Emerging Energy Technologies

Michaele Curley

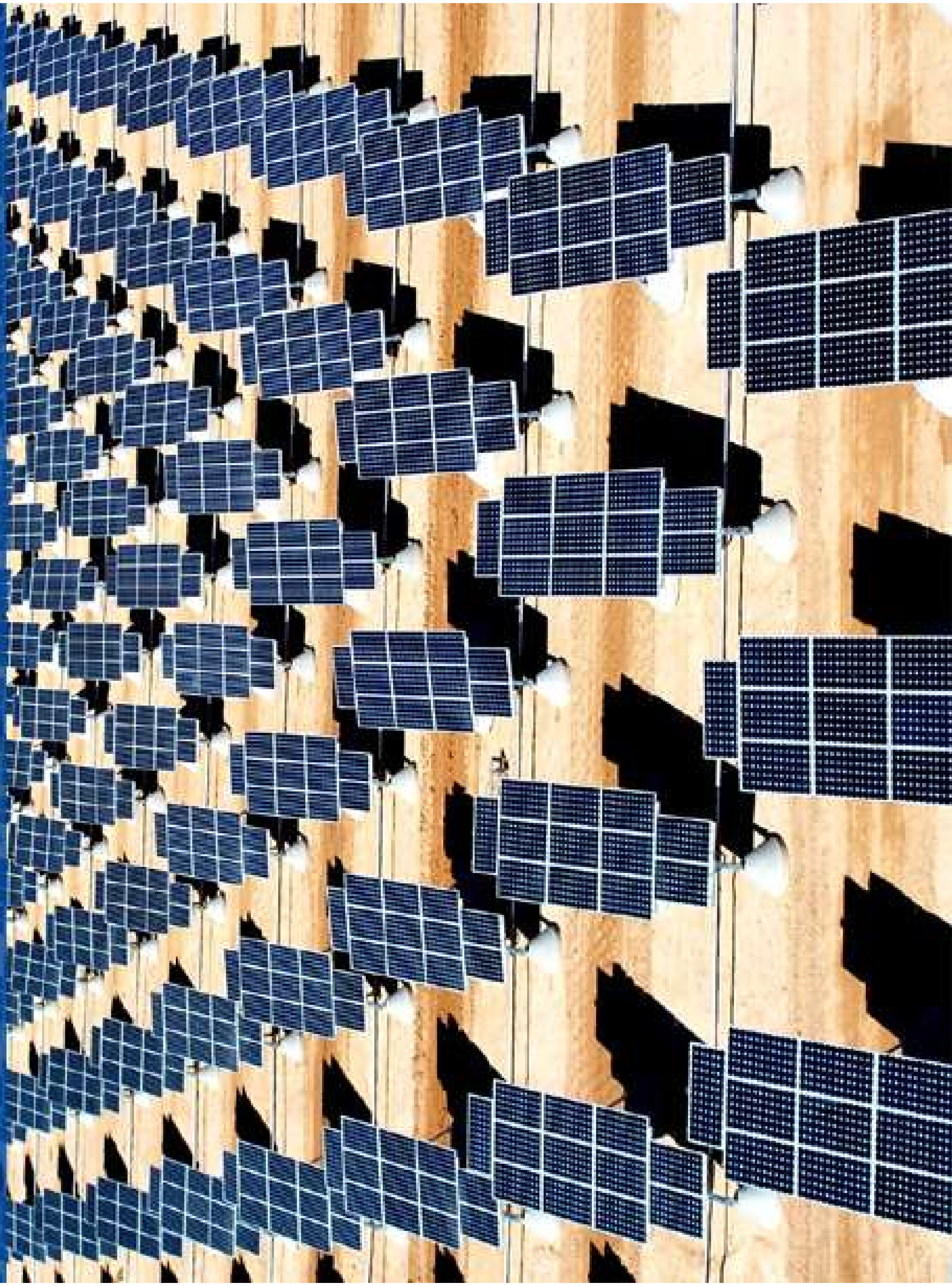

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Table of Contents

Chapter- 1

Concentrated Solar Power

The PS10 Solar Power Plant concentrates sunlight from a field of heliostats onto a central solar power tower.

Concentrated solar power (**CSP**) are systems that use lenses or mirrors to concentrate a large area of sunlight, or solar thermal energy, onto a small area. Electrical power is produced when the concentrated light is converted to heat which drives a heat engine (usually a steam turbine) connected to an electrical power generator.

CSP should not be confused with photovoltaics, where solar power is directly converted to electricity without the use of steam turbines. The concentration of sunlight onto photovoltaic surfaces, similar to CSP, is known as concentrated photovoltaics (CPV).

History

Concentrated sunlight has been used to perform useful tasks from the time of ancient China. A legend has it that Archimedes used a "burning glass" to concentrate sunlight on the invading Roman fleet and repel them from Syracuse. In 1973 a Greek scientist, Dr. Ioannis Sakkas, curious about whether Archimedes could really have destroyed the Roman fleet in 212 BC lined up nearly 60 Greek sailors, each holding an oblong mirror tipped to catch the Sun's rays and direct them at a tar-covered plywood silhouette 160 feet away. The ship caught fire after a few minutes; however, historians continue to doubt the Archimedes story.

In 1866, Auguste Mouchout used a parabolic trough to produce steam for the first solar steam engine. The first patent for a Solar Collector was obtained by the Italian Alessandro Battaglia in Genoa, Italy, in 1886. Over the following years, inventors such as John Ericsson and Frank Shuman developed concentrating solar-powered devices for irrigation, refrigeration, and locomotion. In 1913 Shuman finished a 55 HP parabolic solar thermal energy station in Meadi, Egypt for irrigation. Another Genoese, Professor Giovanni Francia (1911–1980), designed and built the first solar concentrated plant which entered in operation in Sant'Ilario, near Genoa, Italy in 1968. This plant had the architecture of today's solar concentrated plants with a solar receiver in the center of a field of solar collectors. The plant was able to produce 1 MW with superheated steam at 100 bar and 500 degrees celsius. The 10 MW Solar One power tower was developed in Southern California in 1981 but the parabolic trough technology of the nearby Solar Energy Generating Systems (SEGS), begun in 1984, was more workable. The 354 MW SEGS is still the largest solar power plant in the world.

Current technology

CSP is used to produce renewable heat or cool or electricity (called solar thermoelectricity, usually generated through steam). Concentrated solar technology systems use lenses or mirrors and tracking systems to focus a large area of sunlight onto a small area. The concentrated light is then used as heat or as a heat source for a conventional power plant (solar thermoelectricity).

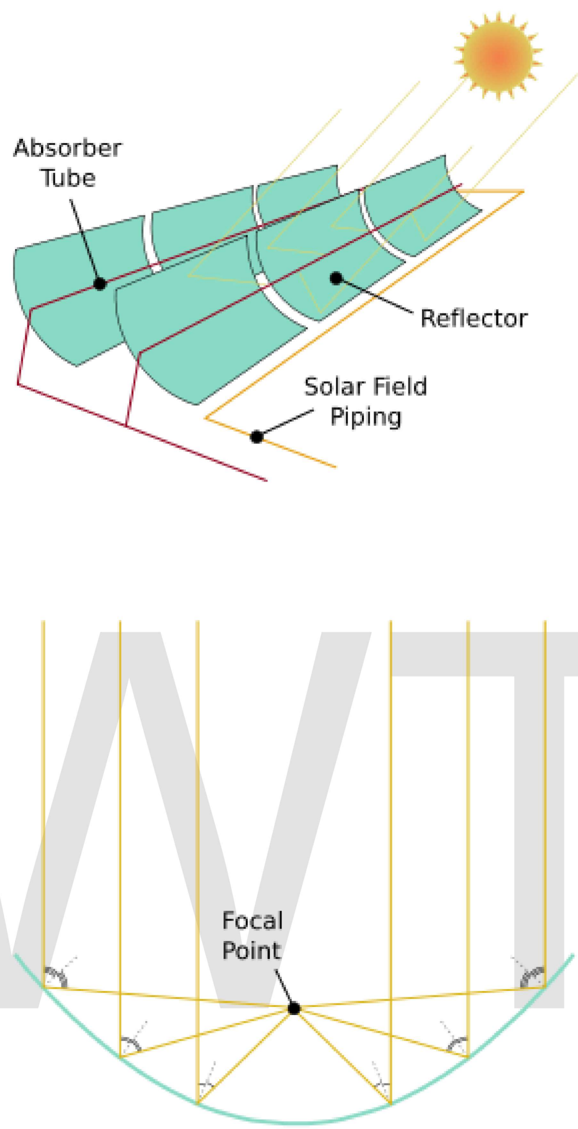
Concentrating technologies exist in four common forms, namely parabolic trough, dish stirlings, concentrating linear fresnel reflector, and solar power tower. Each concentration method is capable of producing high temperatures and correspondingly high thermodynamic efficiencies, but they vary in the way that they track the Sun and focus light. Due to new innovations in the technology, concentrating solar thermal is becoming more and more cost-effective.

Parabolic trough

A parabolic trough is the most widely deployed and proven type of solar thermal power technology.

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 directly above the middle of the parabolic mirror and is filled with a working fluid. The reflector follows the Sun during the daylight hours by tracking along a single axis. A working fluid (e.g. molten salt) is heated to 150–350 °C (423–623 K (302–662 °F)) as it flows through the receiver and is then used as a heat source for a power generation system. Trough systems are the most developed CSP technology. The Solar Energy Generating Systems (SEGS) plants in California, Acciona's Nevada Solar One near Boulder City, Nevada, and Plataforma Solar de Almería's SSPS-DCS plant in Spain are representative of this technology.

Array of parabolic troughs at the National Solar Energy Center in Israel



A diagram of a parabolic trough solar farm (top) and an end view of how a parabolic collector focuses sunlight onto its focal point.

A parabolic trough is a type of solar thermal energy collector. It is constructed as a long parabolic mirror (usually coated silver or polished aluminum) with a Dewar tube running its length at the focal point. Sunlight is reflected by the mirror and concentrated on the Dewar tube. The trough is usually aligned on a north-south axis, and rotated to track the sun as it moves across the sky each day.

Alternatively the trough can be aligned on an east-west axis, this reduces the overall efficiency of the collector, due to cosine loss, but only requires the trough to be aligned with the change in seasons, avoiding the need for tracking motors. This tracking method works correctly at the spring and fall equinoxes with errors in the focusing of the light at other times during the year (the magnitude of this error varies throughout the day, taking a minimum value at solar noon). There is also an error introduced due to the daily motion of the sun across the sky, this error also reaches a minimum at solar noon. Due to these sources of error, seasonally adjusted parabolic troughs are generally designed with a lower solar concentration ratio. In order to increase the level of alignment, some measuring devices have also been invented.

Heat transfer fluid (usually oil) runs through the tube to absorb the concentrated sunlight. This increases the temperature of the fluid to some 400°C. The heat transfer fluid is then used to heat steam in a standard turbine generator. The process is economical and, for heating the pipe, thermal efficiency ranges from 60-80%. The overall efficiency from collector to grid, i.e. (Electrical Output Power)/(Total Impinging Solar Power) is about 15%, similar to PV (Photovoltaic Cells) but less than Stirling dish concentrators.

Current commercial plants utilizing parabolic troughs are hybrids; fossil fuels are used during night hours, but the amount of fossil fuel used is limited to a maximum 27% of electricity production, allowing the plant to qualify as a renewable energy source. Because they are hybrids and include cooling stations, condensers, accumulators and other things besides the actual solar collectors, the power generated per square meter of area varies enormously.

Types of mirrors

Usually, mirrors are used which are parabolic and are of a single piece. In addition, V-type parabolic troughs exist which are made from 2 mirrors and placed at an angle towards each other.

Mirror coatings

In 2009, scientists at the National Renewable Energy Laboratory (NREL) and SkyFuel teamed to develop large curved sheets of metal that have the potential to be 30% less expensive than today's best collectors of concentrated solar power by replacing glass-based models with a silver polymer sheet that has the same performance as the heavy glass mirrors, but at a much lower cost and much lower weight. It also is much easier to deploy and install. The glossy film uses several layers of polymers, with an inner layer of pure silver.

Energy storage

As this renewable source of energy is inconsistent by nature, methods for energy storage have been studied, for instance the single-tank (thermocline) storage technology for large-scale solar thermal power plants. The thermocline tank approach uses a mixture of silica sand and quartzite rock to displace a significant portion of the volume in the tank. Then it is filled with the heat transfer fluid, typically a molten nitrate salt.

Existing plants

The largest operational solar power system at present is one of the SEGS plants and is located at Kramer Junction in California, USA, with five fields of 33 MW generation capacity each.

The 64 MW Nevada Solar One also uses this technology. In the new Spanish plant, Andasol 1 solar power station, the 'Eurotrough'-collector is used. This plant went online in November 2008 and has a nominal output of 49.9 MW.

Fresnel lens

These 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 reflector can come in large plants or more compact plants.

Compact Linear Fresnel Reflector

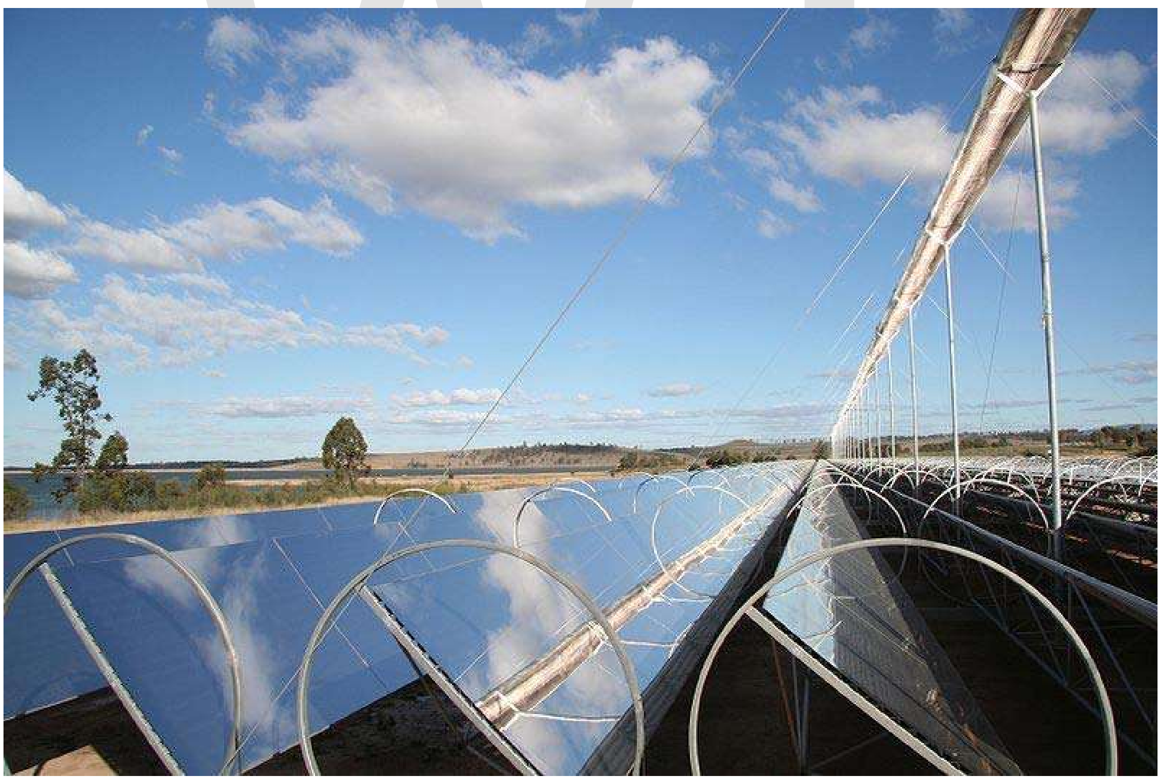


Fig.1: Example of a Traditional Linear Fresnel Reflector with one absorber

A **Concentrating Linear Fresnel Reflector** (**CLFR**) – also referred to as a **Compact Linear Fresnel Reflector -** is a specific type of Linear Fresnel Reflector (LFR) technology. Linear Fresnel Reflectors use long, thin segments of mirrors to focus sunlight onto a fixed absorber located at a common focal point of the reflectors. These mirrors are capable of concentrating the sun's energy to approximately 30 times its normal intensity. This concentrated energy is transferred through the absorber into some thermal fluid (this is typically oil capable of maintaining liquid state at very high temperatures). The fluid then goes through a heat exchanger to power a steam generator. As opposed to traditional LFR's, the CLFR utilizes multiple absorbers within the vicinity of the mirrors.

History

The first Linear Fresnel Reflector was developed in Italy in 1961 by Giorgio Francia of the University of Genoa. Francia demonstrated that such a system could create elevated temperatures capable of making a fluid do work. The technology was further investigated by companies such as the FMC Corporation during the 1973 oil crisis, but remained relatively untouched until the early 1990s. In 1993, the first CLFR was developed at the University of Sydney in 1993 and patented in 1995. In 1999, the CLFR design was enhanced by the introduction of the advanced absorber.

Design

Reflectors

The reflectors are located at the base of the system and converge the sun's rays into the absorber. A key component that makes all LFR's more advantageous than traditional parabolic trough mirror systems is the use of Fresnel reflectors. These reflectors make use of the Fresnel lens effect, which allows for a concentrating mirror with a large aperture and short focal length while simultaneously reducing the volume of material required for the reflector. This greatly reduces the system's cost since sagged-glass parabolic reflectors are typically very expensive. It should be noted, however, that in recent years thin-film nanotechnology has significantly reduced the cost of parabolic mirrors.

A major challenge that must be addressed in any solar concentrating technology is the changing intensity of the incident rays (the rays of sunlight striking the mirrors) as the sun progresses throughout the day. The reflectors of a CLFR are typically aligned in a north-south orientation and turn about a single axis using a computer controlled solar tracker system. This allows the system to maintain the proper angle of incidence between the sun's rays and the mirrors, thereby optimizing energy transfer.

Absorbers

The absorber is located at the focal point of the mirrors. It runs parallel to and above the reflector segments to transport radiation into some working thermal fluid. The basic design of the absorber for the CLFR system is an inverted air cavity with a glass cover enclosing insulated steam tubes, shown in Fig.2. This design has been demonstrated to be simple and cost effective with good optical and thermal performance.

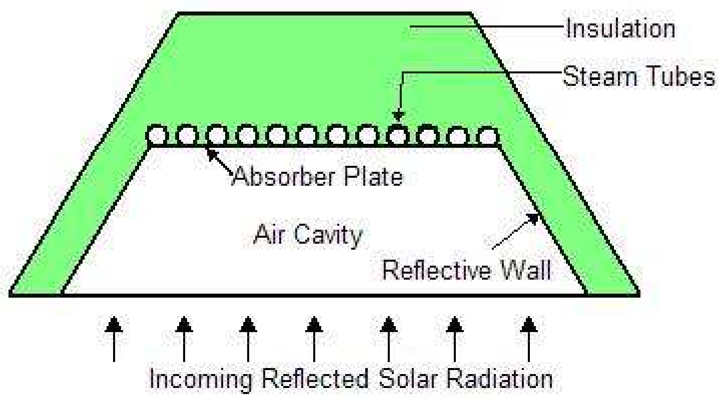


Fig.2: Incident solar rays are concentrated on insulated steam tubes to heat working thermal fluid

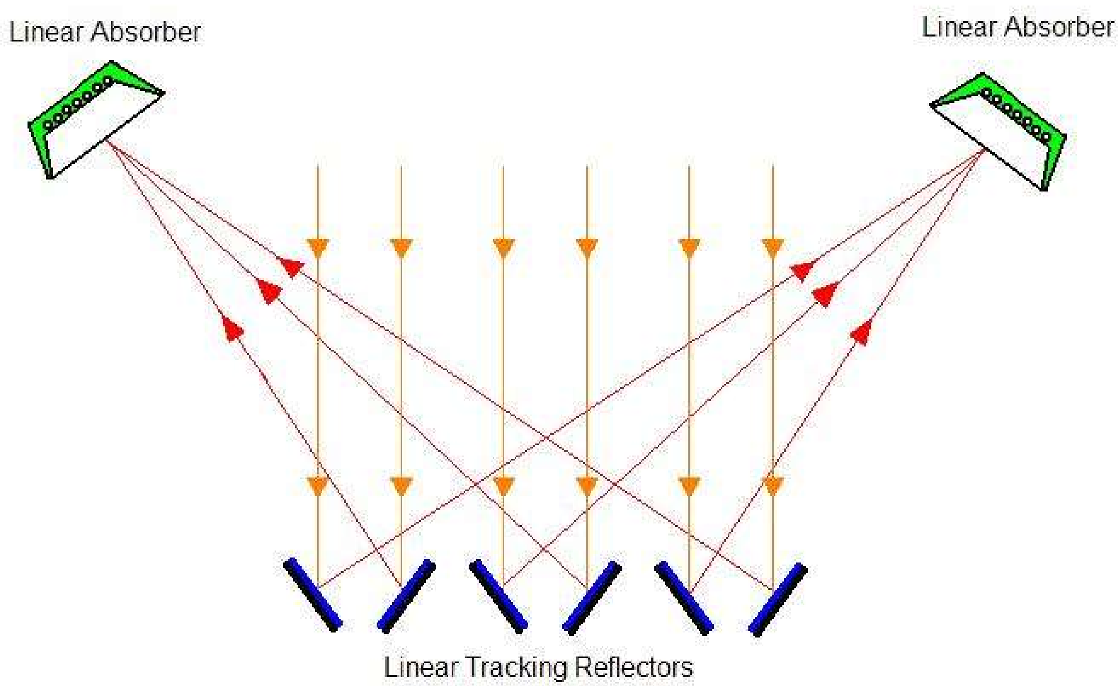


Fig.3: CLFR solar systems use alternate the inclination of their mirrors to focus solar energy on multiple absorbers, improving system efficiency and reducing overall cost.

