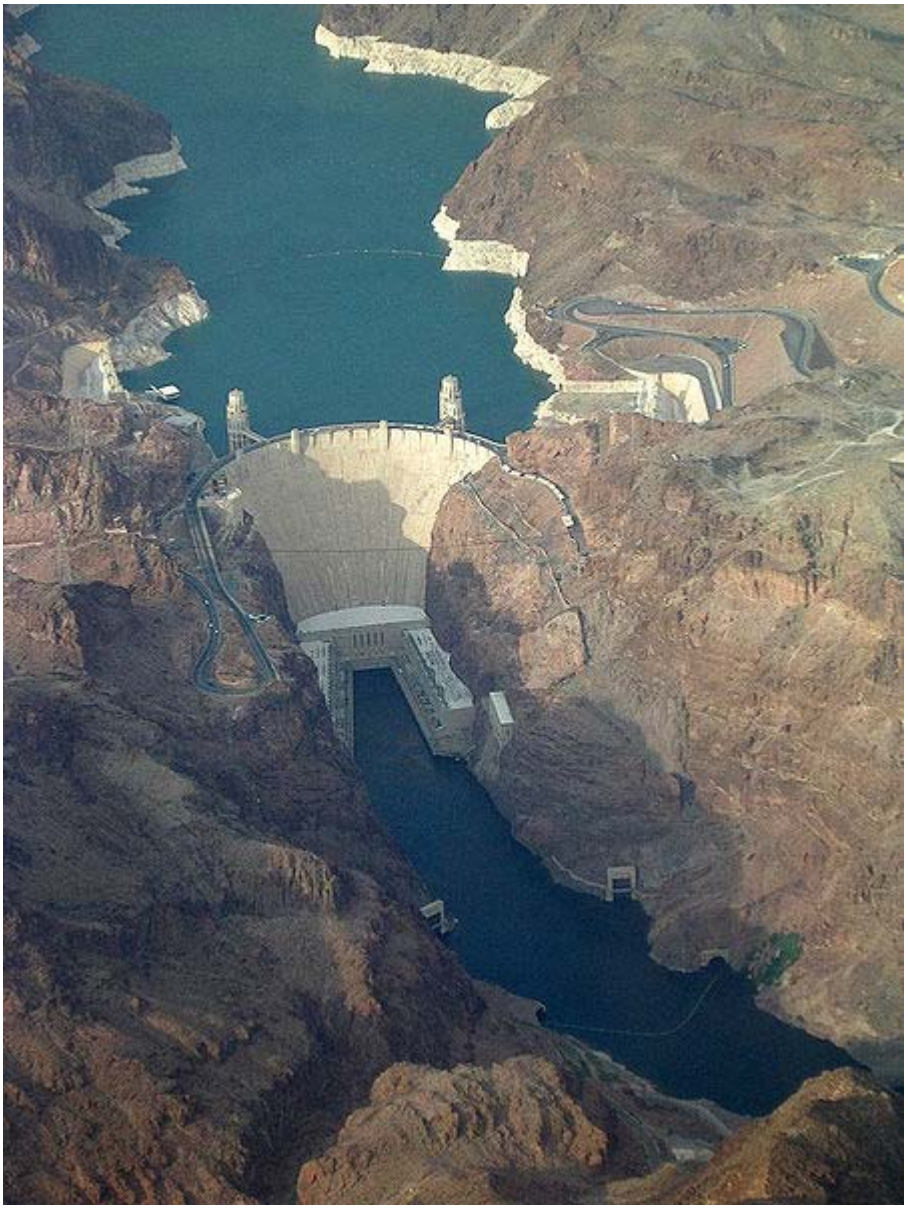
Siltation

When water flows it has the ability to transport particles heavier than itself downstream. This has a negative effect on dams and subsequently their power stations, particularly those on rivers or within catchment areas with high siltation. Siltation can fill a reservoir and reduce its capacity to control floods along with causing additional horizontal pressure on the upstream portion of the dam. Eventually, some reservoirs can become completely full of sediment and useless or over-top during a flood and fail.

Flow shortage

Changes in the amount of river flow will correlate with the amount of energy produced by a dam. Lower river flows because of drought, climate change or upstream dams and diversions will reduce the amount of live storage in a reservoir therefore reducing the amount of water that can be used for hydroelectricity. The result of diminished river flow can be power shortages in areas that depend heavily on hydroelectric power.

Methane emissions (from reservoirs)



The Hoover Dam in the United States is a large conventional dammed-hydro facility, with an installed capacity of 2,080 MW.

Lower positive impacts are found in the tropical regions, as it has been noted that the reservoirs of power plants in tropical regions may produce substantial amounts of methane. This is due to plant material in flooded areas decaying in an anaerobic environment, and forming methane, a potent greenhouse gas. According to the World Commission on Dams report, where the reservoir is large compared to the generating capacity (less than 100 watts per square metre of surface area) and no clearing of the forests in the area was undertaken prior to impoundment of the reservoir, greenhouse gas emissions from the reservoir may be higher than those of a conventional oil-fired thermal

generation plant. Although these emissions represent carbon already in the biosphere, not fossil deposits that had been sequestered from the carbon cycle, there is a greater amount of methane due to anaerobic decay, causing greater damage than would otherwise have occurred had the forest decayed naturally.

In boreal reservoirs of Canada and Northern Europe, however, greenhouse gas emissions are typically only 2% to 8% of any kind of conventional fossil-fuel thermal generation. A new class of underwater logging operation that targets drowned forests can mitigate the effect of forest decay.

In 2007, International Rivers accused hydropower firms of cheating with fake carbon credits under the Clean Development Mechanism, for hydropower projects already finished or under construction at the moment they applied to join the CDM. These carbon credits – of hydropower projects under the CDM in developing countries – can be sold to companies and governments in rich countries, in order to comply with the Kyoto protocol.

Relocation

Another disadvantage of hydroelectric dams is the need to relocate the people living where the reservoirs are planned. In February 2008 it was estimated that 40-80 million people worldwide had been physically displaced as a direct result of dam construction. In many cases, no amount of compensation can replace ancestral and cultural attachments to places that have spiritual value to the displaced population. Additionally, historically and culturally important sites can be flooded and lost.

Such problems have arisen at the Aswan Dam in Egypt between 1960 and 1980, the Three Gorges Dam in China, the Clyde Dam in New Zealand, and the Ilisu Dam in Turkey.

Failure hazard

Because large conventional dammed-hydro facilities hold back large volumes of water, a failure due to poor construction, terrorism, or other cause can be catastrophic to downriver settlements and infrastructure. Dam failures have been some of the largest man-made disasters in history. Also, good design and construction are not an adequate guarantee of safety. Dams are tempting industrial targets for wartime attack, sabotage and terrorism, such as Operation Chastise in World War II.

The Banqiao Dam failure in Southern China directly resulted in the deaths of 26,000 people, and another 145,000 from epidemics. Millions were left homeless. Also, the creation of a dam in a geologically inappropriate location may cause disasters such as 1963 disaster at Vajont Dam in Italy, where almost 2000 people died.

Smaller dams and micro hydro facilities create less risk, but can form continuing hazards even after being decommissioned. For example, the small Kelly Barnes Dam failed in

1967, causing 39 deaths with the Toccoa Flood, ten years after its power plant was decommissioned.