For optimum performance of the CLFR, several design factors of the absorber must be optimized.

- First, heat transfer between the absorber and the thermal fluid must be maximized. This relies on the surface of the steam tubes being selective. A selective surface optimizes the ratio of energy absorbed to energy emitted. Acceptable surfaces generally absorb 96% of incident radiation while emitting only 7% through infra-red radiation. Electro-chemically deposited black chrome is generally used for its ample performance and ability to withstand high temperatures.

- Second, the absorber must be designed so that the temperature distribution across the selective surface is uniform. Non-uniform temperature distribution leads to accelerated degradation of the surface. Typically, a uniform temperature of 300 °C (573 K; 572 °F) is desired. Uniform distributions are obtained by changing absorber parameters such as the thickness of insulation above the plate, the size of the aperture of the absorber and the shape and depth of the air cavity.

As opposed to the traditional LFR, the CLFR makes use of multiple absorbers within the vicinity of its mirrors. These additional absorbers allow the mirrors to alternate their inclination, as illustrated in Fig. 3. This arrangement is advantageous for several reasons.

- First, alternating inclinations minimize the effect of reflectors blocking adjacent reflectors' access to sunlight, thereby improving the systems efficiency.
- Second, multiple absorbers minimize the amount of ground space required for installation. This in turn reduces cost to procure and prepare the land.
- Finally, having the panels in close proximity reduces the length of absorber lines, which reduces both thermal losses through the absorber lines and overall cost for the system.

Applications

In March 2009, the German company Novatec Biosol constructed the Fresnel solar power plant known as PE 1. The solar thermal power plant is based on CLFR technology and has an electrical capacity of 1.4 MW. PE 1 comprises a solar boiler with mirror surface of approximately 18,000 m^2 (1.8 ha; 4.4 acres). The steam is generated by concentrating sunlight directly onto a linear receiver, which is 7.40 metres (24.28 ft) above the ground. An absorber tube is positioned in the focal line of the mirror field where water is heated into 270 °C (543 K; 518 °F) saturated steam. This steam in turn powers a generator.

The commercial success of the PE 1 has led Novatec Biosol to design a 30 MW solar power plant known as PE 2. PE 2 will be constructed in Murcia, Spain in 2010. Novatec Biosol has also obtained permits for another 60 MW of related projects.

In April 2008, the solar thermal company AREVA Solar (Ausra) opened a large factory in Las Vegas, Nevada that will produce linear Fresnel reflectors. The factory will be capable of producing enough solar collectors to provide 200 MW of power per month.

AREVA Solar (Ausra) has finished construction of the 5 MW Kimberlina Solar Thermal Energy plant in Bakersfield, California. This is the first commercial linear Fresnel reflector plant in the United States. The solar collectors were produced at the Ausra factory in Las Vegas.

AREVA Solar (Ausra) also built and operates a linear fresnel reflector plant in New South Wales, Australia. This reflector plant supplements the 2,000 MW coal-fired Liddell Power Station. The power generated by the solar thermal steam system is used to provide electricity for the plant's operation, offsetting the plant’s internal power usage.

Dish stirling

Dish engine systems eliminate the need to transfer heat to a boiler by placing a Stirling engine at the focal point.

A dish stirling 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. The working fluid in the receiver is heated to 250–700 °C (523–973 K (482–1,292 °F)) and then used by a Stirling engine to generate power. Parabolic dish systems provide the highest solar-to-electric efficiency among CSP technologies, and their modular nature provides scalability. The Stirling Energy Systems (SES) and Science Applications International Corporation (SAIC) dishes at UNLV, and Australian National University's Big Dish in Canberra, Australia are representative of this technology.

Solar power tower

A solar power tower consists of an array of dual-axis tracking reflectors (heliostats) that concentrate light on a central receiver atop a tower; the receiver contains a fluid deposit, which can consist of sea water. The working fluid in the receiver is heated to 500–1000 °C (773–1,273 K (932–1,832 °F)) and then used as a heat source for a power generation or energy storage system. Power tower development is less advanced than trough systems, but they offer higher efficiency and better energy storage capability. The Solar Two in Daggett, California and the Planta Solar 10 (PS10) in Sanlucar la Mayor, Spain are representative of this technology. eSolar's 5 MW Sierra SunTower located in Lancaster, California and is the only CSP tower facility operating in North America.

Efficiency

For thermodynamic solar systems, the maximum solar-to-work (ex: electricity) efficiency η can be deduced by considering both thermal radiation properties and Carnot's principle. Indeed, solar irradiations must first be converted into heat via a solar receiver with an efficiency $\eta_{Receiver}$, then this heat is converted into work with the Carnot efficiency η_{Carnot}. Hence, for a solar receiver providing a heat source at temperature T_H and a heat sink at temperature T° (e.g.: atmosphere at T° = 300 K):

$\eta = \eta_{Receiver} * \eta_{Carnot}$

with $\eta_{Carnot} = 1 - \frac{T^0}{T_H}$

and $\eta_{Receiver} = \frac{Q_{absorbed} - Q_{lost}}{Q_{solar}}$

where Q_{solar}, $Q_{absorbed}$, Q_{lost} are respectively the incoming solar flux and the fluxes absorbed and lost by the system solar receiver.

For a solar flux I (e.g. $I = 1000$ W/m^2) concentrated C times with an efficiency η_{Optics} on the system solar receiver with a collecting area A and an absorptivity α:

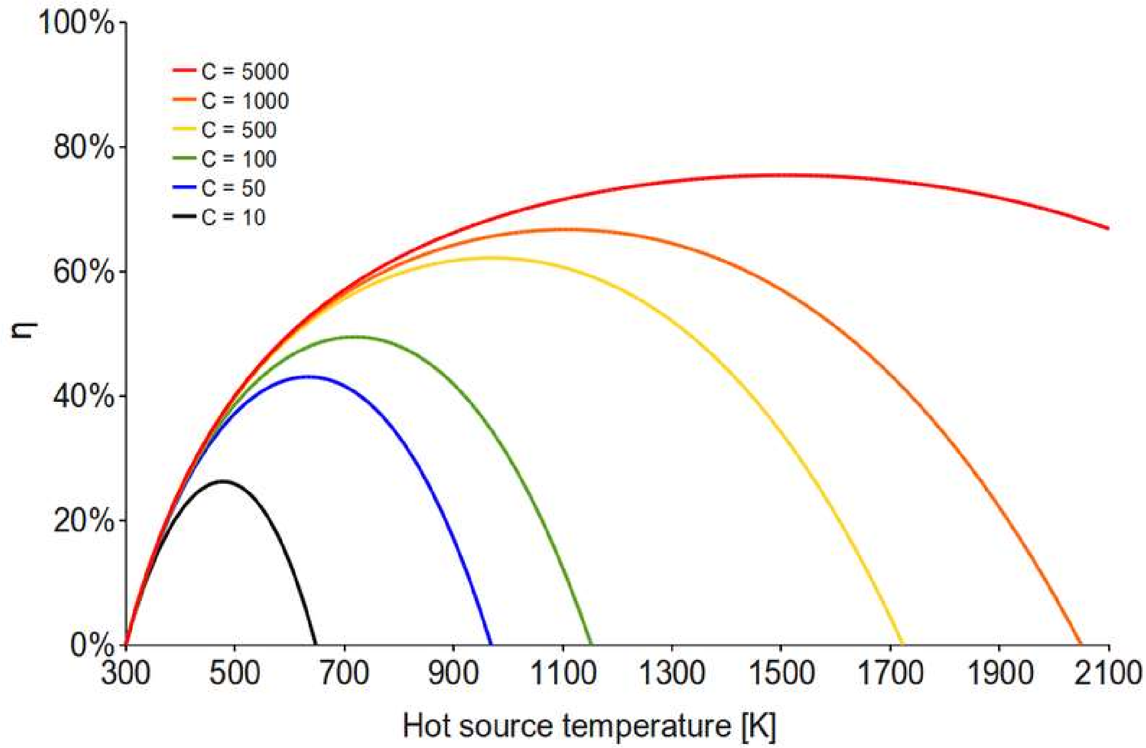
$Q_{solar} = \eta_{Optics} ICA$,
$Q_{absorbed} = \alpha Q_{solar}$,

For simplicity's sake, one can assume that the losses are only radiative ones (fair assumption for high temperatures), thus for a reradiating area a and an emissivity ε applying the Stefan-Boltzmann law yields:

$$Q_{lost} = a\epsilon\sigma T_H^4$$

Simplifying these equations by considering perfect optics ($\eta_{Optics} = 1$), collecting and reradiating areas equal and maximum absorptivity and emissivity (α = 1, ε = 1) then injecting them in the first equation gives,

$$\eta = (1 - \frac{\sigma T_H^4}{IC})(1 - \frac{T^0}{T_H})$$



One sees that efficiency does not simply increase monotonically with the receiver temperature. Indeed, the higher the temperature, the higher the Carnot's efficiency, but also the lower the receiver efficiency. Hence, the maximum reachable temperature (i.e.: when the receiver efficiency is null, blue curve on the figure below) is:

$$T_{max} = (\frac{IC}{\sigma})^{0.25}$$

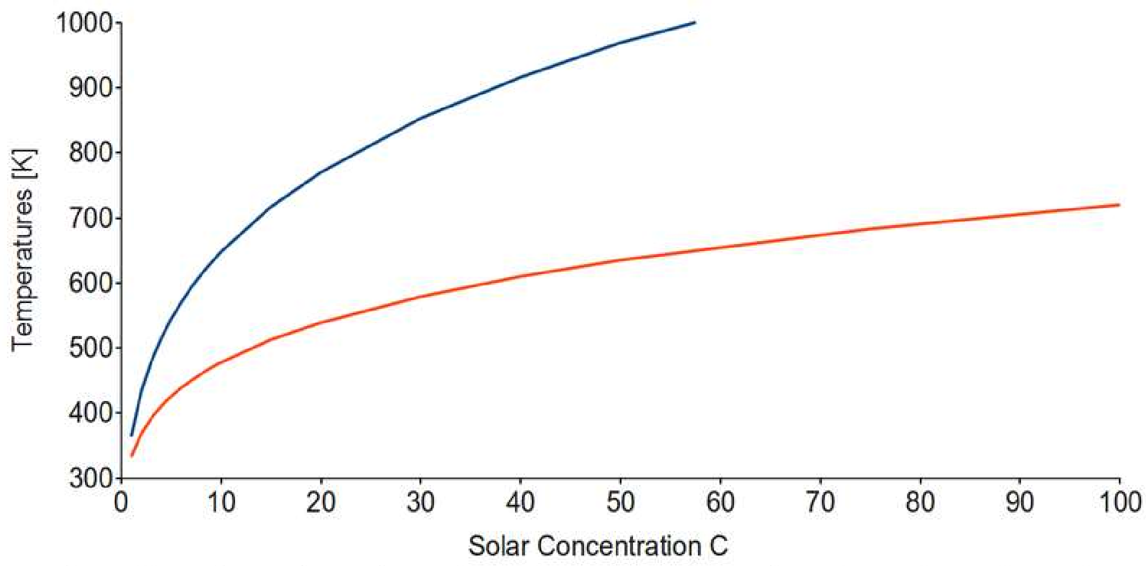
There is a temperature T_{opt} for which the efficiency is maximum, i.e. when the efficiency derivative relative to the receiver temperature is null:

$$\frac{d\eta}{dT_H}(T_{opt}) = 0$$

Consequently, this lead us to the following equation:

$$T_{opt}^5 - (0.75T^0)T_{opt}^4 - \frac{T^0 IC}{4\sigma} = 0$$

Solving numerically this equation allows to obtain the optimum process temperature according to the solar concentration ratio *C* (red curve on the figure below)



C	500	1000	5000	10000	45000 (max. for Earth)
T_{max}	1720	2050	3060	3640	5300
T_{opt}	970	1100	1500	1720	2310

Costs

As of September 9, 2009; 16 months ago, the cost of building a CSP station was typically about $2.5 to $4 per watt, while the fuel (the sun's radiation) is free. Therefore a 250 MW CSP station would have cost $600–1000 million to build. That works out to 12 to 18 cents per kilowatt-hour.

Future of CSP

A study done by Greenpeace International, the European Solar Thermal Electricity Association, and the International Energy Agency's SolarPACES group investigated the potential and future of concentrated solar power. The study found that concentrated solar power could account for up to 25% of the world's energy needs by 2050. The increase in investment would be from 2 billion euros worldwide to 92.5 billion euros in that time period. Spain is the leader in concentrated solar power technology, with more than 50 projects approved by the government in the works. Also, it exports its technology, further increasing the technology's stake in energy worldwide. Because of the nature of the technology needing a desert like area, experts predicted the biggest growth in places like Africa, Mexico, the southwest United States. The study examined three different outcomes for this technology: no increases in CSP technology, investment continuing as it has been in Spain and the US, and finally the true potential of CSP without any barriers on its growth. The findings of the third part are shown in the table below:

Time	Investment	Capacity
2015	21 billion euros a year	420 megawatts
2050	174 billion euros a year	1500 gigawatts

Finally, the study acknowledged how technology for CSP was improving and how this would result in a drastic price decrease by 2050. It predicted a drop from the current range of .23 to .15 euros per kilowatthour, down to .14 to .10 euros a kilowatthour. Recently the EU has begun to look into developing a €400 billion ($774 billion) solar power plant based in the Sahara region using CSP technology known as Desertec. It is part of a wider plan to create "a new carbon-free network linking Europe, the Middle East and North Africa". The plan is backed mainly by German industrialists and predicts production of 15% of Europe's power by 2050. Morocco is a major partner in Desertec and as it has barely 1% of the electricity consumption of the EU, it will produce more than enough energy for the entire country with a large energy surplus to deliver to Europe.

Other organizations expect CSP to cost $0.06(US)/kWh by 2015 due to efficiency improvements and mass production of equipment. That would make CSP as cheap as conventional power. Investors such as venture capitalist Vinod Khosla expect CSP to continuously reduce costs and actually be cheaper than coal power after 2015.

On September 9, 2009; 16 months ago, Bill Weihl, Google.org's green energy czar said that the firm was conducting research on the heliostat mirrors and gas turbine technology, which he expects will drop the cost of solar thermal electric power to less than $0.05/kWh in 2 or 3 years.

In 2009, scientists at the National Renewable Energy Laboratory (NREL) and SkyFuel teamed to develop large curved sheets of metal that have the potential to be 30% less expensive than today's best collectors of concentrated solar power by replacing glass-based models with a silver polymer sheet that has the same performance as the heavy glass mirrors, but at a much lower cost and much lower weight. It also is much easier to deploy and install. The glossy film uses several layers of polymers, with an inner layer of pure silver.

Chapter- 2

Solar Thermal Energy

Solar thermal system for water heating in Santorini, Greece

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

Low-temperature collectors

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

Heating, cooling, and ventilation

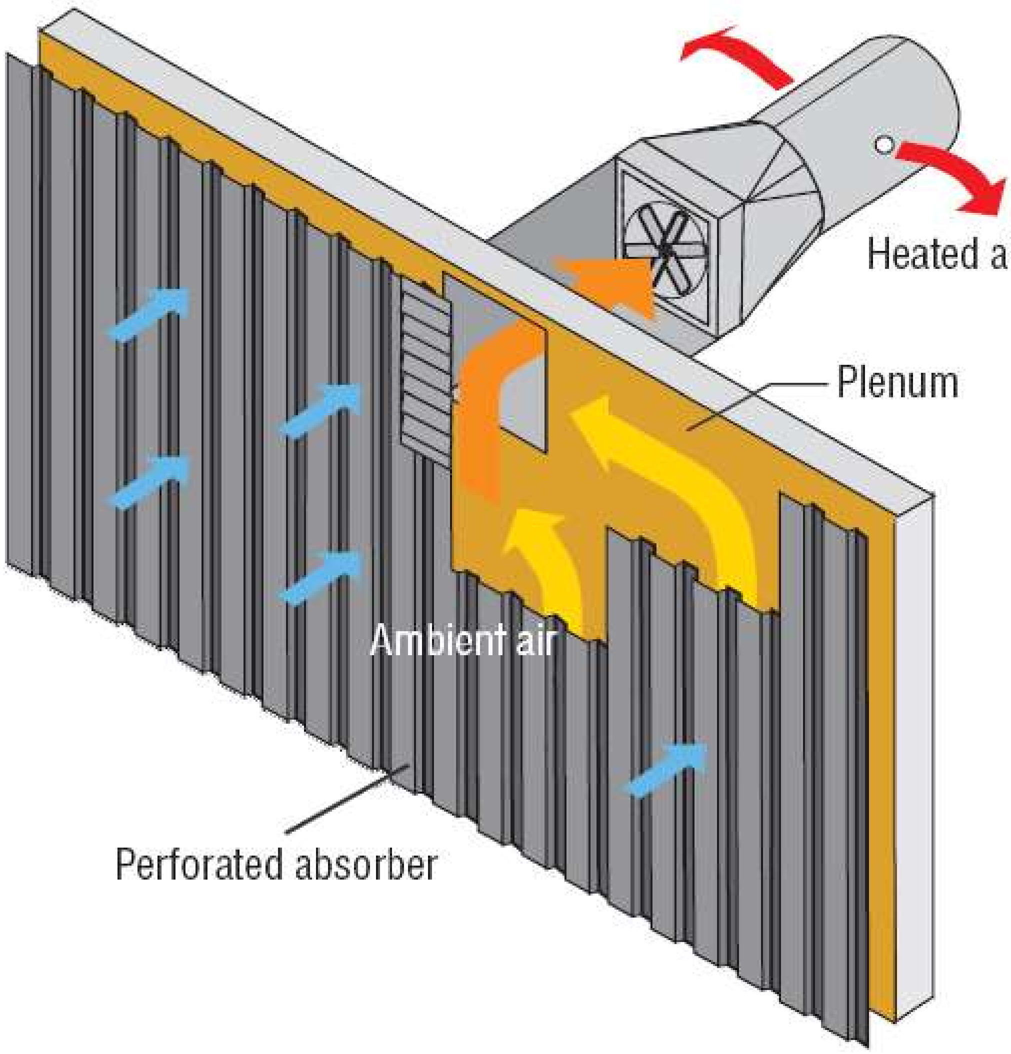
MIT's Solar House #1 built in 1939 used seasonal thermal storage for year round heating

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

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

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

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



Unglazed, "transpired" air collector

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

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

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

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

Process heat

Solar Evaporation Ponds in the Atacama Desert

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

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

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

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

Medium-temperature collectors

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

Solar drying

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

Cooking

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

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

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

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

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

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

Distillation

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

High-temperature collectors

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

Concentrated solar power plant using parabolic trough design

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

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

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

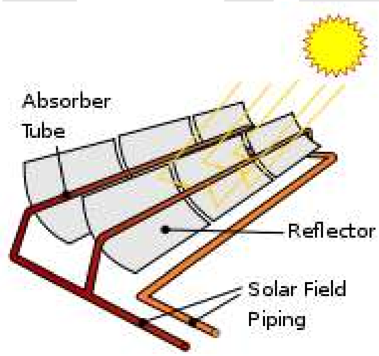
Since the CSP plant generates heat first of all, it can store the heat before conversion to electricity. With current technology, storage of heat is much cheaper and more efficient than storage of electricity. In this way, the CSP plant can produce electricity day and night. If the CSP site has predictable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

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

System designs

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

Parabolic trough designs



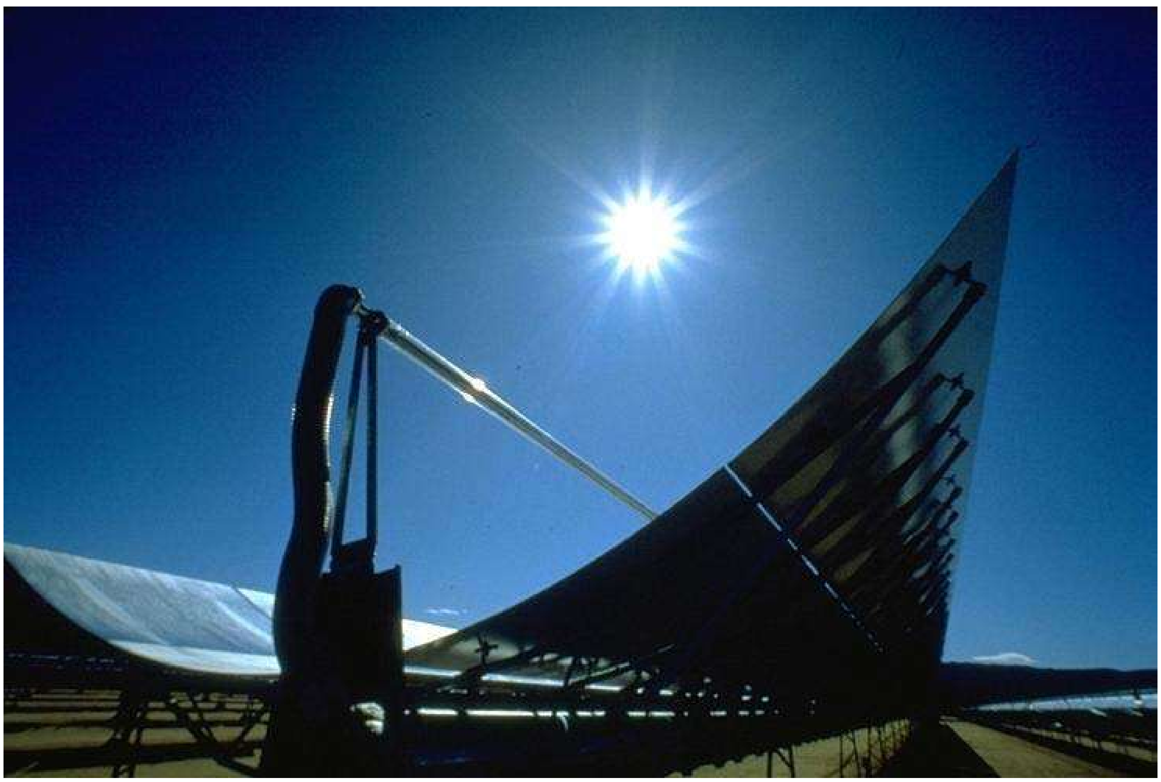
Sketch of a parabolic trough design. A change of position of the sun parallel to the receiver does not require adjustment of the mirrors.

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

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

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

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



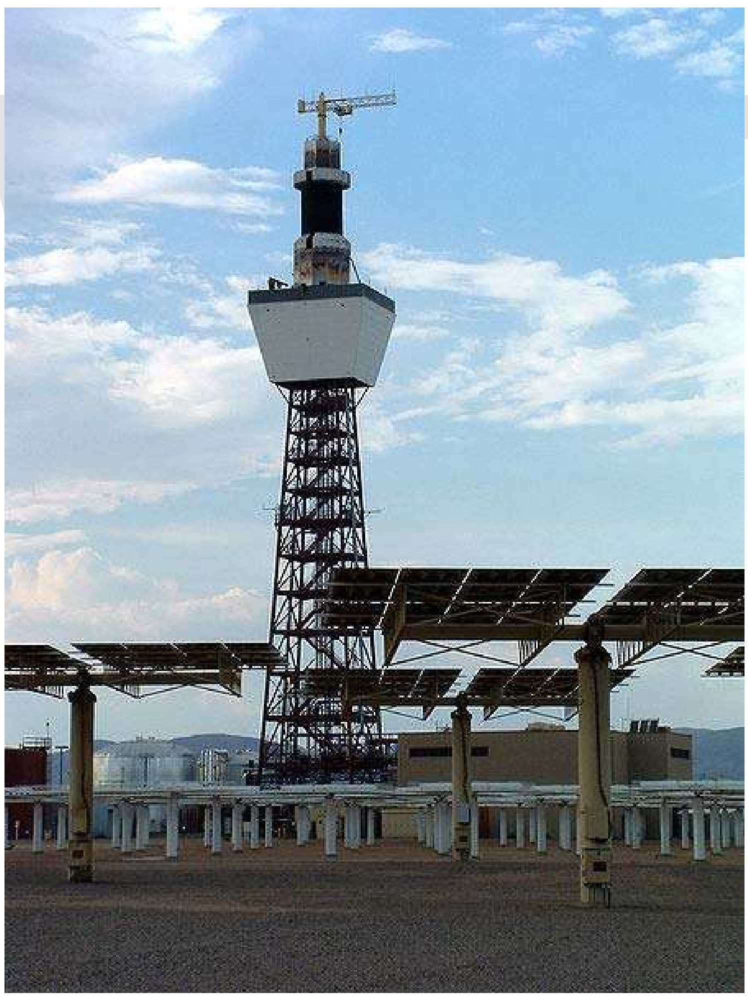
Concentrating solar power systems are a fast growing source of sustainable energy

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

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

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

Power tower designs



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

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

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

> *Some or all of the following reads like a press release or commercial promotion, please assist by rewriting, simplifying, and trimming as needed*

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

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

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

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

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

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

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

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

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

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

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

Dish designs

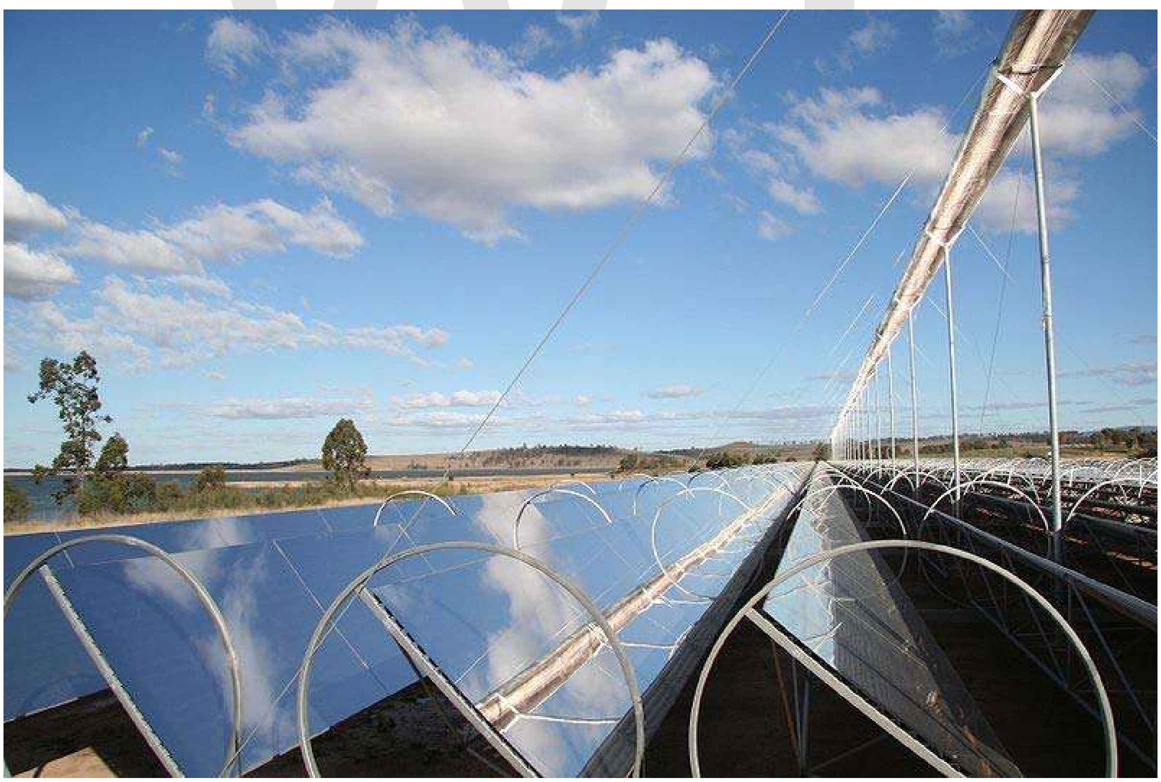
A parabolic solar dish concentrating the sun's rays on the heating element of a Stirling engine. The entire unit acts as a solar tracker.

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

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

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

Fresnel reflectors



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

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

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

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

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

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

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

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

Linear Fresnel reflector technologies

Fresnel solar power plant PE 1 in southern Spain

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

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

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

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

Fresnel lenses

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

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

MicroCSP

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

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

Heat exchange

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

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

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

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

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

Heat storage

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

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

Steam accumulator

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

Molten salt storage

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

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

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

Graphite heat storage

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

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

Phase-change materials for storage

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

Use of water

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

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

Conversion rates from solar energy to electrical energy

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

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

The gross conversion efficiencies (taking into account that the solar dishes or troughs occupy only a fraction of the total area of the power plant) are determined by net generating capacity over the solar energy that falls on the total area of the solar plant. The 500-megawatt (MW) SCE/SES plant would extract about 2.75% of the radiation (1 kW/m^2) that falls on its 4,500 acres (18.2 km^2). For the 50 MW AndaSol Power Plant that is being built in Spain (total area of 1,300×1,500 m = 1.95 km^2) gross conversion efficiency comes out at 2.6%

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

Levelised cost

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

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

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

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

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

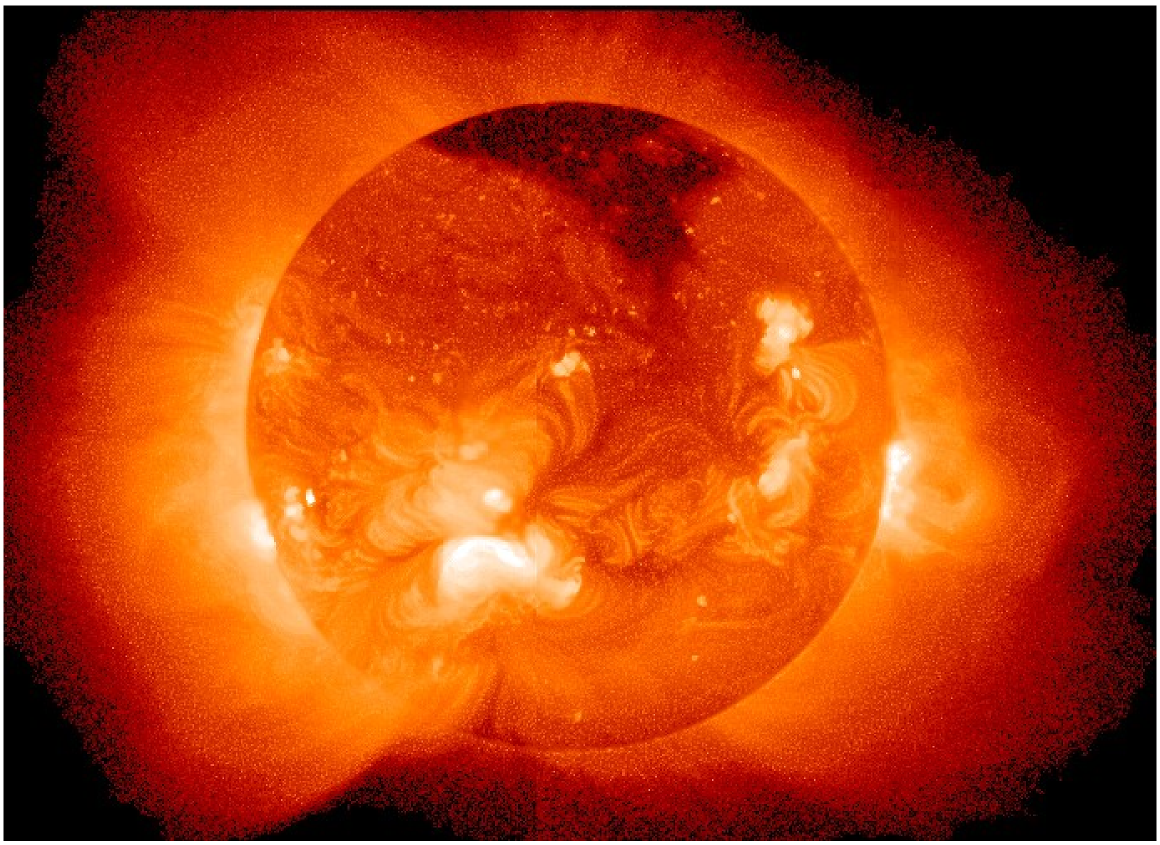
If the cost per kWh may follow the inflation, then the inflation rate can be added to the interest rate. If an investor puts his money on the bank for 7%, then he is not compensated for inflation. However, if the cost per kWh is raised with inflation, then he is compensated and he can add 2% (a normal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

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

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

Chapter- 3

Fusion Power

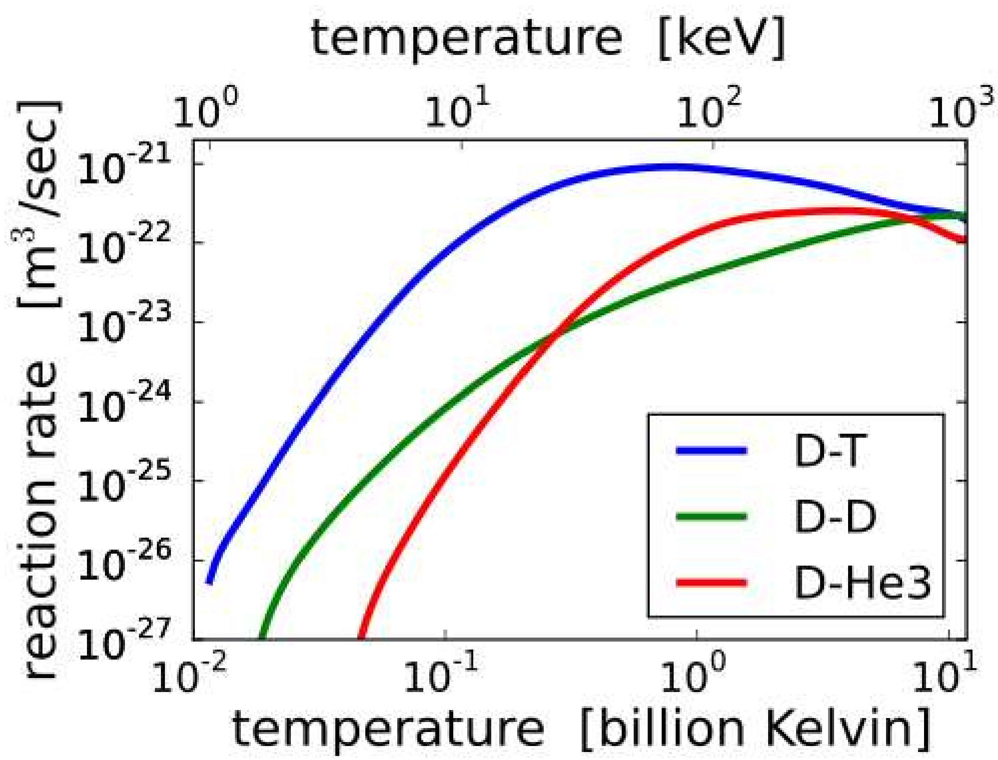


The Sun is a natural fusion reactor

Fusion power is the power generated by nuclear fusion reactions. In this kind of reaction, two light atomic nuclei fuse together to form a heavier nucleus and in doing so, release a large amount of energy. In a more general sense, the term can also refer to the production of net usable power from a fusion source, similar to the usage of the term "steam power." Most design studies for fusion power plants involve using the fusion reactions to create heat, which is then used to operate a steam turbine, which drives generators to produce electricity. Except for the use of a thermonuclear heat source, this is similar to most coal, oil, and gas-fired power stations as well as fission-driven nuclear power stations.

As of July 2010, the largest experiment has been the Joint European Torus (JET). In 1997, JET produced a peak of 16.1 megawatts (21,600 hp) of fusion power (65% of input power), with fusion power of over 10 MW (13,000 hp) sustained for over 0.5 sec. In June of 2005, the construction of a new experimental reactor, ITER, was announced by the six parties involved in the project. These include the U.S., China, the European Union (EU), India, Japan, the Russian Federation, and South Korea. Page text. ITER is designed to produce ten times more fusion power than the power put into the plasma over many minutes, 50MW of input energy to produce 500MW of output energy. Project partners were preparing the site in 2008. The production of net electrical power from fusion is planned for DEMO, the next-generation experiment to follow ITER. Additionally, the European Union High Power laser Energy Research facility (HiPER) is undergoing preliminary design for potential construction starting around 2010.

Fuel cycle



The fusion reaction rate increases rapidly with temperature until it maximizes and then gradually drops off. The DT rate peaks at a lower temperature (about 70 keV, or 800 million kelvins) and at a higher value than other reactions commonly considered for fusion energy.

The basic concept behind any fusion reaction is to bring two or more atoms close enough together so that the residual strong force (nuclear force) in their nuclei will pull them together into one larger atom. If two light nuclei fuse, they will generally form a single nucleus with a slightly smaller mass than the sum of their original masses (though this is not always the case). The difference in mass is released as energy according to Albert Einstein's mass-energy equivalence formula $E = mc^2$. If the input atoms are sufficiently massive, the resulting fusion product will be heavier than the sum of the reactants' original masses, in which case the reaction requires an external source of energy. The dividing line between "light" and "heavy" is iron-56. Above this atomic mass, energy will generally be released by nuclear fission reactions; below it, by fusion.

Fusion between the atoms is opposed by their shared electrical charge, specifically the net positive charge of the protons in the nucleus. To overcome this electrostatic force, or "Coulomb barrier", some external source of energy must be supplied. The easiest way to do this is to heat the atoms, which has the side effect of stripping the electrons from the atoms and leaving them as bare nuclei. In most experiments the nuclei and electrons are left in a fluid known as a plasma. The temperatures required to provide the nuclei with enough energy to overcome their repulsion is a function of the total charge, so hydrogen, which has the smallest nuclear charge therefore reacts at the lowest temperature. Helium has an extremely low mass per nucleon and therefore is energetically favoured as a fusion product. As a consequence, most fusion reactions combine isotopes of hydrogen ("protium", deuterium, or tritium) to form isotopes of helium (^{3}He or ^{4}He).

The reaction **cross section**, denoted σ, is a measure of the probability of a fusion reaction as a function of the relative velocity of the two reactant nuclei. If the reactants have a distribution of velocities, as is the case in a thermal distribution within a plasma, then it is useful to perform an average over the distributions of the product of cross section and velocity. The reaction rate (fusions per volume per time) is <σv> times the product of the reactant number densities:

$$f = (\tfrac{1}{2}n)^2 \langle\sigma v\rangle \text{ (for one reactant)}$$
$$f = n_1 n_2 \langle\sigma v\rangle \text{ (for two reactants)}$$

<σv> increases from virtually zero at room temperatures up to meaningful magnitudes at temperatures of 10–100 keV (2.2–22 fJ). The significance of <σv> as a function of temperature in a device with a particular energy confinement time is found by considering the Lawson criterion.

Perhaps the three most widely considered fuel cycles are based on the D-T, D-D, and p-^{11}B reactions. Other fuel cycles (D-^{3}He and ^{3}He-^{3}He) would require a supply of ^{3}He, either from other nuclear reactions or from extraterrestrial sources, such as the surface of the moon or the atmospheres of the gas giant planets. The details of the calculations comparing these reactions can be found here.

D-T fuel cycle

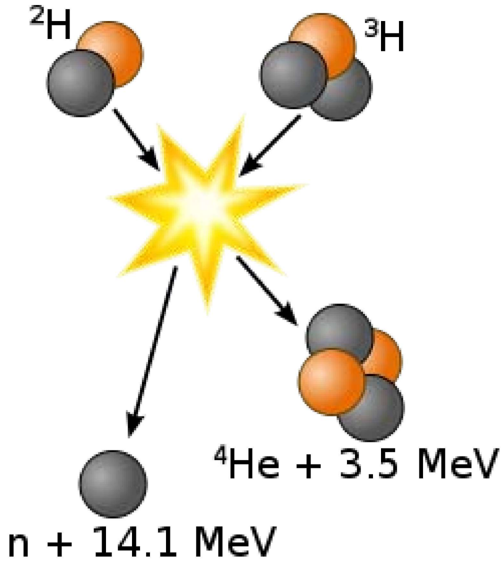


Diagram of the D-T reaction

The easiest (according to the Lawson criterion) and most immediately promising nuclear reaction to be used for fusion power is:

$$2/1\text{D} + 3/1\text{T} \rightarrow 4/2\text{He} + 1/0\text{n}$$

Hydrogen-2 (Deuterium) is a naturally occurring isotope of hydrogen and as such is universally available. The large mass ratio of the hydrogen isotopes makes the separation rather easy compared to the difficult uranium enrichment process. Hydrogen-3 (Tritium) is also an isotope of hydrogen, but it occurs naturally in only negligible amounts due to its radioactive half-life of 12.32 years. Consequently, the deuterium-tritium fuel cycle requires the breeding of tritium from lithium using one of the following reactions:

$$1/0\text{n} + 6/3\text{Li} \rightarrow 3/1\text{T} + 42\text{He}$$
$$1/0\text{n} + 7/3\text{Li} \rightarrow 3/1\text{T} + 4/2\text{He} + 1/0\text{n}$$

The reactant neutron is supplied by the D-T fusion reaction shown above, the one that also produces the useful energy. The reaction with ^{6}Li is exothermic, providing a small energy gain for the reactor. The reaction with ^{7}Li is endothermic but does not consume the neutron. At least some ^{7}Li reactions are required to replace the neutrons lost by reactions with other elements. Most reactor designs use the naturally occurring mix of lithium isotopes. However, the supply of lithium is relatively limited with other applications such as Li-ion batteries increasing its demand.

Several drawbacks are commonly attributed to D-T fusion power:

1. It produces substantial amounts of neutrons that result in induced radioactivity within the reactor structure.

2. Only about 20% of the fusion energy yield appears in the form of charged particles (the rest neutrons), which limits the extent to which direct energy conversion techniques might be applied.
3. The use of D-T fusion power depends on lithium resources, which are less abundant than deuterium resources. However, lithium is relatively abundant on earth.
4. It requires the handling of the radioisotope tritium. Similar to hydrogen, tritium is difficult to contain and may leak from reactors in some quantity. Some estimates suggest that this would represent a fairly large environmental release of radioactivity.

The neutron flux expected in a commercial D-T fusion reactor is about 100 times that of current fission power reactors, posing problems for material design. Design of suitable materials is under way but their actual use in a reactor is not proposed until the generation after ITER. After a single series of D-T tests at JET, the largest fusion reactor yet to use this fuel, the vacuum vessel was sufficiently radioactive that remote handling needed to be used for the year following the tests.

In a production setting, the neutrons would be used to react with lithium in order to create more tritium. This also deposits the energy of the neutrons in the lithium, which would then be cooled to remove this energy and drive electrical production. This reaction protects the outer portions of the reactor from the neutron flux. Newer designs, the advanced tokamak in particular, also use lithium inside the reactor core as a key element of the design. The plasma interacts directly with the lithium, preventing a problem known as "recycling". The advantage of this layout was demonstrated in the Lithium Tokamak Experiment.