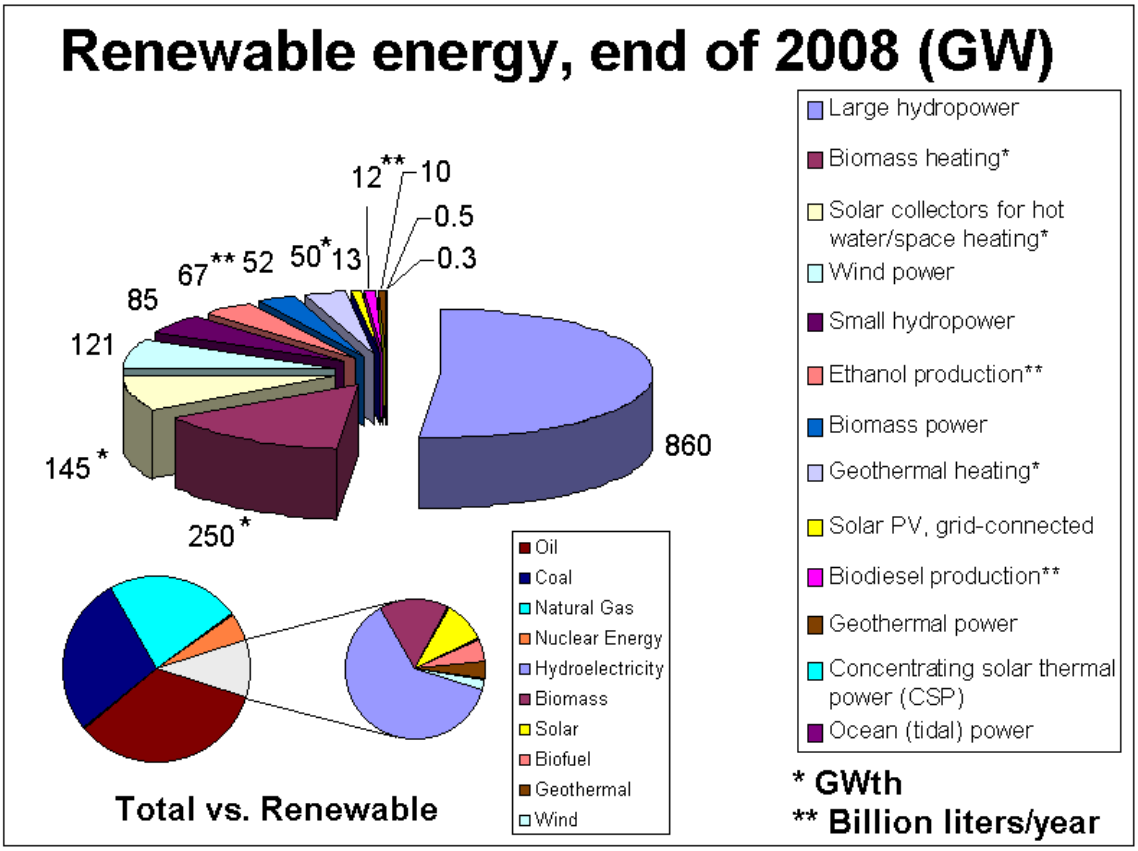
Comparison with other methods of power generation

Hydroelectricity eliminates the flue gas emissions from fossil fuel combustion, including pollutants such as sulfur dioxide, nitric oxide, carbon monoxide, dust, and mercury in the coal. Hydroelectricity also avoids the hazards of coal mining and the indirect health effects of coal emissions. Compared to nuclear power, hydroelectricity generates no nuclear waste, has none of the dangers associated with uranium mining, nor nuclear leaks. Unlike uranium, hydroelectricity is also a renewable energy source.

Compared to wind farms, hydroelectricity power plants have a more predictable load factor. If the project has a storage reservoir, it can generate power when needed. Hydroelectric plants can be easily regulated to follow variations in power demand.

Unlike fossil-fuelled combustion turbines, construction of a hydroelectric plant requires a long lead-time for site studies, hydrological studies, and environmental impact assessment. Hydrological data up to 50 years or more is usually required to determine the best sites and operating regimes for a large hydroelectric plant. Unlike plants operated by fuel, such as fossil or nuclear energy, the number of sites that can be economically developed for hydroelectric production is limited; in many areas the most cost-effective sites have already been exploited. New hydro sites tend to be far from population centers and require extensive transmission lines. Hydroelectric generation depends on rainfall in the watershed, and may be significantly reduced in years of low rainfall or snowmelt. Long-term energy yield may be affected by climate change. Utilities that primarily use hydroelectric power may spend additional capital to build extra capacity to ensure sufficient power is available in low water years.

World hydroelectric capacity



World renewable energy share (2008), with hydroelectricity more than 50% of all renewable energy sources

The ranking of hydro-electric capacity is either by actual annual energy production or by installed capacity power rating. A hydro-electric plant rarely operates at its full power rating over a full year; the ratio between annual average power and installed capacity rating is the capacity factor. The installed capacity is the sum of all generator nameplate power ratings. Sources came from *BP Statistical Review - Full Report 2009*

Brazil, Canada, New Zealand, Norway, Paraguay, Switzerland, and Venezuela are the only countries in the world where the majority of the internal electric energy production is from hydroelectric power. Paraguay produces 100% of its electricity from hydroelectric dams, and exports 90% of its production to Brazil and to Argentina. Norway produces 98–99% of its electricity from hydroelectric sources.

Ten of the largest hydroelectric producers as at 2009.

Country	Annual hydroelectric production (TWh)	Installed capacity (GW)	Capacity factor	% of total capacity
China	652.05	196.79	0.37	22.25
Canada	369.5	88.974	0.59	61.12
Brazil	363.8	69.080	0.56	85.56
United States	250.6	79.511	0.42	5.74
Russia	167.0	45.000	0.42	17.64
Norway	140.5	27.528	0.49	98.25
India	115.6	33.600	0.43	15.80
Venezuela	85.96	14.622	0.67	69.20
Japan	69.2	27.229	0.37	7.21
Sweden	65.5	16.209	0.46	44.34

Major projects under construction

Name	Maximum Capacity	Country	Construction started	Scheduled completion	Comments
Xiluodu Dam	12,600 MW	China	December 26, 2005	2015	Construction once stopped due to lack of environmental impact study.
Belo Monte Dam	11,181 MW	Brazil	March, 2011	2015	Preliminary construction underway.
Siang Upper HE Project	11,000 MW	India	April, 2009	2024	Multi-phase construction over a period of 15 years. Construction was delayed due to dispute with China.
TaSang Dam	7,110 MW	Burma	March, 2007	2022	Controversial 228 meter tall dam with capacity to produce 35,446 Ghw annually.