D-D fuel cycle

Though more difficult to facilitate than the deuterium-tritium reaction, fusion can also be achieved through the reaction of deuterium with itself. This reaction has two branches that occur with nearly equal probability:

$$
\begin{aligned}
{}^{2}H + {}^{2}H &\rightarrow {}^{3}H + {}^{1}H \\
&\rightarrow {}^{3}He + n
\end{aligned}
$$

The optimum temperature for this reaction is 15 keV, only slightly higher than the optimum for the D-T reaction. The first branch does not produce neutrons, but it does produce tritium, so that a D-D reactor will not be completely tritium-free, even though it does not require an input of tritium or lithium. Most of the tritium produced will be burned before leaving the reactor, which reduces the tritium handling required, but also means that more neutrons are produced and that some of these are very energetic. The neutron from the second branch has an energy of only 2.45 MeV (0.393 pJ), whereas the neutron from the D-T reaction has an energy of 14.1 MeV (2.26 pJ), resulting in a wider range of isotope production and material damage. Assuming complete tritium burn-up, the reduction in the fraction of fusion energy carried by neutrons is only about 18%, so that the primary advantage of the D-D fuel cycle is that tritium breeding is not required. Other advantages are independence from limitations of lithium resources and a somewhat softer neutron spectrum. The price to pay compared to D-T is that the energy confinement (at a given pressure) must be 30 times better and the power produced (at a given pressure and volume) is 68 times less.

D-^{3}He fuel cycle

A second-generation approach to controlled fusion power involves combining helium-3 (^{3}He) and deuterium (^{2}H). This reaction produces a helium-4 nucleus (^{4}He) and a high-energy proton. As with the p-^{11}B aneutronic fusion fuel cycle, most of the reaction energy is released as charged particles, reducing activation of the reactor housing and potentially allowing more efficient energy harvesting (via any of several speculative technologies). In practice, D-D side reactions produce a significant number of neutrons, resulting in p-^{11}B being the preferred cycle for aneutronic fusion.

p-^{11}B fuel cycle

If aneutronic fusion is the goal, then the most promising candidate may be the Hydrogen-1 (proton)/boron reaction:

$$^1H + {}^{11}B \rightarrow 3\ {}^4He$$

Under reasonable assumptions, side reactions will result in about 0.1% of the fusion power being carried by neutrons. At 123 keV, the optimum temperature for this reaction is nearly ten times higher than that for the pure hydrogen reactions, the energy confinement must be 500 times better than that required for the D-T reaction, and the power density will be 2500 times lower than for D-T. Since the confinement properties of conventional approaches to fusion such as the tokamak and laser pellet fusion are marginal, most proposals for aneutronic fusion are based on radically different confinement concepts, such as the Polywell and the Dense plasma focus.

History of research

Brief overview

The idea of using human-initiated fusion reactions was first made practical for military purposes in nuclear weapons. In a hydrogen bomb, the energy released by a fission weapon is used to compress and heat fusion fuel, beginning a fusion reaction that releases a large amount of neutrons that increases the rate of fission. The first fission-fusion-fission-based weapons released some 500 times more energy than early fission weapons.

Attempts at controlling fusion had already started by this point. Registration of the first patent related to a fusion reactor by the United Kingdom Atomic Energy Authority, the inventors being Sir George Paget Thomson and Moses Blackman, dates back to 1946.

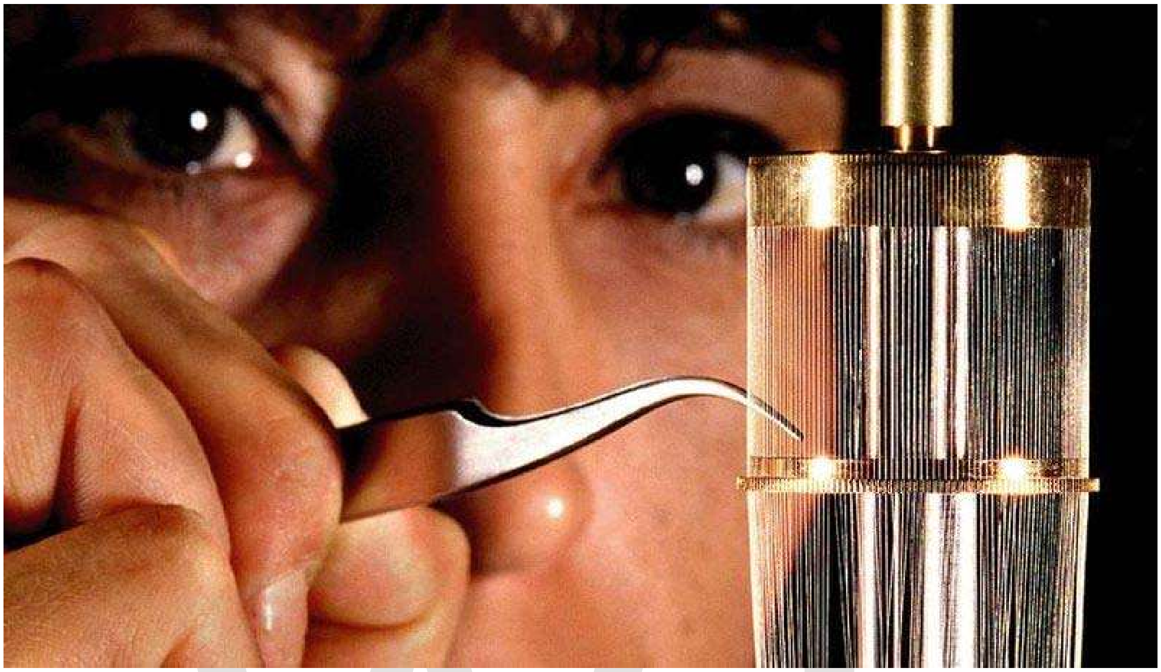
This was the first detailed examination of the pinch concept, and small efforts to experiment with the pinch concept started at several sites in the UK.

Around the same time, an expatriate German proposed the Huemul Project in Argentina, announcing positive results in 1951. Although these results turned out to be false, it sparked off intense interest around the world. The UK pinch programs were greatly expanded, culminating in the ZETA and Sceptre devices. In the US, pinch experiments like those in the UK started at the Los Alamos National Laboratory. Similar devices were built in the USSR after data on the UK program was passed to them by Klaus Fuchs. At Princeton University a new approach developed as the stellarator, and the research establishment formed there continues to this day as the Princeton Plasma Physics Laboratory. Not to be outdone, Lawrence Livermore National Laboratory entered the field with their own variation, the magnetic mirror. These three groups have remained the primary developers of fusion research in the US to this day.

In the time since these early experiments, two new approaches developed that have since come to dominate fusion research. The first was the tokamak approach developed in the Soviet Union, which combined features of the stellarator and pinch to produce a device that dramatically outperformed either. The majority of magnetic fusion research to this day has followed the tokamak approach. In the late 1960s the concept of "mechanical" fusion through the use of lasers was developed in the US, and Lawrence Livermore switched their attention from mirrors to lasers over time.

Civilian applications are still being developed. Although it took less than ten years for fission to go from military applications to civilian fission energy production, it has been very different in the fusion energy field; more than fifty years have already passed without any commercial fusion energy production plant coming into operation.

Pinch devices



A "wires array" used in Z-pinch confinement, during the building process

A major area of study in early fusion power research is the "pinch" concept. Pinch is based on the fact the plasmas are electrically conducting. By running a current through the plasma, a magnetic field will be generated around the plasma. This field will, according to Lenz's law, create an inward directed force that causes the plasma to collapse inward, raising its density. Denser plasmas generate denser magnetic fields, increasing the inward force, leading to a chain reaction. If the conditions are correct, this can lead to the densities and temperatures needed for fusion. The trick is getting the current into the plasma; this is solved by inducing the current from an external magnet, which also produces the external field the internal field acts against.

Pinch was first developed in the UK in the immediate post-war era. Starting in 1947 small experiments were carried out and plans were laid to build a much larger machine. When the Huemul results hit the news, James L. Tuck, a UK physicist working at Los Alamos, introduced the pinch concept in the US and produced a series of machines known as the Perhapsatron. In the Soviet Union, a series of similar machines were being built, unknown in the west. All of these devices quickly demonstrated a series of instabilities in the fusion when the pinch was applied, which broke up the plasma column long before it reached the densities and temperatures needed for fusion. In 1953 Tuck and others suggested a number of solutions to these problems.

The largest "classic" pinch device was the ZETA, including all of these upgrades, starting operations in the UK in 1957. In early 1958 John Cockcroft announced that fusion had been achieved in the ZETA, an announcement that made headlines around the world. When physicists in the US expressed concerns about the claims they were initially dismissed. However, US experiments demonstrated the same neutrons, although measurements suggested these could not be from fusion reactions. The neutrons seen in the UK were later demonstrated to be from different versions of the same instability processes that plagued earlier machines. Cockcroft was forced to retract the fusion claims, which tainted the entire field for years. ZETA ended its experiments in 1968, and most other pinch experiments ended shortly after.

In 1974 a study of the ZETA results demonstrated an interesting side-effect; after the experimental runs ended, the plasma would enter a short period of stability. This led to the reversed field pinch concept which has seen some level of development ever since. Recent work on the basic concept started as a result of the appearance of the "wires array" concept in the 1980s, which allowed a more efficient use of this technique. The Sandia National Laboratory runs a continuing wire-array research program with the Zpinch machine. In addition, the University of Washington's ZaP Lab has shown quiescent periods of stability hundreds of times longer than expected for plasma in a Z-pinch configuration, giving promise to the confinement technique.

In 1995 staged Z-pinch concept was introduced by a team of scientist from University of California Irvine (UCI). This scheme can control one of the most dangerous instability that normally disintegrate conventional Z-pinch before the final implosion. The concept is based on a complex load of radiative liner plasma embedded with a target plasma. During implosion the outer surface of the liner plasma do becomes unstable but the target plasma remains remarkably stable, up until the final implosion, generating a very high energy density stable target plasma. The heating mechanisms are shock heating, adiabatic compression and trapping of charge particles produced in fusion reaction due to a very strong magnetic field, which develops between the liner and the target. Details of this concept are shown in various publications available on the web page of MIFTI.

Early magnetic approaches

The U.S. fusion program began in 1951 when Lyman Spitzer began work on a stellarator under the code name Project Matterhorn. His work led to the creation of the Princeton Plasma Physics Laboratory, where magnetically confined plasmas are still studied. Spitzer planned an aggressive development project of four machines, A, B, C, and D. A and B were small research devices, C would be the prototype of a power-producing machine, and D would be the prototype of a commercial device. A worked without issue, but even by the time B was being used it was clear the stellarator was also suffering from instabilities and plasma leakage. Progress on C slowed as attempts were made to correct for these problems.

At Lawrence Livermore, the magnetic mirror was the preferred approach. The mirror consisted of two large magnets arranged so they had strong fields within them, and a weaker, but connected, field between them. Plasma introduced in the area between the two magnets would "bounce back" from the stronger fields in the middle. Although the design would leak plasma through the mirrors, the rate of leakage would be low enough that a useful fusion rate could be maintained. The simplicity of the design was supposed to make up for its lower performance. In practice the mirror also suffered from mysterious leakage problems, and never reached the expected performance.

Gun Club, MHD, instability; progress slows

By the mid-1950s it was clear that the simple theoretical tools being used to calculate the performance of all fusion machines was simply not predicting their actual behaviour. Machines invariably leaked their plasma from their confinement area at rates far higher than predicted.

In 1954, Edward Teller held a gathering of fusion researchers at the Princeton Gun Club, near the Project Matterhorn (now known as Project Sherwood) grounds. Teller started by pointing out the problems that everyone was having, and suggested that any system where the plasma was confined within concave fields was doomed to fail. Attendees remember him saying something to the effect that the fields were like rubber bands, and they would attempt to snap back to a straight configuration whenever the power was increased, ejecting the plasma. He went on to say that it appeared the only way to confine the plasma in a stable configuration would be to used convex fields, a "cusp" configuration.

When the meeting concluded, most of the researchers quickly turned out papers saying why Teller's concerns did not apply to their particular device. The pinch machines did not use magnetic fields in this way at all, while the mirror and stellarator seemed to have various ways outs. However, this was soon followed by a paper by Martin David Kruskal and Martin Schwarzschild discussing pinch machines, which demonstrated instabilities in those devices were inherent to the design. A series of similar studies followed, abandoning the simplistic theories previously used and introducing a full consideration of magnetohydrodynamics with a partially-resistive plasma. These concepts developed quickly, and by the early 1960s it was clear that small devices simply would not work. A series of much larger and more complex devices followed as researchers attempted to add field upon field in order to provide the required field strength without reaching the unstable regimes. As cost and complexity climbed, the initial optimism of the fusion field faded.

The tokamak is announced

A new approach was outlined in the theoretical works fulfilled in 1950–1951 by I.E. Tamm and A.D. Sakharov in the Soviet Union, which first discussed a tokamak-like approach. Experimental research on these designs began in 1956 at the Kurchatov Institute in Moscow by a group of Soviet scientists led by Lev Artsimovich. The tokamak essentially combined a low-power pinch device with a low-power simple stellarator. The key was to combine the fields in such a way that the particles wound around the reactor a particular number of times, today known as the "safety factor". The combination of these fields dramatically improved confinement times and densities, resulting in huge improvements over existing devices.

The group constructed the first tokamaks, the most successful being the T-3 and its larger version T-4. T-4 was tested in 1968 in Novosibirsk, producing the first quasistationary thermonuclear fusion reaction ever. The tokamak was dramatically more efficient than the other approaches of that era, on the order of 10 to 100 times. When they were first announced the international community was highly skeptical. However, a British team was invited to see T-3, and having measured it in depth they released their results that confirmed the Soviet claims. A burst of activity followed as many planned devices were abandoned and new tokamaks were introduced in their place - the C model stellarator, then under construction after many redesigns, was quickly converted to the Symmetrical Tokamak and the stellarator was abandoned.

Through the 1970s and 80 great strides in understanding the tokamak system were made. A number of improvements to the design are now part of the "advanced tokamak" concept, which includes non-circular plasmas, internal diverters and limiters, often superconducting magnets, and operate in the so-called "H-mode" island of increased stability. Two other designs have also become fairly well studied; the compact tokamak is wired with the magnets on the inside of the vacuum chamber, while the spherical tokamak reduces its cross section as much as possible.

The tokamak dominates modern research, where very large devices like ITER are expected to pass several milestones toward commercial power production, including a burning plasma with long burn times, high power output, and online fueling. There are no guarantees that the project will be successful; previous generations of tokamak machines have uncovered new problems many times. But the entire field of high temperature plasmas is much better understood now than formerly, and there is considerable optimism that ITER will meet its goals. If successful, ITER would be followed by a "commercial demonstrator" system, similar in purpose to the very earliest power-producing fission reactors built in the era before wide-scale commercial deployment of larger machines started in the 1960s and 1970s.

Even with these goals met, there are a number of major engineering problems remaining, notably finding suitable "low activity" materials for reactor construction, demonstrating secondary systems including practical tritium extraction, and building reactor designs that allow their reactor core to be removed when its materials becomes embrittled due to the neutron flux. Practical commercial generators based on the tokamak concept are far in the future. The public at large has been disappointed, as the initial outlook for practical fusion power plants was much rosier; a pamphlet from the 1970s printed by General Atomic stated that "Several commercial fusion reactors are expected to be online by the year 2000."

Laser inertial devices

The technique of implosion of a microcapsule irradiated by laser beams, the basis of laser inertial confinement, was first suggested in 1962 by scientists at Lawrence Livermore National Laboratory, shortly after the invention of the laser itself in 1960. Lasers of the era were very low powered, but low-level research using them nevertheless started as early as 1965. A great advance in the field was John Nuckolls' 1972 paper that ignition would require lasers of about 1 kJ, and efficient burn around 1 MJ. kJ lasers were just beyond the state of the art at the time, and his paper sparked off a tremendous development effort to produce devices of the needed power.

Early machines used a variety of approaches to attack one of two problems - some focused on fast delivery of energy, while others were more interested in beam smoothness. Both were attempts to ensure the energy delivery would be smooth enough to cause an even implosion. However, these experiments demonstrated a serious problem; laser wavelengths in the infrared area lost a tremendous amount of energy before compressing the fuel. Important breakthroughs in this laser technology were made at the Laboratory for Laser Energetics at the University of Rochester, where scientists used frequency-tripling crystals to transform the infrared laser beams into ultraviolet beams. By the late 1970s great strides had been made in laser power, but with each increase new problems were found in the implosion technique that suggested even more power would be required. By the 1980s these increases were so large that using the concept for generating net energy seemed remote. Most research in this field turned to weapons research, always a second line of research, as the implosion concept is somewhat similar to hydrogen bomb operation. Work on very large versions continued as a result, with the very large National Ignition Facility in the US and Laser Mégajoule in France supporting these research programs.

More recent work had demonstrated that significant savings in the required laser energy are possible using a technique known as "fast ignition". The savings are so dramatic that the concept appears to be a useful technique for energy production again, so much so that it is a serious contender for pre-commercial development. There are proposals to build an experimental facility dedicated to the fast ignition approach, known as HiPER. At the same time, advances in solid state lasers appear to improve the "driver" systems' efficiency by about ten times (to 10- 20%), savings that make even the large "traditional" machines almost practical, and might make the fast ignition concept outpace the magnetic approaches in further development.

The laser-based concept has other advantages. The reactor core is mostly exposed, as opposed to being wrapped in a huge magnet as in the tokamak. This makes the problem of removing energy from the system somewhat simpler, and should mean that a laser-based device would be much easier to perform maintenance on, such as core replacement. Additionally, the lack of strong magnetic fields allows for a wider variety of low-activation materials, including carbon fiber, which would reduce both the frequency of such neutron activations and the rate of irradiation to the core. In other ways the program has many of the same problems as the tokamak; practical methods of energy removal and tritium recycling need to be demonstrated.

Other inertial devices

Philo T. Farnsworth, the inventor of the first all-electronic television system in 1927, patented his first Fusor design in 1968, a device that uses inertial electrostatic confinement. This system consists largely of two concentric spherical electrical grids inside a vacuum chamber into which a small amount of fusion fuel is introduced. Voltage across the grids causes the fuel to ionize around them, and positively charged ions are accelerated towards the center of the chamber. Those ions may collide and fuse with ions coming from the other direction, may scatter without fusing, or may pass directly through. In the latter two cases, the ions will tend to be stopped by the electric field and re-accelerated toward the center. Fusors can also use ion guns rather than electric grids. Towards the end of the 1960s, Robert Hirsch designed a variant of the Farnsworth Fusor known as the Hirsch-Meeks fusor. This variant is a considerable improvement over the Farnsworth design, and is able to generate neutron flux in the order of one billion neutrons per second. Although the efficiency was very low at first, there were hopes the device could be scaled up, but continued development demonstrated that this approach would be impractical for large machines. Nevertheless, fusion could be achieved using a "lab bench top" type set up for the first time, at minimal cost. This type of fusor found its first application as a portable neutron generator in the late 1990s. An automated sealed reaction chamber version of this device, commercially named Fusionstar was developed by EADS but abandoned in 2001. Its successor is the NSD-Fusion neutron generator.

Robert W. Bussard's Polywell concept is roughly similar to that of the Fusor, but replaces the problematic grid with a magnetically contained electron cloud, which holds the ions in position and provides an accelerating potential. The polywell consists of electromagnet coils arranged in a polyhedral configuration and positively charged to between several 10s and low 100s of kilovolts. This charged magnetic polyhedron is called a MaGrid (Magnetic Grid). Electrons are introduced outside the "quasi-spherical" MaGrid and are accelerated into the MaGrid due to the electric field. Within the MaGrid, magnetic fields confine most of the electrons and those that escape are retained by the electric field. This configuration traps the electrons in the middle of the device, focusing them near the center to produce a virtual cathode (negative electric potential). The virtual cathode accelerates and confines the ions to be fused which, except for minimal losses, never reach the physical structure of the MaGrid. Bussard had reported a fusion rate of 10^9 per second running D-D fusion reactions at only 12.5 kV (based on detecting a total of nine neutrons in five tests. Bussard claimed a scaled-up version of 2.5–3 m in diameter, would operated at over 100 MW net power (fusion power scales as the fourth power of the B field and the cube of the size)

A recent area of study is the magneto-inertial fusion (MIF) concept, which combines some form of external inertial compression (like lasers) with further compression through an external magnet (like pinch devices). The magnetic field traps heat within the inertial core, causing a variety of effects that improves fusion rates. These improvements are relatively minor, however the magnetic drivers themselves are inexpensive compared to lasers or other systems. There is hope for a sweet spot that allows the combination of features from these devices to create low-density but also low-cost fusion devices. A similar concept is the magnetized target fusion device, which uses a magnetic field in an external metal shell to achieve the same basic goals.

Other systems

Over the years there have been a wide variety of fusion concepts. In general they fall into three groups - those that attempt to reach high temperature/density for brief times (pinch, inertial confinement), those that operate at a steady state (magnetic confinement) or those that try neither and instead attempt to produce low quantities of fusion but do so at an extremely low cost. The later group has largely disappeared, as the difficulties of achieving fusion have demonstrated that any low-energy device is unlikely to produce net gain. This leaves the two major approaches, magnetic and laser inertial, as the leading systems for development funding. However, alternate approaches continue to be developed, and alternate non-power fusion devices have been successfully developed as well.

Focus fusion takes place in a dense plasma focus produced by a dense plasma focus, which typically consists of two coaxial cylindrical electrodes made from copper or beryllium and housed in a vacuum chamber containing a low-pressure gas, which is used as the reactor fuel. An electrical pulse is applied across the electrodes, producing heating and a magnetic field. The current forms the hot gas into many minuscule vortices perpendicular to the surfaces of the electrodes, which then migrate to the end of the inner electrode to pinch-and-twist off as tiny balls of plasma called plasmoids. The electron beam collides with the plasmoid, heating it to fusion temperatures, will in principle yield more energy in the beams than was input to form them.

In April 2005, a team from UCLA announced it had devised a way of producing fusion using a machine that "fits on a lab bench", using lithium tantalate to generate enough voltage to smash deuterium atoms together. However, the process does not generate net power.

Safety and the environment

Accident potential

There is no possibility of a *catastrophic* accident in a fusion reactor resulting in major release of radioactivity to the environment or injury to non-staff, unlike modern fission reactors. The primary reason is that nuclear fusion requires precisely controlled temperature, pressure, and magnetic field parameters to generate net energy. If the reactor were damaged, these parameters would be disrupted and the heat generation in the reactor would rapidly cease. In contrast, the fission products in a fission reactor continue to generate heat through beta-decay for several hours or even days after reactor shut-down, meaning that melting of fuel rods is possible even after the reactor has been stopped due to continued accumulation of heat.

There is also no risk of a runaway reaction in a fusion reactor, since the plasma is normally burnt at optimal conditions, and any significant change will render it unable to produce excess heat. In fusion reactors the reaction process is so delicate that this level of safety is inherent; no elaborate failsafe mechanism is required. Although the plasma in a fusion power plant will have a volume of 1000 cubic meters or more, the density of the plasma is extremely low, and the total amount of fusion fuel in the vessel is very small, typically a few grams. If the fuel supply is closed, the reaction stops within seconds. In comparison, a fission reactor is typically loaded with enough fuel for one or several years, and no additional fuel is necessary to keep the reaction going.

In the magnetic approach, strong fields are developed in coils that are held in place mechanically by the reactor structure. Failure of this structure could release this tension and allow the magnet to "explode" outward. The severity of this event would be similar to any other industrial accident or an MRI machine quench/explosion, and could be effectively stopped with a containment building similar to those used in existing (fission) nuclear generators. The laser-driven inertial approach is generally lower-stress. Although failure of the reaction chamber is possible, simply stopping fuel delivery would prevent any sort of catastrophic failure.

Most reactor designs rely on the use of liquid lithium as both a coolant and a method for converting stray neutrons from the reaction into tritium, which is fed back into the reactor as fuel. Lithium is highly flammable, and in the case of a fire it is possible that the lithium stored on-site could be burned up and escape. In this case the tritium contents of the lithium would be released into the atmosphere, posing a radiation risk. However, calculations suggest that the total amount of tritium and other radioactive gases in a typical power plant would be so small, about 1 kg, that they would have diluted to legally acceptable limits by the time they blew as far as the plant's perimeter fence.

The likelihood of *small industrial* accidents including the local release of radioactivity and injury to staff cannot be estimated yet. These would include accidental releases of lithium, tritium, or mis-handling of decommissioned radioactive components of the reactor itself.

Effluents during normal operation

The natural product of the fusion reaction is a small amount of helium, which is completely harmless to life. Of more concern is tritium, which, like other isotopes of hydrogen, is difficult to retain completely. During normal operation, some amount of tritium will be continually released. There would be no acute danger, but the cumulative effect on the world's population from a fusion economy could be a matter of concern.

Although tritium is volatile and biologically active, the health risk posed by a release is much lower than that of most radioactive contaminants, due to tritium's short half-life (12 years), very low decay energy (~14.95 keV), and the fact that it does not bioaccumulate (instead being cycled out of the body as water, with a biological half-life of 7 to 14 days) (refer to Gianni Petrangeli's work "Nuclear Safety", page 226).. Current ITER designs are investigating total containment facilities for any tritium.

Waste management

The large flux of high-energy neutrons in a reactor will make the structural materials radioactive. The radioactive inventory at shut-down may be comparable to that of a fission reactor, but there are important differences.

The half-life of the radioisotopes produced by fusion tend to be less than those from fission, so that the inventory decreases more rapidly. Unlike fission reactors, whose waste remains radioactive for thousands of years, most of the radioactive material in a fusion reactor would be the reactor core itself, which would be dangerous for about 50 years, and low-level waste another 100. Although this waste will be considerably more radioactive during those 50 years than fission waste, the very short half-life makes the process very attractive, as the waste management is fairly straightforward. By 300 years the material would have the same radioactivity as coal ash.

Additionally, the choice of materials used in a fusion reactor is less constrained than in a fission design, where many materials are required for their specific neutron cross-sections. This allows a fusion reactor to be designed using materials that are selected specifically to be "low activation", materials that do not easily become radioactive. Vanadium, for example, would become much less radioactive than stainless steel. Carbon fiber materials are also low-activation, as well as being strong and light, and are a promising area of study for laser-inertial reactors where a magnetic field is not required.

In general terms, fusion reactors would create far less radioactive material than a fission reactor, the material it would create is less damaging biologically, and the radioactivity "burns off" within a time period that is well within existing engineering capabilities.

Nuclear proliferation

Although fusion power uses nuclear technology, the overlap with nuclear weapons technology is small. Tritium is a component of the trigger of hydrogen bombs, but not a major problem in production. The copious neutrons from a fusion reactor could be used to breed plutonium for an atomic bomb, but not without extensive redesign of the reactor, so that production would be difficult to conceal. The theoretical and computational tools needed for hydrogen bomb design are closely related to those needed for inertial confinement fusion, but have very little in common with the more scientifically developed magnetic confinement fusion.

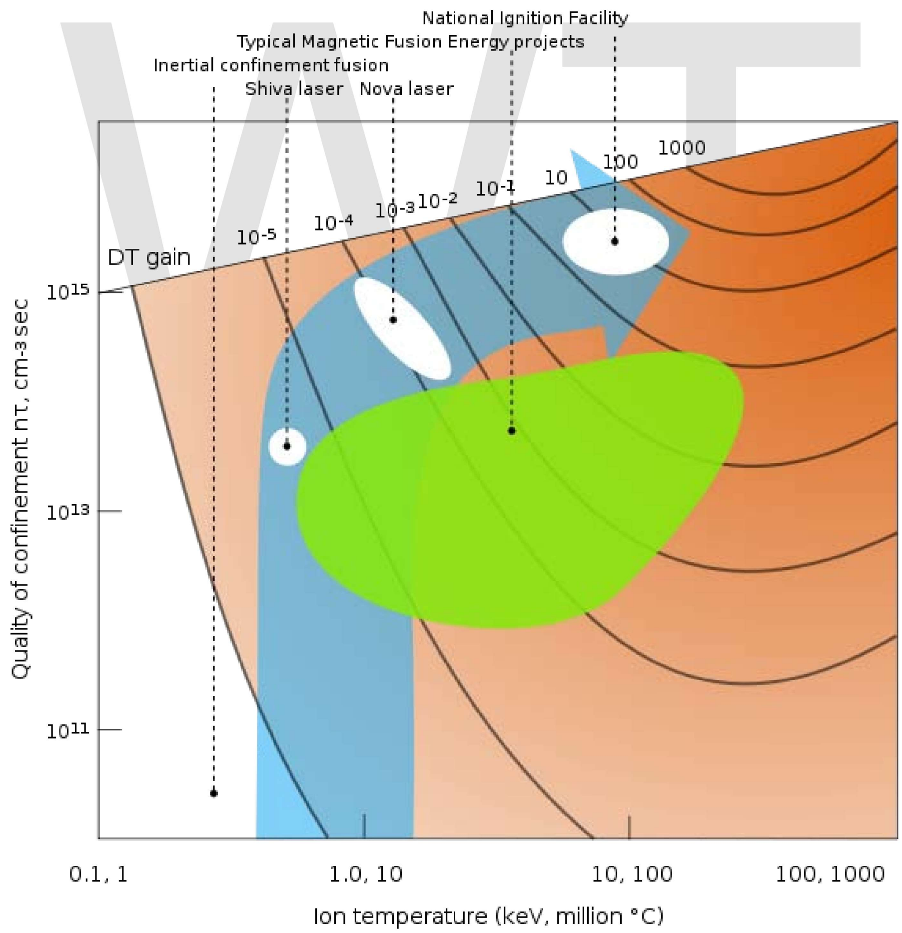
As a sustainable energy source

Large-scale reactors using neutronic fuels (e.g. ITER) and thermal power production (turbine based) are most comparable to fission power from an engineering and economics viewpoint. Both fission and fusion power plants involve a relatively compact heat source powering a conventional steam turbine-based power plant, while producing enough neutron radiation to make activation of the plant materials problematic. The main distinction is that fusion power produces no high-level radioactive waste (though activated plant materials still need to be disposed of). There are some power plant ideas which may significantly lower the cost or size of such plants; however, research in these areas is nowhere near as advanced as in tokamaks.

Fusion power commonly proposes the use of deuterium, an isotope of hydrogen, as fuel and in many current designs also use lithium. Assuming a fusion energy output equal to the 1995 global power output of about 100 EJ/yr (= 1 x 10^{20} J/yr) and that this does not increase in the future, then the known current lithium reserves would last 3000 years, lithium from sea water would last 60 million years, and a more complicated fusion process using only deuterium from sea water would have fuel for 150 billion years. To put this in context, 150 billion years is over ten times the currently measured age of the universe, and is close to 30 times the remaining lifespan of the sun.

Theoretical power plant designs

Confinement concepts



Parameter space occupied by inertial fusion energy and magnetic fusion energy devices as of the mid 1990s. The regime allowing thermonuclear ignition with high gain lies near the upper right corner of the plot.

Confinement refers to all the conditions necessary to keep a plasma dense and hot long enough to undergo fusion:

- Equilibrium: There must be no net forces on any part of the plasma, otherwise it will rapidly disassemble. The exception, of course, is inertial confinement, where the relevant physics must occur faster than the disassembly time.
- Stability: The plasma must be so constructed that small deviations are restored to the initial state, otherwise some unavoidable disturbance will occur and grow exponentially until the plasma is destroyed.
- Transport: The loss of particles and heat in all channels must be sufficiently slow. The word "confinement" is often used in the restricted sense of "energy confinement".

The first human-made, large-scale fusion reaction was the test of the hydrogen bomb, Ivy Mike, in 1952. As part of the PACER project, it was once proposed to use hydrogen bombs as a source of power by detonating them in underground caverns and then generating electricity from the heat produced, but such a power plant is unlikely ever to be constructed, for a variety of reasons. *Controlled* thermonuclear fusion (CTF) refers to the alternative of continuous power production, or at least the use of explosions that are so small that they do not destroy a significant portion of the machine that produces them.

To produce self-sustaining fusion, the energy released by the reaction (or at least a fraction of it) must be used to heat new reactant nuclei and keep them hot long enough that they also undergo fusion reactions. Retaining the heat is called energy confinement and may be accomplished in a number of ways.

The hydrogen bomb really has no confinement at all. The fuel is simply allowed to fly apart, but it takes a certain length of time to do this, and during this time fusion can occur. This approach is called inertial confinement. If more than milligram quantities of fuel are used (and efficiently fused), the explosion would destroy the machine, so theoretically, controlled thermonuclear fusion using inertial confinement would be done using tiny pellets of fuel which explode several times a second. To induce the explosion, the pellet must be compressed to about 30 times solid density with energetic beams. If the beams are focused directly on the pellet, it is called direct drive, which can in principle be very efficient, but in practice it is difficult to obtain the needed uniformity. An alternative approach is indirect drive, in which the beams heat a shell, and the shell radiates x-rays, which then implode the pellet. The beams are commonly laser beams, but heavy and light ion beams and electron beams have all been investigated.

Inertial confinement produces plasmas with impressively high densities and temperatures, and appears to be best suited to weapons research, X-ray generation, very small reactors, and perhaps in the distant future, spaceflight. They require fuel pellets with close to a perfect shape in order to generate a symmetrical inward shock wave to produce the high-density plasma, and in practice these have proven difficult to produce. A recent development in the field of laser induced ICF is the use of ultrashort pulse multi-petawatt lasers to heat the plasma of an imploding pellet at exactly the moment of greatest density after it is imploded conventionally using terawatt scale lasers. This research will be carried out on the (currently being built) OMEGA EP petawatt and OMEGA lasers at the University of Rochester and at the GEKKO XII laser at the institute for laser engineering in Osaka Japan, which if fruitful, may have the effect of greatly reducing the cost of a laser fusion based power source.

At the temperatures required for fusion, the fuel is in the form of a plasma with very good electrical conductivity. This opens the possibility to confine the fuel and the energy with magnetic fields, an idea known as magnetic confinement. The Lorenz force works only perpendicular to the magnetic field, so that the first problem is how to prevent the plasma from leaking out the ends of the field lines. There are basically two solutions.

The first is to use the magnetic mirror effect. If particles following a field line encounter a region of higher field strength, then some of the particles will be stopped and reflected. Advantages of a magnetic mirror power plant would be simplified construction and maintenance due to a linear topology and the potential to apply direct conversion in a natural way, but the confinement achieved in the experiments was so poor that this approach has been essentially abandoned.

The second possibility to prevent end losses is to bend the field lines back on themselves, either in circles or more commonly in nested toroidal surfaces. The most highly developed system of this type is the *tokamak*, with the *stellarator* being next most advanced, followed by the Reversed field pinch. Compact toroids, especially the *Field-Reversed Configuration* and the spheromak, attempt to combine the advantages of toroidal magnetic surfaces with those of a simply connected (non-toroidal) machine, resulting in a mechanically simpler and smaller confinement area. Compact toroids still have some enthusiastic supporters but are not backed as readily by the majority of the fusion community.

Finally, there are also *electrostatic confinement fusion* systems, in which ions in the reaction chamber are confined and held at the center of the device by electrostatic forces, as in the Farnsworth-Hirsch Fusor, which is not believed to be able to be developed into a power plant. The Polywell, an advanced variant of the fusor, has shown a degree of research interest as of late; however, the technology is relatively immature, and major scientific and engineering questions remain which researchers under the auspices of the U.S. Office of Naval Research hope to further investigate.

Other approaches

A more subtle technique is to use more unusual particles to catalyse fusion. The best known of these is Muon-catalyzed fusion which uses muons, which behave somewhat like electrons and replace the electrons around the atoms. These muons allow atoms to get much closer and thus reduce the kinetic energy required to initiate fusion. Muons require more energy to produce than can be obtained from muon-catalysed fusion, making this approach impractical for the generation of power.

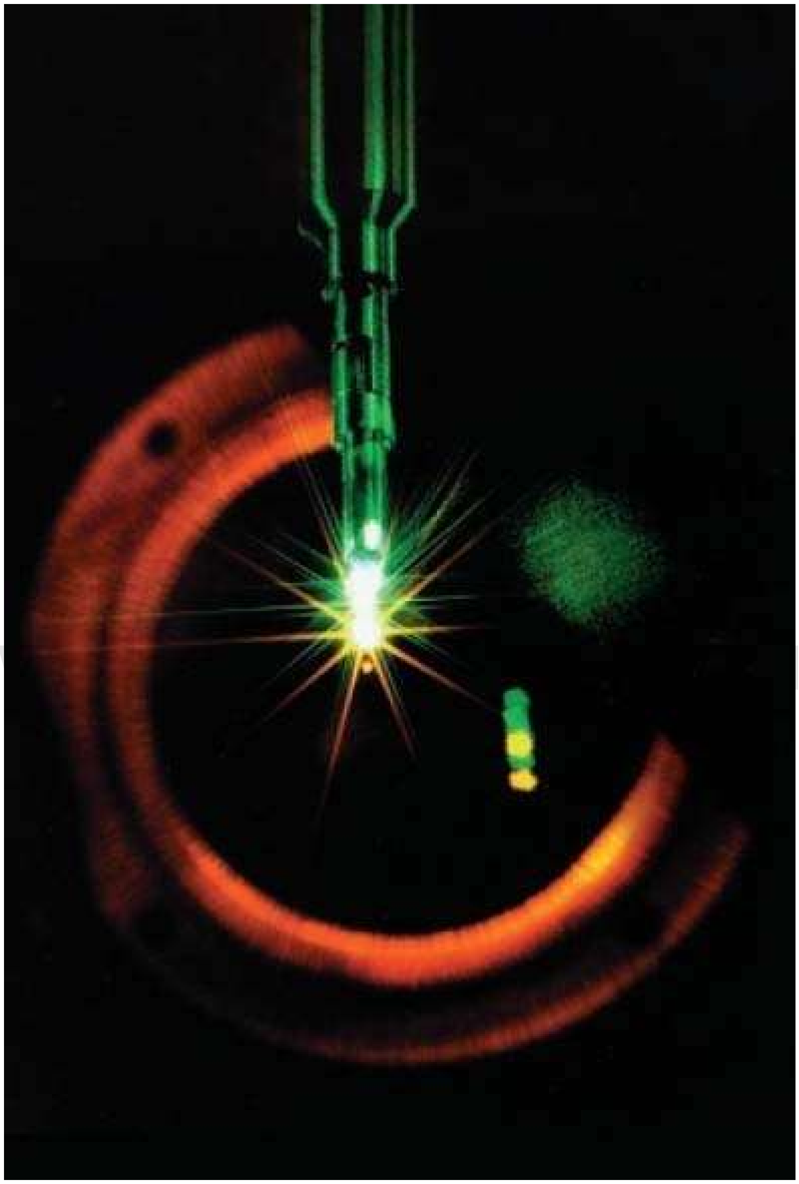
Some scientists have reported excess heat, neutrons, tritium, helium and other nuclear effects in so-called cold fusion systems. In 2004, a peer review panel was commissioned by the U.S. Department of Energy to study these claims. This identified basic areas of research which were necessary for acceptance of the idea, but did not recommend a federally funded program.

Research into sonoluminescence induced fusion, sometimes known as "*bubble fusion*", also continues, although it is met with as much skepticism as cold fusion is by most of the scientific community.

Subsystems

In fusion research, achieving a fusion energy gain factor $Q = 1$ is called breakeven and is considered a significant although somewhat artificial milestone. Ignition refers to an infinite Q, that is, a self-sustaining plasma where the losses are made up for by fusion power without any external input. In a practical fusion reactor, some external power will always be required for things like current drive, refueling, profile control, and burn control. A value on the order of $Q = 20$ will be required if the plant is to deliver much more energy than it uses internally.

There have been many design studies for fusion power plants. Despite many differences, there are several systems that are common to most. To begin with, a fusion power plant, like a fission power plant, is customarily divided into the nuclear island and the balance of plant. The balance of plant is the conventional part that converts high-temperature heat into electricity via steam turbines. It is much the same in a fusion power plant as in a fission or coal power plant. In a fusion power plant, the nuclear island has a plasma chamber with an associated vacuum system, surrounded by plasma-facing components (first wall and divertor) maintaining the vacuum boundary and absorbing the thermal radiation coming from the plasma, surrounded in turn by a blanket where the neutrons are absorbed to breed tritium and heat a working fluid that transfers the power to the balance of plant. If magnetic confinement is used, a magnet system, using primarily cryogenic superconducting magnets, is needed, and usually systems for heating and refueling the plasma and for driving current. In inertial confinement, a driver (laser or accelerator) and a focusing system are needed, as well as a means for forming and positioning the pellets.



Inertial confinement fusion implosion on the Nova laser creates "microsun" conditions of tremendously high density and temperature.

Although the standard solution for electricity production in fusion power plant designs is conventional steam turbines using the heat deposited by neutrons, there are also designs for direct conversion of the energy of the charged particles into electricity. These are of little value with a D-T fuel cycle, where 80% of the power is in the neutrons, but are indispensable with aneutronic fusion, where less than 1% is. Direct conversion has been most commonly proposed for open-ended magnetic configurations like magnetic mirrors or Field-Reversed Configurations, where charged particles are lost along the magnetic field lines, which are then expanded to convert a large fraction of the random energy of the fusion products into directed motion. The particles are then collected on electrodes at various large electrical potentials. Typically the claimed conversion efficiency is in the range of 80%, but the converter may approach the reactor itself in size and expense.

Materials

Developing materials for fusion reactors has long been recognized as a problem nearly as difficult and important as that of plasma confinement, but it has received only a fraction of the attention. The neutron flux in a fusion reactor is expected to be about 100 times that in existing pressurized water reactors (PWR). Each atom in the blanket of a fusion reactor is expected to be hit by a neutron and displaced about a hundred times before the material is replaced. Furthermore the high-energy neutrons will produce hydrogen and helium in various nuclear reactions that tends to form bubbles at grain boundaries and result in swelling, blistering or embrittlement. One also wishes to choose materials whose primary components and impurities do not result in long-lived radioactive wastes. Finally, the mechanical forces and temperatures are large, and there may be frequent cycling of both.

The problem is exacerbated because realistic material tests must expose samples to neutron fluxes of a similar level for a similar length of time as those expected in a fusion power plant. Such a neutron source is nearly as complicated and expensive as a fusion reactor itself would be. Proper materials testing will not be possible in ITER, and a proposed materials testing facility, IFMIF, was still at the design stage in 2005.

The material of the plasma facing components (PFC) is a special problem. The PFC do not have to withstand large mechanical loads, so neutron damage is much less of an issue. They do have to withstand extremely large thermal loads, up to 10 MW/m^2, which is a difficult but solvable problem. Regardless of the material chosen, the heat flux can only be accommodated without melting if the distance from the front surface to the coolant is not more than a centimeter or two. The primary issue is the interaction with the plasma. One can choose either a low-Z material, typified by graphite although for some purposes beryllium might be chosen, or a high-Z material, usually tungsten with molybdenum as a second choice. Use of liquid metals (lithium, gallium, tin) has also been proposed, e.g., by injection of 1–5 mm thick streams flowing at 10 m/s on solid substrates.

If graphite is used, the gross erosion rates due to physical and chemical sputtering would be many meters per year, so one must rely on redeposition of the sputtered material. The location of the redeposition will not exactly coincide with the location of the sputtering, so one is still left with erosion rates that may be prohibitive. An even larger problem is the tritium co-deposited with the redeposited graphite. The tritium inventory in graphite layers and dust in a reactor could quickly build up to many kilograms, representing a waste of resources and a serious radiological hazard in case of an accident. The consensus of the fusion community seems to be that graphite, although a very attractive material for fusion experiments, cannot be the primary PFC material in a commercial reactor.