Xiangjiaba Dam	6,400 MW	China	November 26, 2006	2015	
Nuozhadu Dam	5,850 MW	China	2006	2017	
Jinping 2 Hydropower Station	4,800 MW	China	January 30, 2007	2014	To build this dam, 23 families and 129 local residents need to be moved. It works with Jinping 1 Hydropower Station as a group.
Jinping 1 Hydropower Station	3,600 MW	China	November 11, 2005	2014	
Jirau Dam	3,300 MW	Brazil	2008	2012	Construction halted in March 2011 due to worker riots.
Santo Antônio Dam	3,150 MW	Brazil	September 2008	2011	Run-of-the-river project
Pubugou Dam	3,300 MW	China	March 30, 2004	2010	
Goupitan Dam	3,000 MW	China	November 8, 2003	2011	
Guanyinyan Dam	3,000 MW	China	2008	2015	Construction of the roads and spillway started.
Lianghekou Dam	3,000 MW	China	2009	2015	
Boguchan Dam	3,000 MW	Russia	1980	2010	
Dagangshan Dam	2,600 MW	China	August 15, 2008	2014	
Guandi Dam	2,400 MW	China	November 11, 2007	2012	

Liyuan Dam	2,400 MW	China	2008		
Tocoma Dam Bolívar State	2,160 MW	Venezuela	2004	2014	This power plant would be the last development in the Low Caroni Basin, bringing the total to six power plants on the same river, including the 10,000MW Guri Dam.
Ludila Dam	2,100 MW	China	2007	2015	Construction halt due to lack of the evnironmental assessment.
Shuangjiangkou Dam	2,000 MW	China	December, 2007		The dam will be 314 m high.
Ahai Dam	2,000 MW	China	July 27, 2006		
Lower Subansiri Dam	2,000 MW	India	2005	2012	

Chapter 7

Electric Power Transmission

400 kV high-tension transmission lines near Madrid

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

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

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

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

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

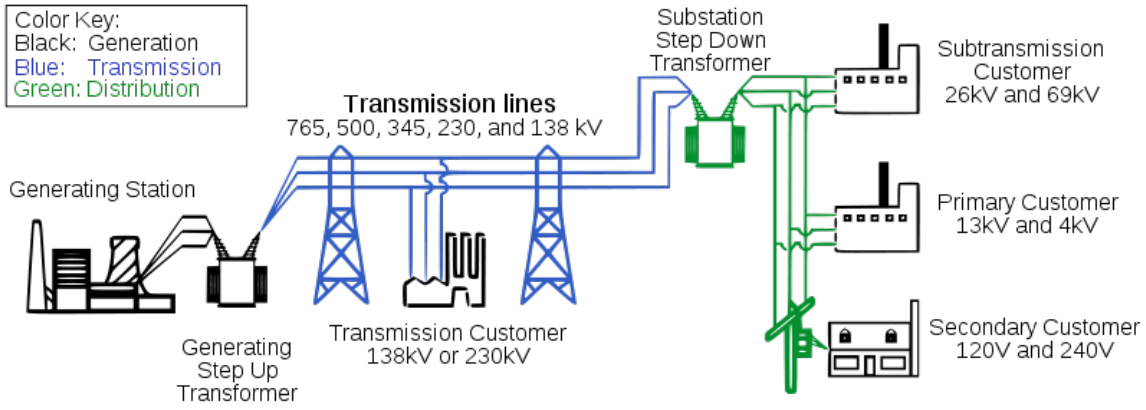
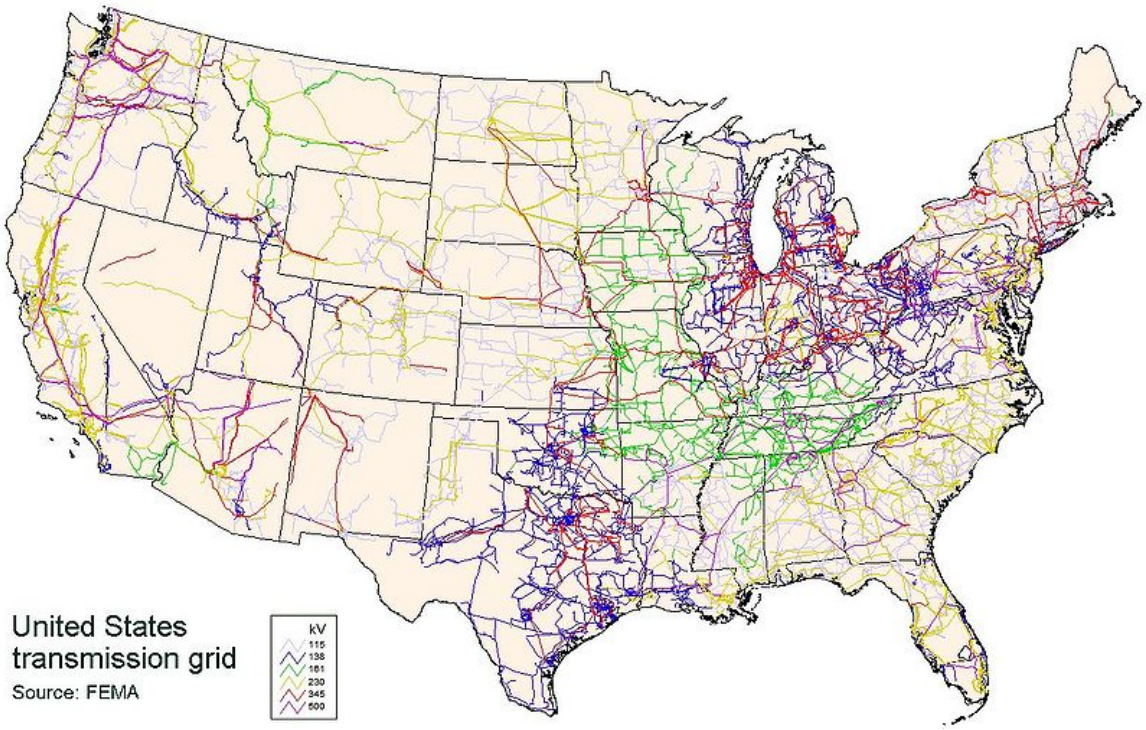


Diagram of an electrical system.

Overhead transmission



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

High-voltage overhead conductors are not covered by insulation. The conductor material is nearly always an aluminium alloy, made into several strands and possibly reinforced with steel strands. Copper was sometimes used for overhead transmission but aluminium is lower in weight for only marginally reduced performance, and much lower in cost. Overhead conductors are a commodity supplied by several companies worldwide. Improved conductor material and shapes are regularly used to allow increased capacity

and modernize transmission circuits. Conductor sizes range from 12 mm^2 (#6 American wire gauge) to 750 mm^2 (1,590,000 circular mils area), with varying resistance and current-carrying capacity. Thicker wires would lead to a relatively small increase in capacity due to the skin effect, that causes most of the current to flow close to the surface of the wire.