The sputtering rate of tungsten can be orders of magnitude smaller than that of carbon, and tritium is not so easily incorporated into redeposited tungsten, making this a more attractive choice. On the other hand, tungsten impurities in a plasma are much more damaging than carbon impurities, and self-sputtering of tungsten can be high, so it will be necessary to ensure that the plasma in contact with the tungsten is not too hot (a few tens of eV rather than hundreds of eV). Tungsten also has disadvantages in terms of eddy currents and melting in off-normal events, as well as some radiological issues.

Economics

While fusion power is still in early stages of development, substantial sums have been and continue to be invested in research. In the EU almost € 10 billion was spent on fusion research up to the end of the 1990s, and the new ITER reactor alone is budgeted at € 10 billion. It is estimated that up to the point of possible implementation of electricity generation by nuclear fusion, R&D will need further promotion totalling around € 60-80 billion over a period of 50 years or so (of which € 20-30 billion within the EU). Nuclear fusion research receives € 750 million (excluding ITER funding), compared with € 810 million for all non-nuclear energy research combined, putting research into fusion power well ahead of that of any single rivaling technology.

Advantages

Fusion power would provide much more energy for a given weight of fuel than any technology currently in use, and the fuel itself (primarily deuterium) exists abundantly in the Earth's ocean: about 1 in 6500 hydrogen atoms in seawater is deuterium. Although this may seem a low proportion (about 0.015%), because nuclear fusion reactions are so much more energetic than chemical combustion and seawater is easier to access and more plentiful than fossil fuels, some experts estimate that fusion could supply the world's energy needs for millions of years.

An important aspect of fusion energy in contrast to many other energy sources is that the cost of production does not suffer from diseconomies of scale. The cost of wind energy, for example, goes up as the optimal locations are developed first, while further generators must be sited in less ideal conditions. With fusion energy, the production cost will not increase much, even if large numbers of plants are built. It has been suggested that even 100 times the current energy consumption of the world is possible.

Some problems which are expected to be an issue in this century such as fresh water shortages can actually be regarded merely as problems of energy supply. For example, in desalination plants, seawater can be purified through distillation or reverse osmosis. However, these processes are energy intensive. Even if the first fusion plants are not competitive with alternative sources, fusion could still become competitive if large scale desalination requires more power than the alternatives are able to provide. Further as refining suggested fusion fuels (deuterium, and tritium) via distillation of hydrogen or electrolysis from seawater would produce a waste product of pure hydrogen the fusion plants themselves could produce a small amount of drinking water by reclaiming the lost energy. At perfect conditions this would be to produce 1g deuterium per 30 kg of water worth of hydrogen.

Despite being technically non-renewable, fusion power has many of the benefits of long-term renewable energy sources (such as being a sustainable energy supply compared to presently utilized sources and emitting no greenhouse gases) as well as some of the benefits of the much more limited energy sources as hydrocarbons and nuclear fission (without reprocessing). Like these currently dominant energy sources, fusion could provide very high power-generation density and uninterrupted power delivery (due to the fact that it is not dependent on the weather, unlike wind and solar power).

A scenario has been presented of the effect of the commercialization of fusion power on the future of human civilization. ITER and later Demo are envisioned to bring online the first commercial nuclear fusion energy reactor by 2050. Using this as the starting point and the history of the uptake of nuclear fission reactors as a guide, the scenario depicts a not unreasonable rapid take up of nuclear fusion energy starting after the middle of this century. Just into the next century fusion energy should be able to take up the slack and allow Mankind to continue its progress and growth. Because the development of fusion energy is such a complex technological task it is probable that there will be several decades when the constraints of energy shortage will be severely felt as shown by the flattening of the energy consumption from around 2040 to 2100. Such a period of stagnation seems unavoidable even with the envisaged development and rapid adoption of fusion energy. On the other hand without nuclear fusion energy the scenario depicts a severe downturn unavoidably in the fortunes of Mankind with world population shrinking below 5 billion and eventually even lower.

Current status

Despite optimism dating back to the 1950s about the wide-scale harnessing of fusion power, there are still significant barriers standing between current scientific understanding and technological capabilities and the practical realization of fusion as an energy source. Research, while making steady progress, has also continually thrown up new difficulties. Therefore it remains unclear whether an economically viable fusion plant is possible. A 2006 editorial in *New Scientist* magazine opined that "if commercial fusion is viable, it may well be a century away." Interestingly, a pamphlet printed by General Atomics in 1970s stated that "By the year 2000, several commercial fusion reactors are expected to be on-line."

Several fusion D-T burning tokamak test devices have been built (TFTR, JET), but these were not built to produce more thermal energy than electrical energy consumed. The ITER project is currently leading the effort to commercialize fusion power.

A paper published in January 2009 and part of the IAEA Fusion Conference Proceedings at Geneva last October claims that small 50 MW Tokamak style reactors are feasible.

On May 30, 2009, the US Lawrence Livermore National Laboratory (LLNL), primarily a weapons lab, announced the creation of a high-energy laser system, the National Ignition Facility, which can heat hydrogen atoms to temperatures only existing in nature in the cores of stars. The new laser is expected to have the ability to produce, for the first time, more energy from controlled, inertially confined nuclear fusion than was required to initiate the reaction.

On January 28, 2010, the LLNL announced tests using all 192 laser beams, although with lower laser energies, smaller hohlraum targets, and substitutes for the fusion fuel capsules. More than one megajoule of ultraviolet energy was fired into the hohlraum, besting the previous world record by a factor of more than 30. The results gave the scientists confidence that they will be able to achieve ignition in more realistic tests scheduled to begin in the summer of 2010.

NIF researchers are currently conducting a series of "tuning" shots to determine the optimal target design and laser parameters for high-energy ignition experiments with fusion fuel in the coming months. Two firing tests have been performed on October 31 and November 2.

Chapter- 4

Biofuel

Information on pump regarding ethanol fuel blend up to 10%, California

Bus run on biodiesel

Biofuels are a wide range of fuels which are in some way derived from biomass. The term covers solid biomass, liquid fuels and various biogases. Biofuels are gaining increased public and scientific attention, driven by factors such as oil price spikes, the need for increased energy security, and concern over greenhouse gas emissions from fossil fuels.

Bioethanol is an alcohol made by fermenting the sugar components of plant materials and it is made mostly from sugar and starch crops. With advanced technology being developed, cellulosic biomass, such as trees and grasses, are also used as feedstocks for ethanol production. Ethanol can be used as a fuel for vehicles in its pure form, but it is usually used as a gasoline additive to increase octane and improve vehicle emissions. Bioethanol is widely used in the USA and in Brazil.

Biodiesel is made from vegetable oils, animal fats or recycled greases. Biodiesel can be used as a fuel for vehicles in its pure form, but it is usually used as a diesel additive to reduce levels of particulates, carbon monoxide, and hydrocarbons from diesel-powered vehicles. Biodiesel is produced from oils or fats using transesterification and is the most common biofuel in Europe.

Biofuels provided 1.8% of the world's transport fuel in 2008. Investment into biofuels production capacity exceeded $4 billion worldwide in 2007 and is growing.

Liquid fuels for transportation

Most transportation fuels are liquids, because vehicles usually require high energy density, as occurs in liquids and solids. High power density can be provided most inexpensively by an internal combustion engine; these engines require clean burning fuels, to keep the engine clean and minimize air pollution.

The fuels that are easiest to burn cleanly are typically liquids and gases. Thus liquids (and gases that can be stored in liquid form) meet the requirements of being both portable and clean burning. Also, liquids and gases can be pumped, which means handling is easily mechanized, and thus less laborious.

First generation biofuels

'First-generation biofuels' are biofuels made from sugar, starch, and vegetable oil.

Bioalcohols

Neat ethanol on the left (A), gasoline on the right (G) at a filling station in Brazil

Biologically produced alcohols, most commonly ethanol, and less commonly propanol and butanol, are produced by the action of microorganisms and enzymes through the fermentation of sugars or starches (easiest), or cellulose (which is more difficult). Biobutanol (also called biogasoline) is often claimed to provide a direct replacement for gasoline, because it can be used directly in a gasoline engine (in a similar way to biodiesel in diesel engines).

Ethanol fuel is the most common biofuel worldwide, particularly in Brazil. Alcohol fuels are produced by fermentation of sugars derived from wheat, corn, sugar beets, sugar cane, molasses and any sugar or starch that alcoholic beverages can be made from (like potato and fruit waste, etc.). The ethanol production methods used are enzyme digestion (to release sugars from stored starches), fermentation of the sugars, distillation and drying. The distillation process requires significant energy input for heat (often unsustainable natural gas fossil fuel, but cellulosic biomass such as bagasse, the waste left after sugar cane is pressed to extract its juice, can also be used more sustainably).

The Koenigsegg CCXR Edition at the 2008 Geneva Motor Show. This is an "environmentally friendly" version of the CCX, which can use E85 and E100.

Ethanol can be used in petrol engines as a replacement for gasoline; it can be mixed with gasoline to any percentage. Most existing car petrol engines can run on blends of up to 15% bioethanol with petroleum/gasoline. Ethanol has a smaller energy density than gasoline, which means it takes more fuel (volume and mass) to produce the same amount of work. An advantage of ethanol (CH_3CH_2OH) is that it has a higher octane rating than ethanol-free gasoline available at roadside gas stations which allows an increase of an engine's compression ratio for increased thermal efficiency. In high altitude (thin air) locations, some states mandate a mix of gasoline and ethanol as a winter oxidizer to reduce atmospheric pollution emissions.

Ethanol is also used to fuel bioethanol fireplaces. As they do not require a chimney and are "flueless", bio ethanol fires are extremely useful for new build homes and apartments without a flue. The downside to these fireplaces, is that the heat output is slightly less than electric and gas fires.

In the current alcohol-from-corn production model in the United States, considering the total energy consumed by farm equipment, cultivation, planting, fertilizers, pesticides, herbicides, and fungicides made from petroleum, irrigation systems, harvesting, transport of feedstock to processing plants, fermentation, distillation, drying, transport to fuel terminals and retail pumps, and lower ethanol fuel energy content, the net energy content value added and delivered to consumers is very small. And, the net benefit (all things considered) does little to reduce un-sustainable imported oil and fossil fuels required to produce the ethanol.

Although ethanol-from-corn and other food stocks has implications both in terms of world food prices and limited, yet positive energy yield (in terms of energy delivered to customer/fossil fuels used), the technology has led to the development of cellulosic ethanol. According to a joint research agenda conducted through the U.S. Department of Energy, the fossil energy ratios (FER) for cellulosic ethanol, corn ethanol, and gasoline are 10.3, 1.36, and 0.81, respectively.

Many car manufacturers are now producing flexible-fuel vehicles (FFV's), which can safely run on any combination of bioethanol and petrol, up to 100% bioethanol. They dynamically sense exhaust oxygen content, and adjust the engine's computer systems, spark, and fuel injection accordingly. This adds initial cost and ongoing increased vehicle maintenance. As with all vehicles, efficiency falls and pollution emissions increase when FFV system maintenance is needed (regardless of the fuel mix being used), but is not performed. FFV internal combustion engines are becoming increasingly complex, as are multiple-propulsion-system FFV hybrid vehicles, which impacts cost, maintenance, reliability, and useful lifetime longevity.

Even dry ethanol has roughly one-third lower energy content per unit of volume compared to gasoline, so larger / heavier fuel tanks are required to travel the same distance, or more fuel stops are required. With large current unsustainable, non-scalable subsidies, ethanol fuel still costs much more per distance traveled than current high gasoline prices in the United States.

Methanol is currently produced from natural gas, a non-renewable fossil fuel. It can also be produced from biomass as biomethanol. The methanol economy is an interesting alternative to get to the hydrogen economy, compared to today's hydrogen production from natural gas. But this process is not the state-of-the-art clean solar thermal energy process, where hydrogen production is directly produced from water.

Butanol is formed by ABE fermentation (acetone, butanol, ethanol) and experimental modifications of the process show potentially high net energy gains with butanol as the only liquid product. Butanol will produce more energy and allegedly can be burned "straight" in existing gasoline engines (without modification to the engine or car), and is less corrosive and less water soluble than ethanol, and could be distributed via existing infrastructures. DuPont and BP are working together to help develop Butanol. E. coli have also been successfully engineered to produce Butanol by hijacking their amino acid metabolism.

Fermentation is not the only route to forming biofuels or bioalcohols. One can obtain methanol, ethanol, butanol or mixed alcohol fuels through pyrolysis of biomass including agricultural waste or algal biomass. The most exciting of these pyrolysis alcoholic fuels is the pyrolysis biobutanol. The product can be made with limited water use and most places in the world.

Green diesel

Green diesel, also known as renewable diesel, is a form of diesel fuel which is derived from renewable feedstock rather than the fossil feedstock used in most diesel fuels. Green diesel feedstock can be sourced from a variety of oils including canola, algae, jatropha and salicornia in addition to tallow. Green diesel uses traditional fractional distillation to process the oils, not to be confused with biodiesel which is chemically quite different and processed using transesterification.

"Green Diesel" as commonly known in Ireland should not be confused with dyed green diesel sold at a lower tax rate for agriculture purposes, using the dye allows custom officers to determine if a person is using the cheaper diesel in higher taxed applications such as commercial haulage or cars.

Biodiesel

In some countries biodiesel is less expensive than conventional diesel

Biodiesel is the most common biofuel in Europe. It is produced from oils or fats using transesterification and is a liquid similar in composition to fossil/mineral diesel. Chemically, it consists mostly of fatty acid methyl (or ethyl) esters (FAMEs). Feedstocks for biodiesel include animal fats, vegetable oils, soy, rapeseed, jatropha, mahua, mustard, flax, sunflower, palm oil, hemp, field pennycress, pongamia pinnata and algae. Pure biodiesel (B100) is the lowest emission diesel fuel. Although liquefied petroleum gas and hydrogen have cleaner combustion, they are used to fuel much less efficient petrol engines and are not as widely available.

Biodiesel can be used in any diesel engine when mixed with mineral diesel. In some countries manufacturers cover their diesel engines under warranty for B100 use, although Volkswagen of Germany, for example, asks drivers to check by telephone with the VW environmental services department before switching to B100. B100 may become more viscous at lower temperatures, depending on the feedstock used. In most cases, biodiesel is compatible with diesel engines from 1994 onwards, which use 'Viton' (by DuPont) synthetic rubber in their mechanical fuel injection systems.

Electronically controlled 'common rail' and 'unit injector' type systems from the late 1990s onwards may only use biodiesel blended with conventional diesel fuel. These engines have finely metered and atomized multi-stage injection systems that are very sensitive to the viscosity of the fuel. Many current generation diesel engines are made so that they can run on B100 without altering the engine itself, although this depends on the fuel rail design. Since biodiesel is an effective solvent and cleans residues deposited by mineral diesel, engine filters may need to be replaced more often, as the biofuel dissolves old deposits in the fuel tank and pipes. It also effectively cleans the engine combustion chamber of carbon deposits, helping to maintain efficiency. In many European countries, a 5% biodiesel blend is widely used and is available at thousands of gas stations. Biodiesel is also an *oxygenated fuel*, meaning that it contains a reduced amount of carbon and higher hydrogen and oxygen content than fossil diesel. This improves the combustion of fossil diesel and reduces the particulate emissions from un-burnt carbon.

Biodiesel is also safe to handle and transport because it is as biodegradable as sugar, 10 times less toxic than table salt, and has a high flash point of about 300 F (148 C) compared to petroleum diesel fuel, which has a flash point of 125 F (52 C).

In the USA, more than 80% of commercial trucks and city buses run on diesel. The emerging US biodiesel market is estimated to have grown 200% from 2004 to 2005. "By the end of 2006 biodiesel production was estimated to increase fourfold [from 2004] to more than 1 billion gallons".

Vegetable oil

Filtered waste vegetable oil

Straight unmodified edible vegetable oil is generally not used as fuel, but lower quality oil can be used for this purpose. Used vegetable oil is increasingly being processed into biodiesel, or (more rarely) cleaned of water and particulates and used as a fuel.

Also here, as with 100% biodiesel (B100), to ensure that the fuel injectors atomize the vegetable oil in the correct pattern for efficient combustion, vegetable oil fuel must be heated to reduce its viscosity to that of diesel, either by electric coils or heat exchangers. This is easier in warm or temperate climates. Big corporations like MAN B&W Diesel, Wärtsilä, and Deutz AG as well as a number of smaller companies such as Elsbett offer engines that are compatible with straight vegetable oil, without the need for after-market modifications.

Vegetable oil can also be used in many older diesel engines that do not use common rail or unit injection electronic diesel injection systems. Due to the design of the combustion chambers in indirect injection engines, these are the best engines for use with vegetable oil. This system allows the relatively larger oil molecules more time to burn. Some older engines, especially Mercedes are driven experimentally by enthusiasts without any conversion, a handful of drivers have experienced limited success with earlier pre-"Pumpe Duse" VW TDI engines and other similar engines with direct injection. Several companies like Elsbett or Wolf have developed professional conversion kits and successfully installed hundreds of them over the last decades.

Oils and fats can be hydrogenated to give a diesel substitute. The resulting product is a straight chain hydrocarbon, high in cetane, low in aromatics and sulfur and does not contain oxygen. Hydrogenated oils can be blended with diesel in all proportions Hydrogenated oils have several advantages over biodiesel, including good performance at low temperatures, no storage stability problems and no susceptibility to microbial attack.

Bioethers

Bio ethers (also referred to as fuel ethers or oxygenated fuels) are cost-effective compounds that act as octane rating enhancers. They also enhance engine performance, whilst significantly reducing engine wear and toxic exhaust emissions. Greatly reducing the amount of ground-level ozone, they contribute to the quality of the air we breathe.

Biogas

Pipes carrying biogas

Biogas is methane produced by the process of anaerobic digestion of organic material by anaerobes. It can be produced either from biodegradable waste materials or by the use of energy crops fed into anaerobic digesters to supplement gas yields. The solid byproduct, digestate, can be used as a biofuel or a fertilizer.

- Biogas can be recovered from mechanical biological treatment waste processing systems.

  Note:Landfill gas is a less clean form of biogas which is produced in landfills through naturally occurring anaerobic digestion. If it escapes into the atmosphere it is a potential greenhouse gas.

- Farmers can produce biogas from manure from their cows by getting a anaerobic digester (AD).

Syngas

Syngas, a mixture of carbon monoxide and hydrogen, is produced by partial combustion of biomass, that is, combustion with an amount of oxygen that is not sufficient to convert the biomass completely to carbon dioxide and water. Before partial combustion the biomass is dried, and sometimes pyrolysed. The resulting gas mixture, syngas, is more efficient than direct combustion of the original biofuel; more of the energy contained in the fuel is extracted.

- Syngas may be burned directly in internal combustion engines or turbines. The wood gas generator is a wood-fueled gasification reactor mounted on an internal combustion engine.
- Syngas can be used to produce methanol, DME and hydrogen, or converted via the Fischer-Tropsch process to produce a diesel substitute, or a mixture of alcohols that can be blended into gasoline. Gasification normally relies on temperatures >700°C.
- Lower temperature gasification is desirable when co-producing biochar but results in a Syngas polluted with tar.

Solid biofuels

Examples include wood, sawdust, grass cuttings, domestic refuse, charcoal, agricultural waste, non-food energy crops, and dried manure.

When raw biomass is already in a suitable form (such as firewood), it can burn directly in a stove or furnace to provide heat or raise steam. When raw biomass is in an inconvenient form (such as sawdust, wood chips, grass, urban waste wood, agricultural residues), the typical process is to densify the biomass. This process includes grinding the raw biomass to an appropriate particulate size (known as hogfuel), which depending on the densification type can be from 1 to 3 cm (1 in), which is then concentrated into a fuel product. The current types of processes are wood pellet, cube, or puck. The pellet process is most common in Europe and is typically a pure wood product. The other types of densification are larger in size compared to a pellet and are compatible with a broad range of input feedstocks. The resulting densified fuel is easier to transport and feed into thermal generation systems such as boilers.

A problem with the combustion of raw biomass is that it emits considerable amounts of pollutants such as particulates and PAHs (polycyclic aromatic hydrocarbons). Even modern pellet boilers generate much more pollutants than oil or natural gas boilers. Pellets made from agricultural residues are usually worse than wood pellets, producing much larger emissions of dioxins and chlorophenols.

Notwithstanding the above noted study, numerous studies have shown that biomass fuels have significantly less impact on the environment than fossil based fuels. Of note is the U.S. Department of Energy Laboratory, Operated by Midwest Research Institute Biomass Power and Conventional Fossil Systems with and without CO2 Sequestration – Comparing the Energy Balance, Greenhouse Gas Emissions and Economics Study. Power generation emits significant amounts of greenhouse gases (GHGs), mainly carbon dioxide (CO_2). Sequestering CO_2 from the power plant flue gas can significantly reduce the GHGs from the power plant itself, but this is not the total picture. CO_2 capture and sequestration consumes additional energy, thus lowering the plant's fuel-to-electricity efficiency. To compensate for this, more fossil fuel must be procured and consumed to make up for lost capacity.

Taking this into consideration, the global warming potential (GWP), which is a combination of CO_2, methane (CH_4), and nitrous oxide (N_2O) emissions, and energy balance of the system need to be examined using a life cycle assessment. This takes into account the upstream processes which remain constant after CO_2 sequestration as well as the steps required for additional power generation. firing biomass instead of coal led to a 148% reduction in GWP.