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

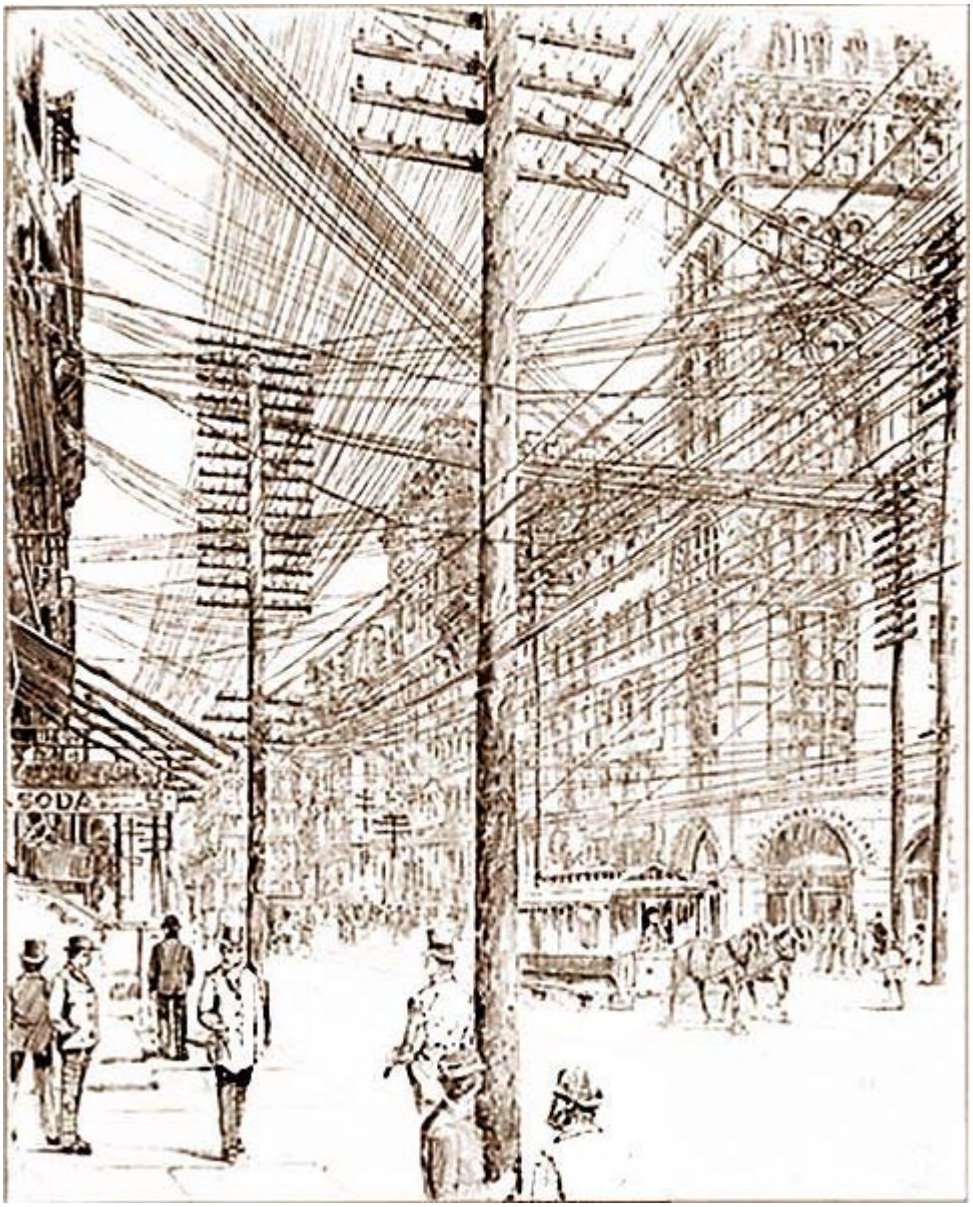
Since overhead transmission lines are uninsulated, design of these lines requires minimum clearances to be observed to maintain safety. Adverse weather conditions of high wind and low temperatures can lead to power outages: wind speeds as low as 23 knots (43 km/h) can permit conductors to encroach operating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

High Voltage Lines in Washington State

Underground transmission

Electric power can also be transmitted by underground power cables instead of overhead power lines.

History

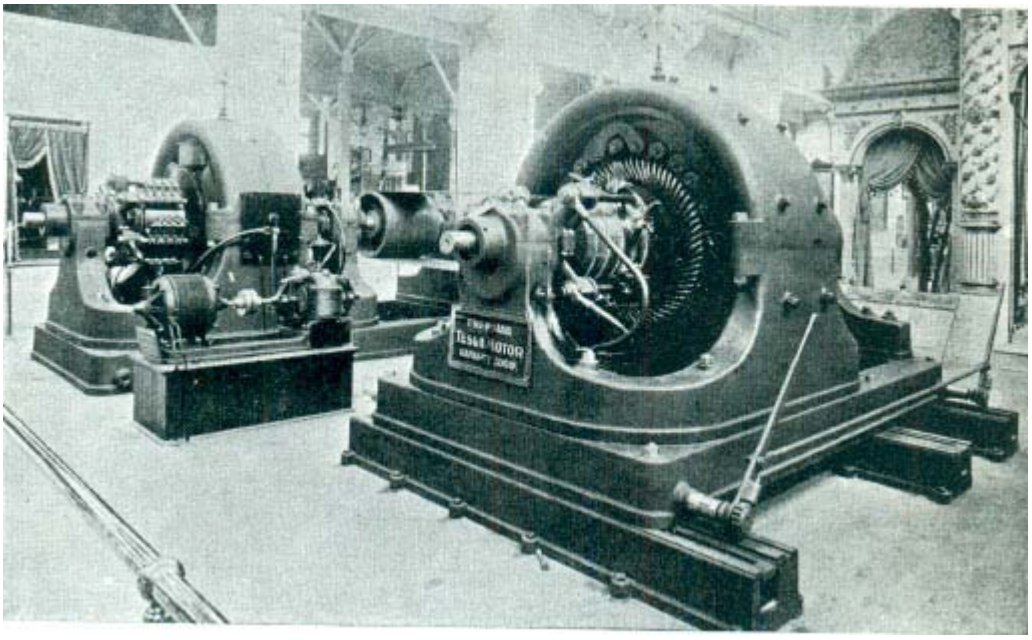


New York City streets in 1890. Besides telegraph lines, multiple electric lines were required for each class of device requiring different voltages.

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

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

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



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

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

investment was required, load factor on each plant was increased allowing for higher efficiency, a lower cost for the consumer and increased overall use of electric power.