A derivative of solid biofuel is biochar, which is produced by biomass pyrolysis. Bio-char made from agricultural waste can substitute for wood charcoal. As wood stock becomes scarce this alternative is gaining ground. In eastern Democratic Republic of Congo, for example, biomass briquettes are being marketed as an alternative to charcoal in order to protect Virunga National Park from deforestation associated with charcoal production.

Second generation biofuels

Supporters of biofuels claim that a more viable solution is to increase political and industrial support for, and rapidity of, second-generation biofuel implementation from non-food crops. These include waste biomass, the stalks of wheat, corn, wood, and special-energy-or-biomass crops (e.g. Miscanthus). Some second generation (2G) biofuels use biomass to liquid technology, including cellulosic biofuels. Many second generation biofuels are under development such as biohydrogen, biomethanol, DMF, BioDME, Fischer-Tropsch diesel, biohydrogen diesel, mixed alcohols and wood diesel.

Cellulosic ethanol production uses non-food crops or inedible waste products and does not divert food away from the animal or human food chain. Lignocellulose is the "woody" structural material of plants. This feedstock is abundant and diverse, and in some cases (like citrus peels or sawdust) it is in itself a significant disposal problem.

Producing ethanol from cellulose is a difficult technical problem to solve. In nature, ruminant livestock (like cattle) eat grass and then use slow enzymatic digestive processes to break it into glucose (sugar). In cellulosic ethanol laboratories, various experimental processes are being developed to do the same thing, and then the sugars released can be fermented to make ethanol fuel. In 2009 scientists reported developing, using "synthetic biology", "15 new highly stable fungal enzyme catalysts that efficiently break down cellulose into sugars at high temperatures", adding to the 10 previously known. The use of high temperatures, has been identified as an important factor in improving the overall economic feasibility of the biofuel industry and the identification of enzymes that are stable and can operate efficiently at extreme temperatures is an area of active research. In addition, research conducted at TU Delft by Jack Pronk has shown that elephant yeast, when slightly modified can also create ethanol from non-edible ground sources (e.g. straw).

The recent discovery of the fungus Gliocladium roseum points toward the production of so-called myco-diesel from cellulose. This organism was recently discovered in the rainforests of northern Patagonia and has the unique capability of converting cellulose into medium length hydrocarbons typically found in diesel fuel. Scientists also work on experimental recombinant DNA genetic engineering organisms that could increase biofuel potential.

Scientists working in New Zealand have developed a technology to use industrial waste gases from steel mills as a feedstock for a microbial fermentation process to produce ethanol.

Second, third, and fourth generation biofuels are also called advanced biofuels.

Third generation biofuels

Algae fuel, also called oilgae or third generation biofuel, is a biofuel from algae. Algae are low-input, high-yield feedstocks to produce biofuels. Based on laboratory experiments, it is claimed that algae can produce up to 30 times more energy per acre than land crops such as soybeans, but these yields have yet to be produced commercially. With the higher prices of fossil fuels (petroleum), there is much interest in algaculture (farming algae). One advantage of many biofuels over most other fuel types is that they are biodegradable, and so relatively harmless to the environment if spilled. Algae fuel still has its difficulties though, for instance to produce algae fuels it must be mixed uniformly, which, if done by agitation, could affect biomass growth.

The United States Department of Energy estimates that if algae fuel replaced all the petroleum fuel in the United States, it would require only 15,000 square miles (38,849 square kilometers), which is roughly the size of Maryland, or less than one seventh the amount of land devoted to corn in 2000.

Algae, such as *Botryococcus braunii* and *Chlorella vulgaris* are relatively easy to grow, but the algal oil is hard to extract. There are several approaches, some of which work better than others. Macroalgae (seaweed) also have a great potential for bioethanol and biogas production.

Ethanol from living algae

Most biofuel production comes from harvesting organic matter and then converting it to fuel but an alternative approach relies on the fact that some algae naturally produce ethanol and this can be collected without killing the algae. The ethanol evaporates and then can be condensed and collected. The company Algenol is trying to commercialize this process.

Fourth generation biofuels

A number of companies are pursuing advanced "bio-chemical" and "thermo-chemical" processes that produce "drop in" fuels like "green gasoline," "green diesel," and "green aviation fuel." While there is no one established definition of "fourth-generation biofuels," some have referred to it as the biofuels created from processes other than first generation ethanol and biodiesel, second generation cellulosic ethanol, and third generation algae biofuel. Some fourth generation technology pathways include: pyrolysis, gasification, upgrading, solar-to-fuel, and genetic manipulation of organisms to secrete hydrocarbons.

- GreenFuel Technologies Corporation developed a patented bioreactor system that uses nontoxic photosynthetic algae to take in smokestacks flue gases and produce biofuels such as biodiesel, biogas and a dry fuel comparable to coal.
- With thermal depolymerization of biological waste one can extract methane and other oils similar to petroleum.

Hydrocarbon plants or petroleum plants are plants which produce terpenoids as secondary metabolites that can be converted to gasoline-like fuels. Latex producing members of the Euphorbiaceae such as *Euphorbia lathyris* and *E. tirucalli* and members of Apocynaceae have been studied for their potential energy uses.

Green fuels

However, if biocatalytic cracking and traditional fractional distillation are used to process properly prepared algal biomass i.e. biocrude, then as a result we receive the following distillates: jet fuel, gasoline, diesel, etc.. Hence, we may call them third generation or green fuels.

Biofuels by region

There are international organizations such as IEA Bioenergy, established in 1978 by the OECD International Energy Agency (IEA), with the aim of improving cooperation and information exchange between countries that have national programs in bioenergy research, development and deployment. The U.N. International Biofuels Forum is formed by Brazil, China, India, South Africa, the United States and the European Commission. The world leaders in biofuel development and use are Brazil, United States, France, Sweden and Germany.

Russia is willing to play one of the main roles in the solid biofuel production in the near future in Europe. The biggest pellet plant with production capacity of 1 mio tons of pellets is run in 2011 near the borderwith European Union. The biggest biomass (solid biofuels) resources are concentrated in Russia (25% of world forests are in Russia)

Issues with biofuel production and use

There are various social, economic, environmental and technical issues with biofuel production and use, which have been discussed in the popular media and scientific journals. These include: the effect of moderating oil prices, the "food vs fuel" debate, poverty reduction potential, carbon emissions levels, sustainable biofuel production, deforestation and soil erosion, loss of biodiversity, impact on water resources, as well as energy balance and efficiency.

Chapter- 5

Hydrogen Economy

The **hydrogen economy** is a proposed system of delivering energy using hydrogen. The term *hydrogen economy* was coined by John Bockris during a talk he gave in 1970 at General Motors (GM) Technical Center.

Hydrogen advocates promote hydrogen as potential fuel for motive power (including cars and boats), the energy needs of buildings and portable electronics. Free hydrogen does not occur naturally in quantity, and thus it must be generated from some other energy source by steam reformation of natural gas or another method. Hydrogen is therefore an energy carrier (like electricity), not a primary energy source (like coal). The utility of a hydrogen economy depends on issues of energy sourcing, including fossil fuel use, climate change, and sustainable energy generation.

Rationale

Elements of the hydrogen economy

A hydrogen economy is proposed to solve some of the negative effects of using hydrocarbon fuels where the carbon is released to the atmosphere. Modern interest in the hydrogen economy can generally be traced to a 1970 technical report by Lawrence W. Jones of the University of Michigan.

In the current hydrocarbon economy, transportation is fueled primarily by petroleum. Burning of hydrocarbon fuels emits carbon dioxide and other pollutants. The supply of economically usable hydrocarbon resources in the world is limited, and the demand for hydrocarbon fuels is increasing, particularly in China, India and other developing countries.

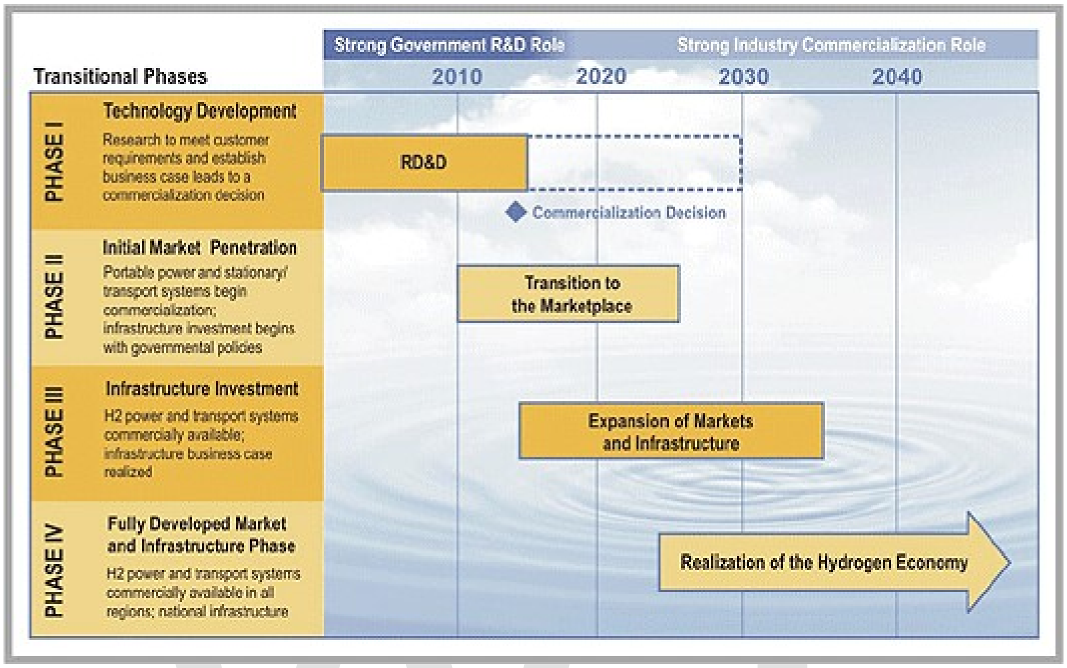
Proponents of a world-scale hydrogen economy argue that hydrogen can be an environmentally cleaner source of energy to end-users, particularly in transportation applications, without release of pollutants (such as particulate matter) or carbon dioxide at the point of end use. A 2004 analysis asserted that "most of the hydrogen supply chain pathways would release significantly less carbon dioxide into the atmosphere than would gasoline used in hybrid electric vehicles" and that significant reductions in carbon dioxide emissions would be possible if carbon capture or carbon sequestration methods were utilized at the site of energy or hydrogen production.

Hydrogen has a high energy density by weight. An Otto cycle internal combustion engine running on hydrogen is said to have a maximum efficiency of about 38%, 8% higher than gasoline internal combustion engine.

The combination of the fuel cell and electric motor is 2-3 times more efficient than an internal combustion engine. However, the high capital costs of fuel cells, about $5,500/kW in 2002, are one of the major obstacles of its development, meaning that the fuel cell is only technically, but not economically, more efficient than an internal combustion engine.

Other technical obstacles include hydrogen storage issues and the purity requirement of hydrogen used in fuel cells – with current technology, an operating fuel cell requires the purity of hydrogen to be as high as 99.999%. On the other hand, hydrogen engine conversion technology is more economical than fuel cells.

Perspective: current hydrogen market (current hydrogen economy)



Timeline

Hydrogen production is a large and growing industry. Globally, some 50 million metric tons of hydrogen, equal to about 170 million tons of oil equivalent, were produced in 2004. The growth rate is around 10% per year. Within the United States, 2004 production was about 11 million metric tons (MMT), an average power flow of 48 gigawatts. (For comparison, the average electric production in 2003 was some 442 gigawatts.) As of 2005, the economic value of all hydrogen produced worldwide is about $135 billion per year.

There are two primary uses for hydrogen today. About half is used to produce ammonia (NH_3) via the Haber process, which is then used directly or indirectly as fertilizer. Because both the world population and the intensive agriculture used to support it are growing, ammonia demand is growing. The other half of current hydrogen production is used to convert heavy petroleum sources into lighter fractions suitable for use as fuels. This latter process is known as hydrocracking. Hydrocracking represents an even larger growth area, since rising oil prices encourage oil companies to extract poorer source material, such as tar sands and oil shale. The scale economies inherent in large scale oil refining and fertilizer manufacture make possible on-site production and "captive" use. Smaller quantities of "merchant" hydrogen are manufactured and delivered to end users as well.

If energy for hydrogen production were available (from wind, solar or nuclear power), use of the substance for hydrocarbon synfuel production could expand captive use of hydrogen by a factor of 5 to 10. Present U.S. use of hydrogen for hydrocracking is roughly 4 million metric tons per year (4 MMT/yr). It is estimated that 37.7 MMT/yr of hydrogen would be sufficient to convert enough domestic coal to liquid fuels to end U.S. dependence on foreign oil importation, and less than half this figure to end dependence on Middle East oil. Coal liquefaction would present significantly worse emissions of carbon dioxide than does the current system of burning fossil petroleum, but it would eliminate the political and economic vulnerabilities inherent in oil importation.

Currently, global hydrogen production is 48% from natural gas, 30% from oil, and 18% from coal; water electrolysis accounts for only 4%. The distribution of production reflects the effects of thermodynamic constraints on economic choices: of the four methods for obtaining hydrogen, partial combustion of natural gas in a NGCC (natural gas combined cycle) power plant offers the most efficient chemical pathway and the greatest off-take of usable heat energy.

The large market and sharply rising prices in fossil fuels have also stimulated great interest in alternate, cheaper means of hydrogen production. As of 2002, most hydrogen is produced on site and the cost is approximately $0.32/lb and, if not produced on site, the cost of liquid hydrogen is about $1.00/lb to $1.40/lb.

Production, storage, infrastructure

Today hydrogen is mainly produced (90%) from fossil sources. Linking its centralized production to a fleet of light-duty fuel cell vehicles will require the siting and construction of a distribution infrastructure with large investment of capital. Further, the technological challenge of providing safe, energy-dense storage of hydrogen on-board the vehicle must be overcome to provide sufficient range between fillups.

Methods of production

Molecular hydrogen is not available on Earth in convenient natural reservoirs. Most hydrogen on Earth is bonded to oxygen in water. Manufacturing elemental hydrogen does require the consumption of a hydrogen carrier such as a fossil fuel or water. The former consumes the fossil resource and produces carbon dioxide, but often requires no further energy input beyond the fossil fuel. Decomposing water requires electrical or heat input, generated from some primary energy source (fossil fuel, nuclear power or a renewable energy).

Current production methods

Hydrogen is industrially produced from steam reforming, which uses fossil fuels such as natural gas, oil, or coal. The energy content of the produced hydrogen is less than the energy content of the original fuel, some of it being lost as excessive heat during production. Steam reforming leads to carbon dioxide emissions, in the same way as a car engine would do.

A small part (4% in 2006) is produced by electrolysis using electricity and water, consuming approximately 50 kilowatt-hours of electricity per kilogram of hydrogen produced.

Kværner-process

The Kværner-process or Kvaerner carbon black & hydrogen process (CB&H) is a method, developed in the 1980s by a Norwegian company of the same name, for the production of hydrogen from hydrocarbons (C_nH_m), such as methane, natural gas and biogas. Of the available energy of the feed, approximately 48% is contained in the Hydrogen, 40% is contained in activated carbon and 10% in superheated steam.

Biological production

Fermentative hydrogen production is the fermentative conversion of organic substrate to biohydrogen manifested by a diverse group bacteria using multi enzyme systems involving three steps similar to anaerobic conversion. Dark fermentation reactions do not require light energy, so they are capable of constantly producing hydrogen from organic compounds throughout the day and night. Photofermentation differs from dark fermentation because it only proceeds in the presence of light. For example photo-fermentation with Rhodobacter sphaeroides SH2C can be employed to convert small molecular fatty acids into hydrogen. Electrohydrogenesis is used in microbial fuel cells where hydrogen is produced from organic matter (e.g. from sewage, or solid matter) while 0.2 - 0.8 V is applied.

Biological hydrogen can be produced in an algae bioreactor. In the late 1990s it was discovered that if the algae is deprived of sulfur it will switch from the production of oxygen, i.e. normal photosynthesis, to the production of hydrogen.

Biological hydrogen can be produced in bioreactors that use feedstocks other than algae, the most common feedstock being waste streams. The process involves bacteria feeding on hydrocarbons and excreting hydrogen and CO_2. The CO_2 can be sequestered successfully by several methods, leaving hydrogen gas. A prototype hydrogen bioreactor using waste as a feedstock is in operation at Welch's grape juice factory in North East, Pennsylvania.

Biocatalysed electrolysis

Besides regular electrolysis, electrolysis using microbes is another possibility. With biocatalysed electrolysis, hydrogen is generated after running through the microbial fuel cell and a variety of aquatic plants can be used. These include reed sweetgrass, cordgrass, rice, tomatoes, lupines, algae

Electrolysis of water

Electrolysis of water ship Hydrogen Challenger

Hydrogen can be made via high pressure electrolysis or low pressure electrolysis of water. Current best processes have an efficiency of 50% to 80%, so that 1 kg of hydrogen requires 50 to 80 kWh of electricity. At 8 cents/kWh, that's $4.00/kg, which is 3 to 10 times the price of hydrogen from steam reformation of natural gas. The price difference is due to the efficiency of direct conversion of fossil fuels to produce hydrogen, rather than burning fuel to produce electricity. Hydrogen from natural gas, used to replace e.g. gasoline, emits more CO2 than the gasoline it would replace, and so is no help in reducing greenhouse gases.

High-pressure electrolysis

High pressure electrolysis is the electrolysis of water by decomposition of water (H_2O) into oxygen (O_2) and hydrogen gas (H_2) by means of an electric current being passed through the water. The difference with a standard electrolyzer is the compressed hydrogen output around 120-200 Bar (1740-2900 psi). By pressurising the hydrogen in the electrolyser the need for an external hydrogen compressor is eliminated, the average energy consumption for internal compression is around 3%.

High-temperature electrolysis

Hydrogen can be generated from energy supplied in the form of heat and electricity through high-temperature electrolysis (HTE). Because some of the energy in HTE is supplied in the form of heat, less of the energy must be converted twice (from heat to electricity, and then to chemical form), and so potentially far less energy is required per kilogram of hydrogen produced.

While nuclear-generated electricity could be used for electrolysis, nuclear heat can be directly applied to split hydrogen from water. High temperature (950–1000 °C) gas cooled nuclear reactors have the potential to split hydrogen from water by thermochemical means using nuclear heat. Research into high-temperature nuclear reactors may eventually lead to a hydrogen supply that is cost-competitive with natural gas steam reforming. General Atomics predicts that hydrogen produced in a High Temperature Gas Cooled Reactor (HTGR) would cost $1.53/kg. In 2003, steam reforming of natural gas yielded hydrogen at $1.40/kg. At 2005 natural gas prices, hydrogen costs $2.70/kg.

High-temperature electrolysis has been demonstrated in a laboratory, at 108 megajoules (thermal) per kilogram of hydrogen produced, but not at a commercial scale. In addition, this is lower-quality "commercial" grade Hydrogen, unsuitable for use in fuel cells.

Photoelectrochemical water splitting

Using electricity produced by photovoltaic systems offers the cleanest way to produce hydrogen. Water is broken into hydrogen and oxygen by electrolysis—a photoelectrochemical cell (PEC) process which is also named artificial photosynthesis. Research aimed toward developing higher-efficiency multijunction cell technology is underway by the photovoltaic industry.

Concentrating solar thermal

Very high temperatures are required to dissociate water into hydrogen and oxygen. A catalyst is required to make the process operate at feasible temperatures. Heating the water can be achieved through the use of concentrating solar power. Hydrosol-2 is a 100-kilowatt pilot plant at the Plataforma Solar de Almería in Spain which uses sunlight to obtain the required 800 to 1,200 °C to heat water. Hydrosol II has been in operation since 2008. The design of this 100-kilowatt pilot plant is based on a modular concept. As a result, it may be possible that this technology could be readily scaled up to the megawatt range by multiplying the available reactor units and by connecting the plant to heliostat fields (fields of sun-tracking mirrors) of a suitable size.

Photoelectrocatalytic production

A method studied by Thomas Nann and his team at the University of East Anglia consists of a gold electrode covered in layers of indium phosphide (InP) nanoparticles. They introduced an iron-sulfur complex into the layered arrangement, which when submerged in water and irradiated with light under a small electric current, produced hydrogen with an efficiency of 60%.

Thermochemical production

There are more than 352 thermochemical cycles which can be used for water splitting, around a dozen of these cycles such as the iron oxide cycle, cerium(IV) oxide-cerium(III) oxide cycle, zinc zinc-oxide cycle, sulfur-iodine cycle, copper-chlorine cycle and hybrid sulfur cycle are under research and in testing phase to produce hydrogen and oxygen from water and heat without using electricity. These processes can be more efficient than high-temperature electrolysis, typical in the range from 35 % - 49 % LHV efficiency. Thermochemical production of hydrogen using chemical energy from coal or natural gas is generally not considered, because the direct chemical path is more efficient.

None of the thermochemical hydrogen production processes have been demonstrated at production levels, although several have been demonstrated in laboratories.

Storage

Although molecular hydrogen has very high energy density on a mass basis, partly because of its low molecular weight, as a gas at ambient conditions it has very low energy density by volume. If it is to be used as fuel stored on board the vehicle, pure hydrogen gas must be pressurized or liquefied to provide sufficient driving range. Increasing gas pressure improves the energy density by volume, making for smaller, but not lighter container tanks. Achieving higher pressures necessitates greater use of external energy to power the compression. Alternatively, higher volumetric energy density liquid hydrogen or slush hydrogen may be used. However, liquid hydrogen is cryogenic and boils at 20.268 K (–252.882 °C or –423.188 °F). Cryogenic storage cuts weight but requires large liquification energies. The liquefaction process, involving pressurizing and cooling steps, is energy intensive. The liquefied hydrogen has lower energy density by volume than gasoline by approximately a factor of four, because of the low density of liquid hydrogen — there is actually more hydrogen in a liter of gasoline (116 grams) than there is in a liter of pure liquid hydrogen (71 grams). Liquid hydrogen storage tanks must also be well insulated to minimize boil off. Ice may form around the tank and help corrode it further if the liquid hydrogen tank insulation fails.