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

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

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

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

Bulk power transmission

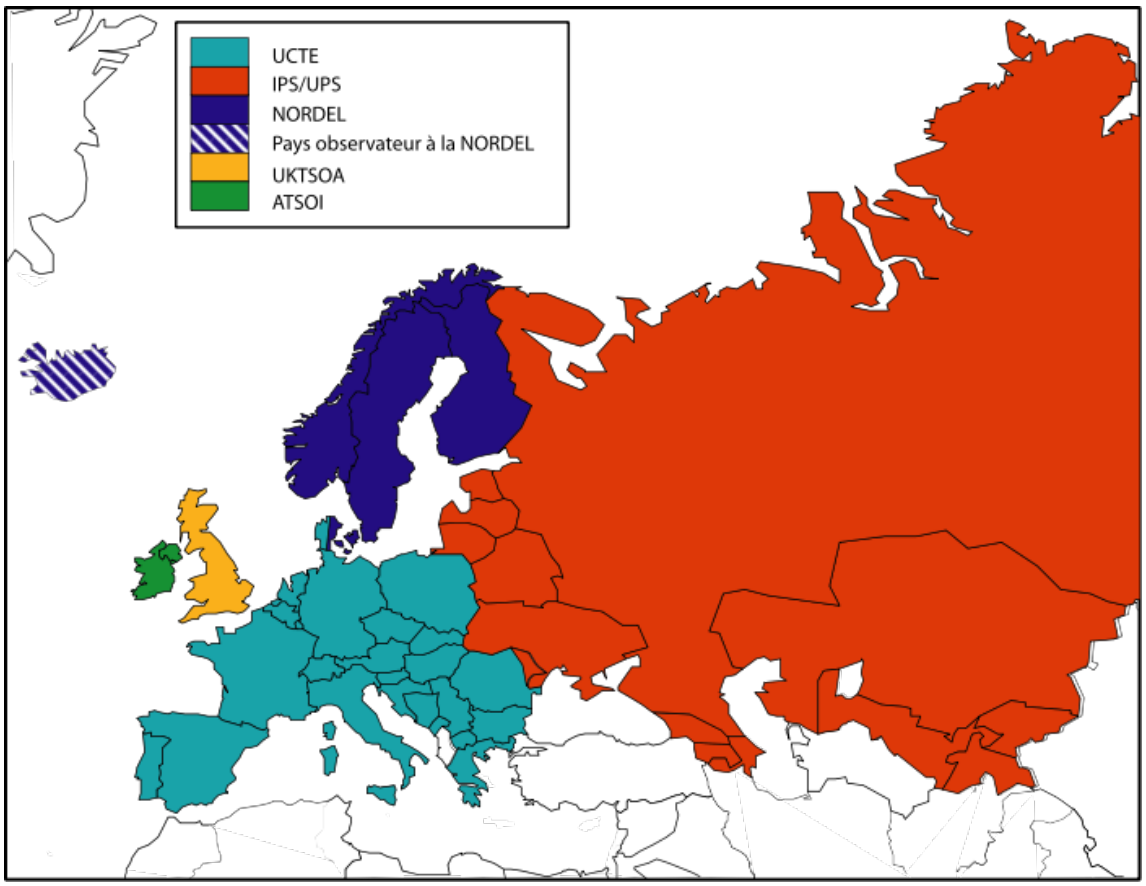
A transmission substation decreases the voltage of incoming electricity, allowing it to connect from long distance high voltage transmission, to local lower voltage distribution. It also reroutes power to other transmission lines that serve local markets. A transmission substation may include phase-shifting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

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

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

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

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



The synchronous grids of Eurasia.

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

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

A high-power electrical transmission tower.

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

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

Grid input

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

Losses

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

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

As of 1980, the longest cost-effective distance for DC electricity was 7,000 km (4,300 mi) (4,000 km (2,500 mi) for AC), although all present transmission lines are considerably shorter.

In an alternating current circuit, the inductance and capacitance of the phase conductors can be significant. The currents that flow in these components of the circuit impedance constitute reactive power, which transmits no energy to the load. Reactive current causes extra losses in the transmission circuit. The ratio of real power (transmitted to the load) to apparent power is the power factor. As reactive current increases, the reactive power increases and the power factor decreases. For systems with low power factors, losses are

higher than for systems with high power factors. Utilities add capacitor banks and other components (such as phase-shifting transformers; static VAR compensators; physical transposition of the phase conductors; and flexible AC transmission systems, FACTS) throughout the system to control reactive power flow for reduction of losses and stabilization of system voltage.

Subtransmission

Subtransmission is part of an electric power transmission system that runs at relatively lower voltages. It is uneconomical to connect all distribution substations to the high main transmission voltage, because the equipment is larger and more expensive. Typically, only larger substations connect with this high voltage. It is stepped down and sent to smaller substations in towns and neighborhoods. Subtransmission circuits are usually arranged in loops so that a single line failure does not cut off service to a large number of customers for more than a short time. While subtransmission circuits are usually carried on overhead lines, in urban areas buried cable may be used.

There is no fixed cutoff between subtransmission and transmission, or subtransmission and distribution. The voltage ranges overlap somewhat. Voltages of 69 kV, 115 kV and 138 kV are often used for substranmission in North America. As power systems evolved, voltages formerly used for transmission were used for subtransmission, and subtransmission voltages became distribution voltages. Like transmission, subtransmission moves relatively large amonts of power, and like distribution, subtransmission covers an area instead of just point to point.

Transmission grid exit

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

High-voltage direct current

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

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

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

Limitations

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

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

Control

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

Load balancing

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

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

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

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

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

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

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

Failure protection

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

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

Communications

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

- Microwaves
- Power line communication
- Optical fibers

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

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

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

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

Electricity market reform

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

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

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

Cost of electric power transmission

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

Merchant transmission

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

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

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

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

Health concerns

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

There are established biological effects for acute *high* level exposure to magnetic fields well above 100 μT. In a residential setting, there is "limited evidence of carcinogenicity in humans and less than sufficient evidence for carcinogenicity in experimental animals", in particular, childhood leukaemia, *associated with* average exposure to residential power-frequency magnetic field above 0.3 to 0.4 μT. These levels exceed average residential power-frequency magnetic fields in homes which are about 0.07 μT in Europe and 0.11 μT in North America.

Government policy

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

Special transmission

Grids for railways

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

Superconducting cables

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

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

Single wire earth return

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

Wireless power transmission

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

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

Security of control systems

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

Chapter 8

Solar Power

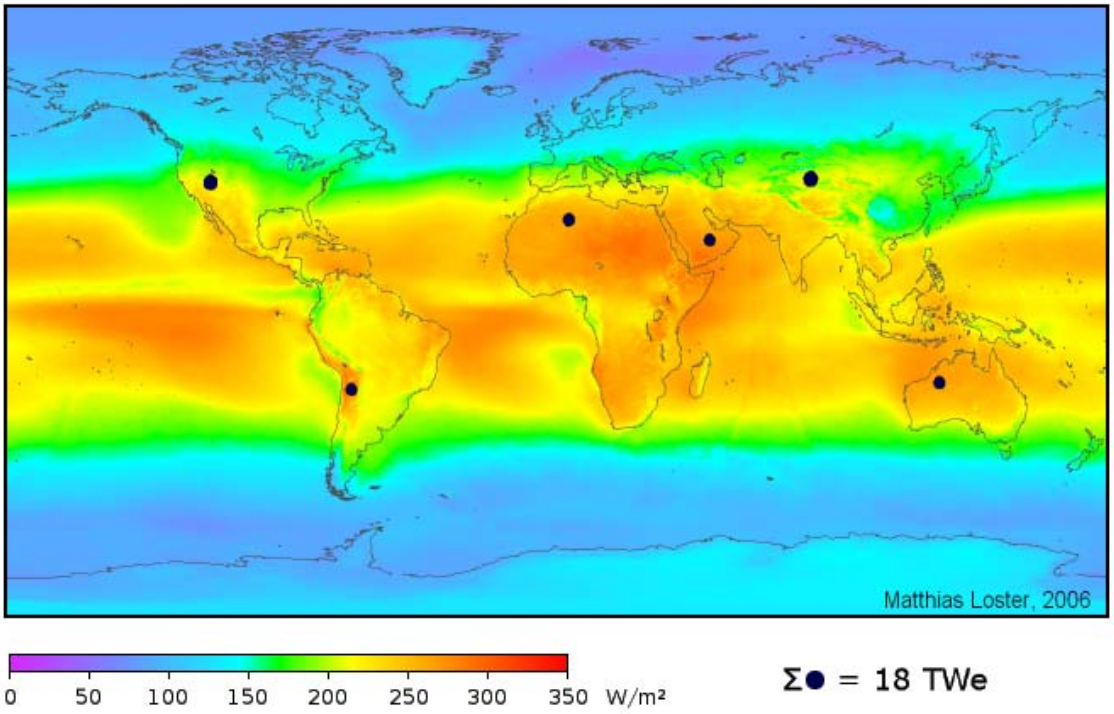
The PS10 concentrates sunlight from a field of heliostats on a central tower.

Solar power is the conversion of sunlight into electricity, either directly using photovoltaics (PV), or indirectly using concentrated solar power (CSP). Concentrated solar power systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. Photovoltaics converts light into electric current using the photoelectric effect.

Commercial concentrated solar power plants were first developed in the 1980s, and the 354 MW SEGS CSP installation is the largest solar power plant in the world and is located in the Mojave Desert of California. Other large CSP plants include the Solnova Solar Power Station (150 MW) and the Andasol solar power station (100 MW), both in

Spain. The 97 MW Sarnia Photovoltaic Power Plant in Canada, is the world's largest photovoltaic plant.

Applications



Average insolation showing land area (small black dots) required to replace the world primary energy supply with solar electricity. 18 TW is 568 Exajoule (EJ) per year. Insolation for most people is from 150 to 300 W/m² or 3.5 to 7.0 kWh/m²/day.

Solar power has great potential, but in 2008 supplied less than 0.02% of the world's total energy supply. There are many competing technologies, including fourteen types of photovoltaic cells, such as thin film, monocrystalline silicon, polycrystalline silicon, and amorphous cells, as well as multiple types of concentrating solar power. It is too early to know which technology will become dominant.

The earliest significant application of solar cells was as a back-up power source to the Vanguard I satellite in 1958, which allowed it to continue transmitting for over a year after its chemical battery was exhausted. The successful operation of solar cells on this mission was duplicated in many other Soviet and American satellites, and by the late 1960s, PV had become the established source of power for them. Photovoltaics went on to play an essential part in the success of early commercial satellites such as Telstar, and they remain vital to the telecommunications infrastructure today.

The high cost of solar cells limited terrestrial uses throughout the 1960s. This changed in the early 1970s when prices reached levels that made PV generation competitive in remote areas without grid access. Early terrestrial uses included powering telecommunication stations, off-shore oil rigs, navigational buoys and railroad crossings. These off-grid applications accounted for over half of worldwide installed capacity until 2004.

Building-integrated photovoltaics cover the roofs of an increasing number of homes.

The 1973 oil crisis stimulated a rapid rise in the production of PV during the 1970s and early 1980s. Economies of scale which resulted from increasing production along with improvements in system performance brought the price of PV down from 100 USD/watt in 1971 to 7 USD/watt in 1985. Steadily falling oil prices during the early 1980s led to a reduction in funding for photovoltaic R&D and a discontinuation of the tax credits associated with the Energy Tax Act of 1978. These factors moderated growth to approximately 15% per year from 1984 through 1996.

Since the mid-1990s, leadership in the PV sector has shifted from the US to Japan and Europe. Between 1992 and 1994 Japan increased R&D funding, established net metering guidelines, and introduced a subsidy program to encourage the installation of residential PV systems. As a result, PV installations in the country climbed from 31.2 MW in 1994

to 318 MW in 1999, and worldwide production growth increased to 30% in the late 1990s.

Germany became the leading PV market worldwide since revising its Feed-in tariff system as part of the Renewable Energy Sources Act. Installed PV capacity has risen from 100 MW in 2000 to approximately 4,150 MW at the end of 2007. After 2007, Spain became the largest PV market after adopting a similar feed-in tariff structure in 2004, installing almost half of the photovoltaics (45%) in the world, in 2008, while France, Italy, South Korea and the U.S. have seen rapid growth recently due to various incentive programs and local market conditions. Recent Studies have shown that the global PV market is forecast to exceed 16 GW in the year 2010. The power output of domestic photovoltaic devices is usually described in kilowatt-peak (kWp) units, as most are from 1 to 10 kW.

A significant problem with solar power is the capital installation cost, although cost has been decreasing due to the learning curve. Developing countries in particular may not have the funds to build solar power plants, although small solar applications are now replacing other sources in the developing world.

Concentrating solar power

Solar troughs are the most widely deployed.

Concentrating Solar Power (CSP) systems use lenses or mirrors and tracking systems to focus a large area of sunlight into a small beam. The concentrated heat is then used as a

heat source for a conventional power plant. A wide range of concentrating technologies exists; the most developed are the parabolic trough , the concentrating linear fresnel reflector, the Stirling dish and the solar power tower. Various techniques are used to track the Sun and focus light. In all of these systems a working fluid is heated by the concentrated sunlight, and is then used for power generation or energy storage.

A parabolic trough consists of a linear parabolic reflector that concentrates light onto a receiver positioned along the reflector's focal line. The receiver is a tube positioned right above the middle of the parabolic mirror and is filled with a working fluid. The reflector is made to follow the Sun during the daylight hours by tracking along a single axis. Parabolic trough systems provide the best land-use factor of any solar technology. The SEGS plants in California and Acciona's Nevada Solar One near Boulder City, Nevada are representatives of this technology. The Suntrof-Mulk parabolic trough, developed by Melvin Prueitt, uses a technique inspired by Archimedes' principle to rotate the mirrors.

Concentrating linear fresnel reflectors are CSP-plants which use many thin mirror strips instead of parabolic mirrors to concentrate sunlight onto two tubes with working fluid. This has the advantage that flat mirrors can be used which are much cheaper than parabolic mirrors, and that more reflectors can be placed in the same amount of space, allowing more of the available sunlight to be used. Concentrating linear fresnel reflectors can be used in either large or more compact plants.

A stirling solar dish, or dish engine system, consists of a stand-alone parabolic reflector that concentrates light onto a receiver positioned at the reflector's focal point. The reflector tracks the Sun along two axes. Parabolic dish systems give the highest efficiency among CSP technologies. The 50 kW Big Dish in Canberra, Australia is an example of this technology. The stirling solar dish combines a parabolic concentrating dish with a stirling heat engine which normally drives an electric generator. The advantages of stirling solar over photovoltaic cells are higher efficiency of converting sunlight into electricity and longer lifetime.

A solar power tower uses an array of tracking reflectors (heliostats) to concentrate light on a central receiver atop a tower. Power towers are more cost effective, offer higher efficiency and better energy storage capability among CSP technologies. The Solar Two in Barstow, California and the Planta Solar 10 in Sanlucar la Mayor, Spain are representatives of this technology.

Photovoltaics

11 MW Serpa solar power plant in Portugal

A solar cell, or photovoltaic cell (PV), is a device that converts light into electric current using the photoelectric effect. The first solar cell was constructed by Charles Fritts in the 1880s. In 1931 a German engineer, Dr Bruno Lange, developed a photo cell using silver selenide in place of copper oxide. Although the prototype selenium cells converted less than 1% of incident light into electricity, both Ernst Werner von Siemens and James Clerk Maxwell recognized the importance of this discovery. Following the work of Russell Ohl in the 1940s, researchers Gerald Pearson, Calvin Fuller and Daryl Chapin created the silicon solar cell in 1954. These early solar cells cost 286 USD/watt and reached efficiencies of 4.5–6%.

Development and deployment

Nellis Solar Power Plant, 14 MW power plant installed 2007 in Nevada, USA

The early development of solar technologies starting in the 1860s was driven by an expectation that coal would soon become scarce. However, development of solar technologies stagnated in the early 20th century in the face of the increasing availability, economy, and utility of coal and petroleum. In 1974 it was estimated that only six private homes in all of North America were entirely heated or cooled by functional solar power systems. The 1973 oil embargo and 1979 energy crisis caused a reorganization of energy policies around the world and brought renewed attention to developing solar technologies. Deployment strategies focused on incentive programs such as the Federal Photovoltaic Utilization Program in the US and the Sunshine Program in Japan. Other efforts included the formation of research facilities in the US (SERI, now NREL), Japan (NEDO), and Germany (Fraunhofer Institute for Solar Energy Systems ISE).

Between 1970 and 1983 photovoltaic installations grew rapidly, but falling oil prices in the early 1980s moderated the growth of PV from 1984 to 1996. Since 1997, PV development has accelerated due to supply issues with oil and natural gas, global warming concerns, and the improving economic position of PV relative to other energy technologies. Photovoltaic production growth has averaged 40% per year since 2000 and installed capacity reached 10.6 GW at the end of 2007, and 14.73 GW in 2008. As of November 2010, the largest photovoltaic (PV) power plants in the world are the

Finsterwalde Solar Park (Germany, 80.7 MW), Sarnia Photovoltaic Power Plant (Canada, 80 MW), Olmedilla Photovoltaic Park (Spain, 60 MW), the Strasskirchen Solar Park (Germany, 54 MW), the Lieberose Photovoltaic Park (Germany, 53 MW), and the Puertollano Photovoltaic Park (Spain, 50 MW).

World's largest photovoltaic power stations (50 MW or larger)

PV power station	Country	DC peak power (MW_p)	Notes
Sarnia Photovoltaic Power Plant	Canada	97	Constructed 2009-2010
Montalto di Castro Photovoltaic Power Station	Italy	84.2	Constructed 2009-2010
Finsterwalde Solar Park	Germany	80.7	Phase I completed 2009, phase II and III 2010
Rovigo Photovoltaic Power Plant	Italy	70	Completed November 2010
Olmedilla Photovoltaic Park	Spain	60	Completed September 2008
Strasskirchen Solar Park	Germany	54	
Lieberose Photovoltaic Park	Germany	53	Completed in 2009
Puertollano Photovoltaic Park	Spain	50	231,653 crystalline silicon modules, Suntech and Solaria, opened 2008

Commercial concentrating solar thermal power (CSP) plants were first developed in the 1980s. The 11 MW PS10 power tower in Spain, completed in late 2005, is Europe's first commercial CSP system, and a total capacity of 300 MW is expected to be installed in the same area by 2013. When built, the Ivanpah Solar Power Facility in southeastern California near the Nevada border is expected to have a capacity of 392 Megawatts.

Operational solar thermal power stations

Capacity (MW)	Name	Country	Location	Notes
354	Solar Energy Generating Systems	USA	Mojave Desert California	Collection of 9 units
150	Solnova Solar Power Station	Spain	Seville	Completed 2010
100	Andasol solar power station	Spain	Granada	Completed 2009
64	Nevada Solar One	USA	Boulder City, Nevada	
50	Ibersol Ciudad Real	Spain	Puertollano, Ciudad Real	Completed May 2009

50 Alvarado I	Spain	Badajoz	Completed July 2009
50 Extresol 1	Spain	Torre de Miguel Sesmero (Badajoz)	Completed February 2010
50 La Florida	Spain	Alvarado (Badajoz)	completed July 2010

Economics

The U.S. Energy Information Administration calculates that, all-told, electricity from a Solar PV plants costs 4 times that of conventional coal. Bloomburg energy estimates that solar power costs about $275 per megawatt-hour to produce compared with $60 for a coal-fired power plant. Nevertheless, there are exceptions-- Nellis Air Force Base is receiving photoelectric power for about 2.2 ¢/kWh and grid power for 9 ¢/kWh. Also, since PV systems use no fuel and modules typically last 25 to 40 years, the International Conference on Solar Photovoltaic Investments, organized by EPIA, has estimated that PV systems will pay back their investors in 8 to 12 years. As a result, since 2006 it has been economical for investors to install photovoltaics for free in return for a long term power purchase agreement. Fifty percent of commercial systems were installed in this manner in 2007 and it is expected that 90% will by 2009.

Concentrated Solar Power (CSP) facilities produce power more cheaply than photovoltaic systems and may eventually be price-competitive with conventional power plants. The Ivanpah Solar Power Facility is expected to produce power at costs comparable to natural gas.

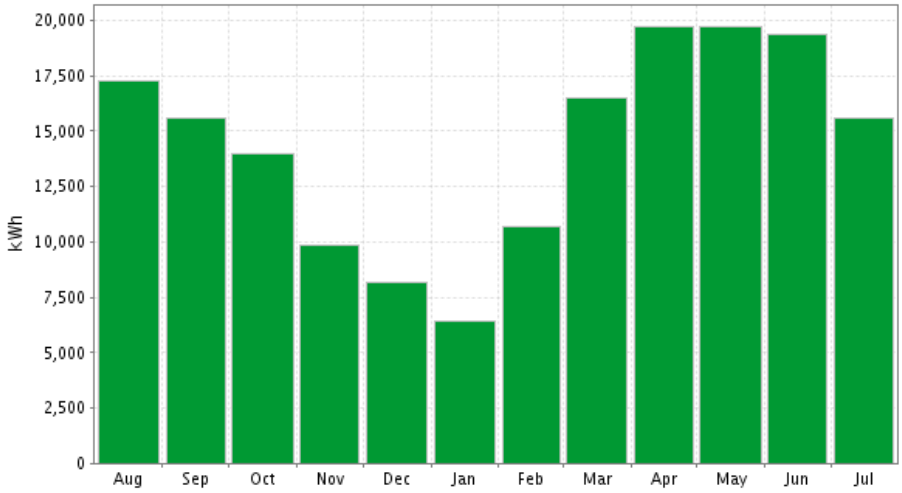
Additionally, governments have created various financial incentives to encourage the use of solar power. Renewable portfolio standards impose a government mandate that utilities generate or acquire a certain percentage of renewable power regardless of increased energy procurement costs. In most states, RPS goals can be achieved by any combination of solar, wind, biomass, landfill gas, ocean, geothermal, municipal solid waste, hydroelectric, hydrogen, or fuel cell technologies. In Canada the RESOP (Renewable Energy Standard Offer Program), introduced in 2006, and updated in 2009 with the passage of the Green Energy Act, allows residential homeowners in Ontario with solar panel installations to sell the energy they produce back to the grid (i.e., the government) at 42¢/kWh, while drawing power from the grid at an average rate of 6¢/kWh. The program is designed to help promote the government's green agenda and lower the strain often placed on the energy grid at peak hours. In March, 2009 the proposed FIT was increased to 80¢/kWh for small, roof-top systems (≤10 kW).

One financial disincentive to solar power is the large land area required. A 1000 Megawatt CSP facility requires 6000 acres of land while a similar coal-fired plant requires less than 640 acres of land. Producing 1000 Megawatts from photovoltaics requires over 12,000 acres of land. In the United States, power companies may avoid purchasing land by leasing public land from the federal government to develop solar power facilities; however this entails different costs such as rental fees, megawatt

surcharges, and the cost of compliance with a complex and time-consuming federal permitting process.

Energy storage methods

This energy park in Geesthacht, Germany, includes solar panels and pumped-storage hydroelectricity.



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

Solar energy is not available at night, making energy storage an important issue in order to provide the continuous availability of energy. Both wind power and solar power are intermittent energy sources, meaning that all available output must be taken when it is

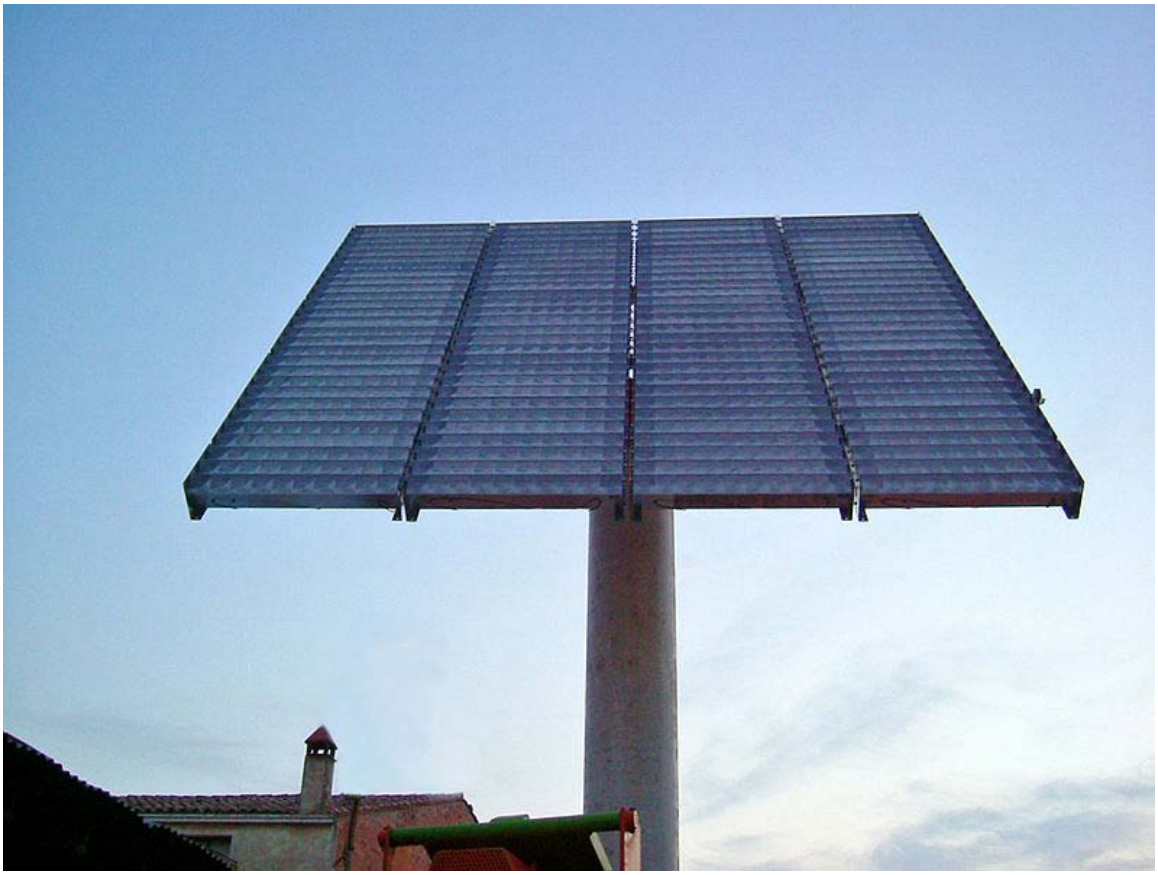
available and either stored for *when* it can be used, or transported, over transmission lines, to *where* it can be used. Wind power and solar power tend to be somewhat complementary, as there tends to be more wind in the winter and more sun in the summer, but on days with no sun and no wind the difference needs to be made up in some manner. The Institute for Solar Energy Supply Technology of the University of Kassel pilot-tested a combined power plant linking solar, wind, biogas and hydrostorage to provide load-following power around the clock, entirely from renewable sources.

Solar energy can be stored at high temperatures using molten salts. Salts are an effective storage medium because they are low-cost, have a high specific heat capacity and can deliver heat at temperatures compatible with conventional power systems. The Solar Two used this method of energy storage, allowing it to store 1.44 TJ in its 68 m^3 storage tank, enough to provide full output for close to 39 hours, with an efficiency of about 99%.

Off-grid PV systems have traditionally used rechargeable batteries to store excess electricity. With grid-tied systems, excess electricity can be sent to the transmission grid. Net metering programs give these systems a credit for the electricity they deliver to the grid. This credit offsets electricity provided from the grid when the system cannot meet demand, effectively using the grid as a storage mechanism. Credits are normally rolled over month to month and any remaining surplus settled annually.

Pumped-storage hydroelectricity stores energy in the form of water pumped when surplus electricity is available, from a lower elevation reservoir to a higher elevation one. The energy is recovered when demand is high by releasing the water: the pump becomes a turbine, and the motor a hydroelectric power generator.

Experimental solar power



Concentrating photovoltaics in Catalonia, Spain

Concentrated photovoltaics (CPV) systems employ sunlight concentrated onto photovoltaic surfaces for the purpose of electrical power production. Solar concentrators of all varieties may be used, and these are often mounted on a solar tracker in order to keep the focal point upon the cell as the Sun moves across the sky. Luminescent solar concentrators (when combined with a PV-solar cell) can also be regarded as a CPV system. Luminescent solar concentrators are useful as they can improve performance of PV-solar panels drastically.

Thermoelectric, or "thermovoltaic" devices convert a temperature difference between dissimilar materials into an electric current. First proposed as a method to store solar energy by solar pioneer Mouchout in the 1800s, thermoelectrics reemerged in the Soviet Union during the 1930s. Under the direction of Soviet scientist Abram Ioffe a concentrating system was used to thermoelectrically generate power for a 1 hp engine. Thermogenerators were later used in the US space program as an energy conversion technology for powering deep space missions such as Cassini, Galileo and Viking. Research in this area is focused on raising the efficiency of these devices from 7–8% to 15–20%.

Space-based solar power is a theoretical design for the collection of solar power in space, for use on Earth. SBSP differs from the usual method of solar power collection in that the solar panels used to collect the energy would reside on a satellite in orbit, often referred to as a solar power satellite (SPS), rather than on Earth's surface. In space, collection of the Sun's energy is unaffected by the day/night cycle, weather, seasons, or the filtering effect of Earth's atmospheric gases. Average solar energy per unit area outside Earth's atmosphere is on the order of ten times that available on Earth's surface. However, there is no shortage of energy reaching the surface. The amount of solar energy reaching the surface of the planet each year is about twice the amount of energy that will be obtained forever from coal, oil, natural gas, and mined Uranium, combined, even using breeder reactors.