The mass of the tanks needed for compressed hydrogen reduces the fuel economy of the vehicle. Because it is a small molecule, hydrogen tends to diffuse through any liner material intended to contain it, leading to the embrittlement, or weakening, of its container.

Distinct from storing molecular hydrogen, hydrogen can be stored as a chemical hydride or in some other hydrogen-containing compound. Hydrogen gas is reacted with some other materials to produce the hydrogen storage material, which can be transported relatively easily. At the point of use the hydrogen storage material can be made to decompose, yielding hydrogen gas. As well as the mass and volume density problems associated with molecular hydrogen storage, current barriers to practical storage schemes stem from the high pressure and temperature conditions needed for hydride formation and hydrogen release. For many potential systems hydriding and dehydriding kinetics and heat management are also issues that need to be overcome.

A third approach is to absorb molecular hydrogen into a solid storage material. Unlike in the hydrides mentioned above, the hydrogen does not dissociate/recombine upon charging/discharging the storage system, and hence does not suffer from the kinetic limitations of many hydride storage systems. Hydrogen densities similar to liquefied hydrogen can be achieved with appropriate absorption media. Some suggested absorbers include MOFs, nanostructured carbons (including CNTs) and clathrate hydrate.

The most common method of on board hydrogen storage in today's demonstration vehicles is as a compressed gas at pressures of roughly 700 bar (70 MPa).

Underground hydrogen storage is the practice of hydrogen storage in underground caverns, salt domes and depleted oil and gas fields. Large quantities of gaseous hydrogen are stored in underground caverns by ICI for many years without any difficulties. The storage of large quantities of hydrogen underground can function as grid energy storage which is essential for the hydrogen economy.

Infrastructure

Praxair Hydrogen Plant

The hydrogen infrastructure consists mainly of industrial hydrogen pipeline transport and hydrogen-equipped filling stations like those found on a hydrogen highway. Hydrogen stations which are not situated near a hydrogen pipeline get supply via hydrogen tanks, compressed hydrogen tube trailers, liquid hydrogen trailers, liquid hydrogen tank trucks or dedicated onsite production.

Because of hydrogen embrittlement of steel, and corrosion natural gas pipes require internal coatings or replacement in order to convey hydrogen. Techniques are well-known; over 700 miles of hydrogen pipeline currently exist in the United States. Although expensive, pipelines are the cheapest way to move hydrogen. Hydrogen gas piping is routine in large oil-refineries, because hydrogen is used to hydrocrack fuels from crude oil.

Hydrogen piping can in theory be avoided in distributed systems of hydrogen production, where hydrogen is routinely made on site using medium or small-sized generators which would produce enough hydrogen for personal use or perhaps a neighborhood. In the end, a combination of options for hydrogen gas distribution may succeed.

While millions of tons of elemental hydrogen are distributed around the world each year in various ways, bringing hydrogen to individual consumers would require an evolution of the fuel infrastructure. For example, according to GM, 70% of the U.S. population lives near a hydrogen-generating facility but has little public access to that hydrogen. The same study however, shows that building the infrastructure in a systematic way is much more doable and affordable than most people think. For example, one article has noted that hydrogen stations could be put within every 10 miles in metro Los Angeles, and on the highways between LA and neighboring cities like Palm Springs, Las Vegas, San Diego and Santa Barbara, for the cost of a Starbuck's latte for every one of the 15 million residents living in these areas.

A key tradeoff: centralized vs. distributed production

In a future full hydrogen economy, primary energy sources and feedstock would be used to produce hydrogen gas as stored energy for use in various sectors of the economy. Producing hydrogen from primary energy sources other than coal, oil, and natural gas, would result in lower production of the greenhouse gases characteristic of the combustion of these fossil energy resources.

One key feature of a hydrogen economy is that in mobile applications (primarily vehicular transport) energy generation and use is decoupled. The primary energy source need no longer travel with the vehicle, as it currently does with hydrocarbon fuels. Instead of tailpipes creating dispersed emissions, the energy (and pollution) can be generated from point sources such as large-scale, centralized facilities with improved efficiency. This allows the possibility of technologies such as carbon sequestration, which are otherwise impossible for mobile applications. Alternatively, distributed energy generation schemes (such as small scale renewable energy sources) can be used, possibly associated with hydrogen stations.

Aside from the energy generation, hydrogen production could be centralized, distributed or a mixture of both. While generating hydrogen at centralized primary energy plants promises higher hydrogen production efficiency, difficulties in high-volume, long range hydrogen transportation (due to factors such as hydrogen damage and the ease of hydrogen diffusion through solid materials) makes electrical energy distribution attractive within a hydrogen economy. In such a scenario, small regional plants or even local filling stations could generate hydrogen using energy provided through the electrical distribution grid. While hydrogen generation efficiency is likely to be lower than for centralized hydrogen generation, losses in hydrogen transport can make such a scheme more efficient in terms of the primary energy used per kilogram of hydrogen delivered to the end user.

The proper balance between hydrogen distribution and long-distance electrical distribution is one of the primary questions that arises in the hydrogen economy.

Again the dilemmas of production sources and transportation of hydrogen can now be overcome using on site (home, business, or fuel station) generation of hydrogen from off grid renewable sources.

Distributed electrolysis

Distributed electrolysis would bypass the problems of distributing hydrogen by distributing electricity instead. It would use existing electrical networks to transport electricity to small, on-site electrolysers located at filling stations. However, accounting for the energy used to produce the electricity and transmission losses will reduce the overall efficiency.

Natural gas combined cycle power plants, which account for almost all builds of new electricity plants in the United States, generate electricity at efficiencies of 60 percent or greater. Increased demand for electricity, whether due to hydrogen cars or other demand, would have the marginal impact of adding new combined cycle power plants. On this basis, distributed production of hydrogen would be roughly 40 percent efficient. However, if the marginal impact is referred to today's power grid, with an efficiency of roughly 40 percent owing to its mix of fuels and conversion methods, the efficiency of distributed hydrogen production would be roughly 25 percent.

The distributed production of hydrogen in this fashion will be expected to generate air emissions of pollutants and carbon dioxide at various points in the supply chain, e.g., electrolysis, transportation and storage. Such externalities as pollution must be weighed against the potential advantages of a hydrogen economy.

Fuel cells as alternative to internal combustion

One of the main offerings of a hydrogen economy is that the fuel can replace the fossil fuel burned in internal combustion engines and turbines as the primary way to convert chemical energy into kinetic or electrical energy; hereby eliminating greenhouse gas emissions and pollution from that engine.

Although hydrogen can be used in conventional internal combustion engines, fuel cells, being electrochemical, have a theoretical efficiency advantage over heat engines. Fuel cells are more expensive to produce than common internal combustion engines, but are becoming cheaper as new technologies and production systems develop.

Some types of fuel cells work with hydrocarbon fuels, while all can be operated on pure hydrogen. In the event that fuel cells become price-competitive with internal combustion engines and turbines, large gas-fired power plants could adopt this technology.

Hydrogen gas must be distinguished as "technical-grade" (five nines pure), which is suitable for applications such as fuel cells, and "commercial-grade", which has carbon- and sulfur-containing impurities, but which can be produced by the much cheaper steam-reformation process. Fuel cells require high purity hydrogen because the impurities would quickly degrade the life of the fuel cell stack.

Much of the interest in the hydrogen economy concept is focused on the use of fuel cells to power electric cars. Current Hydrogen fuel cells suffer from a low power-to-weight ratio, although they store more energy than other electrochemical batteries. Fuel cells are much more efficient than internal combustion engines, and produce no harmful emissions. If a practical method of hydrogen storage is introduced, and fuel cells become cheaper, they can be economically viable to power hybrid fuel cell/battery vehicles, or purely fuel cell-driven ones. The economic viability of fuel cell powered vehicles will improve as the hydrocarbon fuels used in internal combustion engines become more expensive, because of the depletion of easily accessible reserves or economic accounting of environmental impact through such measures as carbon taxes.

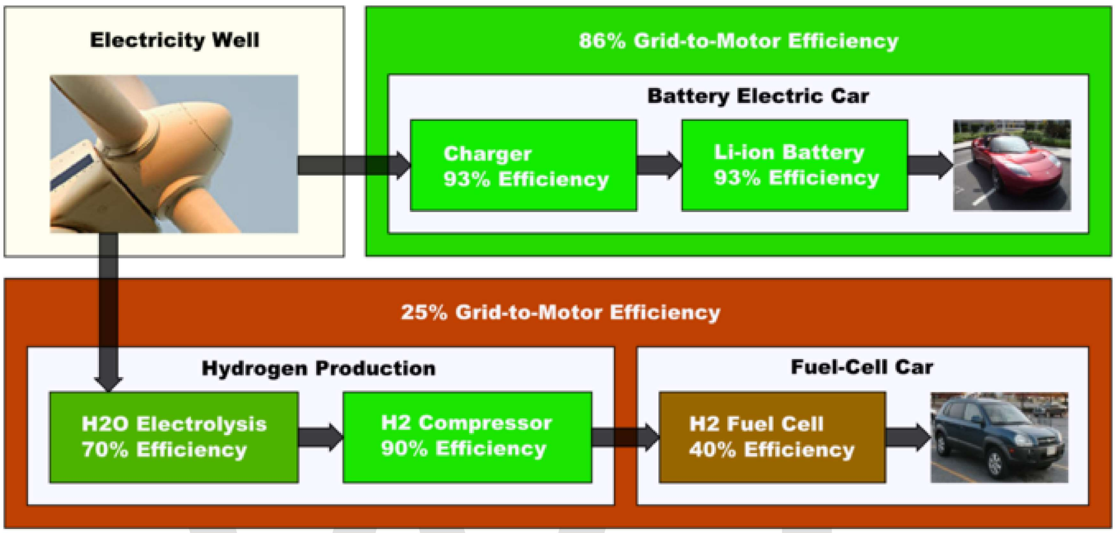
Currently it takes 2½ times as much energy to make a hydrogen fuel cell than is obtained from it during its service life.

Other fuel cell technologies based on the exchange of metal ions (i.e. zinc-air fuel cells) are typically more efficient at energy conversion than hydrogen fuel cells, but the widespread use of any electrical energy → chemical energy → electrical energy systems would necessitate the production of electricity.

Efficiency as an automotive fuel

Hydrogen has been called one of the least efficient and most expensive possible replacements for gasoline (petrol) in terms of reducing greenhouse gases; other technologies may be less expensive and more quickly implemented. A comprehensive study of hydrogen in transportation applications has found that "there are major hurdles on the path to achieving the vision of the hydrogen economy; the path will not be simple or straightforward". The Ford Motor Company has dropped its plans to develop hydrogen cars, stating that "The next major step in Ford's plan is to increase over time the volume of electrified vehicles".

An accounting of the energy utilized during a thermodynamic process, known as an energy balance, can be applied to automotive fuels. With today's technology, the manufacture of hydrogen via steam reforming can be accomplished with a thermal efficiency of 75 to 80 percent. Additional energy will be required to liquefy or compress the hydrogen, and to transport it to the filling station via truck or pipeline. The energy that must be utilized per kilogram to produce, transport and deliver hydrogen (i.e., its well-to-tank energy use) is approximately 50 megajoules using technology available in 2004. Subtracting this energy from the enthalpy of one kilogram of hydrogen, which is 141 megajoules, and dividing by the enthalpy, yields a thermal energy efficiency of roughly 60%. Gasoline, by comparison, requires less energy input, per gallon, at the refinery, and comparatively little energy is required to transport it and store it owing to its high energy density per gallon at ambient temperatures. Well-to-tank, the supply chain for gasoline is roughly 80% efficient (Wang, 2002). The most efficient distribution however is electrical, which is typically 95% efficient. Electric vehicles are typically 3 to 4 times as efficient as hydrogen powered vehicles.



A study of the well-to-wheels efficiency of hydrogen vehicles compared to other vehicles in the Norwegian energy system indicates that hydrogen fuel-cell vehicles tend to be about a third as efficient as EVs when electrolysis is used, with hydrogen Internal Combustion Engines (ICE) being barely a sixth as efficient. Even in the case where hydrogen fuel cells get their hydrogen from natural gas reformation rather than electrolysis, and EVs get their power from a natural gas power plant, the EVs still come out ahead 35% to 25% (and only 13% for a H2 ICE). This compares to 14% for a gasoline ICE, 27% for a gasoline ICE hybrid, and 17% for a diesel ICE, also on a well-to-wheels basis.

Hydrogen safety

Hydrogen has one of the widest explosive/ignition mix range with air of all the gases with few exceptions such as acetylene, silane, and ethylene oxide. That means that whatever the mix proportion between air and hydrogen, a hydrogen leak will most likely lead to an explosion, not a mere flame, when a flame or spark ignites the mixture. This makes the use of hydrogen particularly dangerous in enclosed areas such as tunnels or underground parking. Pure hydrogen-oxygen flames burn in the ultraviolet color range and are nearly invisible to the naked eye, so a flame detector is needed to detect if a hydrogen leak is burning. Hydrogen is odorless and leaks cannot be detected by smell.

Hydrogen codes and standards are codes and standards for hydrogen fuel cell vehicles, stationary fuel cell applications and portable fuel cell applications. There are codes and standards for the safe handling and storage of hydrogen, for example the Standard for the installation of stationary fuel cell power systems from the National Fire Protection Association.

Codes and standards have repeatedly been identified as a major institutional barrier to deploying hydrogen technologies and developing a hydrogen economy. To enable the commercialization of hydrogen in consumer products, new model building codes and equipment and other technical standards are developed and recognized by federal, state, and local governments.

One of the measures on the roadmap is to implement higher safety standards like early leak detection with hydrogen sensors. The Canadian Hydrogen Safety Program concluded that hydrogen fueling is as safe as, or safer than, CNG fueling. The European Commission has funded the first higher educational program in the world in hydrogen safety engineering at the University of Ulster. It is expected that the general public will be able to use hydrogen technologies in everyday life with at least the same level of safety and comfort as with today's fossil fuels.

Environmental concerns

There are many concerns regarding the environmental effects of the manufacture of hydrogen. Hydrogen is made either by electrolysis of water, or by fossil fuel reforming. Reforming a fossil fuel leads to a higher emissions of carbon dioxide compared with direct use of the fossil fuel in an internal combustion engine. Similarly, if hydrogen is produced by electrolysis from fossil-fuel powered generators, increased carbon dioxide is emitted in comparison with direct use of the fossil fuel.

Using renewable energy source to generate hydrogen by electrolysis would require greater energy input than direct use of the renewable energy to operate electric vehicles, because of the extra conversion stages and losses in distribution.

Like any internal combustion engine, an ICE running on hydrogen may produce nitrous oxides and other pollutants. Air input into the combustion cylinder is approximately 78% nitrogen, and the N_2 molecule has a binding energy of approximately 226 kilocalories per mole. The hydrogen reaction has sufficient energy to break this bond and produce unwanted components such as nitric acid (HNO_3), and hydrogen cyanide gas (HCN), both toxic byproducts. Nitrogen compound emissions from internal combustion engines are a root cause of smog. Hydrogen as transportation fuel, however, is mainly used for fuel cells that do not produce greenhouse gas emission, but water.

There have also been some concerns over possible problems related to hydrogen gas leakage. Molecular hydrogen leaks slowly from most containment vessels. It has been hypothesized that if significant amounts of hydrogen gas (H_2) escape, hydrogen gas may, because of ultraviolet radiation, form free radicals (H) in the stratosphere. These free radicals would then be able to act as catalysts for ozone depletion. A large enough increase in stratospheric hydrogen from leaked H_2 could exacerbate the depletion process. However, the effect of these leakage problems may not be significant. The amount of hydrogen that leaks today is much lower (by a factor of 10–100) than the estimated 10–20% figure conjectured by some researchers; for example, in Germany, the leakage rate is only 0.1% (less than the natural gas leak rate of 0.7%). At most, such leakage would likely be no more than 1–2% even with widespread hydrogen use, using present technology.

Costs

When evaluating costs, fossil fuels are generally used as the cheapest reference. The energy content of these fuels is not a product of human effort and so has no cost assigned to it. Only the extraction, refining, transportation and production costs are considered. On the other hand, the energy content of a unit of hydrogen fuel must be manufactured, and so has a significant cost, on top of all the costs of refining, transportation, and distribution. Systems which use renewably generated electricity more directly, for example in trolleybuses, or in battery electric vehicles may have a significant economic advantage because there are fewer conversion processes required between primary energy source and point of use.

The barrier to lowering the price of high purity hydrogen is cost of more than 35 kWh of electricity used to generate each kilogram of hydrogen gas.

Demonstrated advances in electrolyzer and fuel cell technology by ITM Power are claimed to have made significant in-roads into addressing the cost of electrolysing water to make hydrogen, making cost effective production of hydrogen from off-grid renewable sources (compared to hydrocarbon fuels) possible for refueling transport and applications for short range business and residential use.

Hydrogen pipelines are more expensive than even long-distance electric lines. Hydrogen is about three times bulkier in volume than natural gas for the same enthalpy, and hydrogen accelerates the cracking of steel (hydrogen embrittlement), which increases maintenance costs, leakage rates, and material costs. The difference in cost is likely to expand with newer technology: wires suspended in air can utilize higher voltage with only marginally increased material costs, but higher pressure pipes require proportionally more material.

Setting up a hydrogen economy would require huge investments in the infrastructure to store and distribute hydrogen to vehicles. In contrast, battery electric vehicles, which are already publicly available, would not necessitate immediate expansion of the existing infrastructure for electricity transmission and distribution, since much of the electricity currently being generated by power plants goes unused at night when the majority of electric vehicles would be recharged. A study conducted by the Pacific Northwest National Laboratory for the US Department of Energy in December 2006 found that the idle off-peak grid capacity in the US would be sufficient to power 84% of all vehicles in the US if they all were immediately replaced with electric vehicles.

Different production methods each have differing associated investment and marginal costs. The energy and feedstock could originate from a multitude of sources i.e. natural gas, nuclear, solar, wind, biomass, coal, other fossil fuels, and geothermal.

Natural Gas at Small Scale

Uses steam reformation. Requires 15.9 million cubic feet (450,000 m^3) of gas, which, if produced by small 500 kg/day reformers at the point of dispensing (i.e., the filling station), would equate to 777,000 reformers costing $1 trillion dollars and producing 150 million tons of hydrogen gas annually. Obviates the need for distribution infrastructure dedicated to hydrogen. $3.00 per GGE (Gallons of Gasoline Equivalent)

Nuclear

Provides energy for electrolysis of water. Would require 240,000 tons of unenriched uranium — that's 2,000 600-megawatt power plants, which would cost $840 billion, or about $2.50 per GGE.

Solar

Provides energy for electrolysis of water. Would require 2,500 kWh of sun per square meter, 113 million 40-kilowatt systems, which would cost $22 trillion, or about $9.50 per GGE.

Wind

Provides energy for electrolysis of water. At 7 meters per second average wind speed, it would require 1 million 2-MW wind turbines, which would cost $3 trillion dollars, or about $3.00 per GGE.

Biomass

Gasification plants would produce gas with steam reformation. 1.5 billion tons of dry biomass, 3,300 plants which would require 113.4 million acres (460,000 km^2) of farm to produce the biomass. $565 billion dollars in cost, or about $1.90 per GGE

Coal

FutureGen plants use coal gasification then steam reformation. Requires 1 billion tons of coal or about 1,000 275-megawatt plants with a cost of about $500 billion, or about $1 per GGE.

- DOE Cost targets

Examples and pilot programs

A Mercedes-Benz O530 Citaro powered by hydrogen fuel cells, in Brno, Czech Republic

Several domestic U.S. automobile manufactures have committed to develop vehicles using hydrogen. The distribution of hydrogen for the purpose of transportation is currently being tested around the world, particularly in Portugal, Iceland, Norway, Denmark, Germany, California, Japan and Canada, but the cost is very high.

Some hospitals have installed combined electrolyzer-storage-fuel cell units for local emergency power. These are advantageous for emergency use because of their low maintenance requirement and ease of location compared to internal combustion driven generators.

Iceland has committed to becoming the world's first hydrogen economy by the year 2050. Iceland is in a unique position. Presently, it imports all the petroleum products necessary to power its automobiles and fishing fleet. Iceland has large geothermal resources, so much that the local price of electricity actually is *lower* than the price of the hydrocarbons that could be used to produce that electricity.

Iceland already converts its surplus electricity into exportable goods and hydrocarbon replacements. In 2002, it produced 2,000 tons of hydrogen gas by electrolysis—primarily for the production of ammonia (NH_3) for fertilizer. Ammonia is produced, transported, and used throughout the world, and 90% of the cost of ammonia is the cost of the energy to produce it. Iceland is also developing an aluminium -smelting industry. Aluminium costs are primarily driven by the cost of the electricity to run the smelters. Either of these industries could effectively export all of Iceland's potential geothermal electricity.

Neither industry directly replaces hydrocarbons. Reykjavík, Iceland, had a small pilot fleet of city buses running on compressed hydrogen, and research on powering the nation's fishing fleet with hydrogen is under way. For more practical purposes, Iceland might process imported oil with hydrogen to extend it, rather than to replace it altogether.

The Reykjavík buses are part of a larger program, HyFLEET:CUTE, operating hydrogen fueled buses in eight European cities. HyFLEET:CUTE buses also operate in Beijing and Perth (see below).

A pilot project demonstrating a hydrogen economy is operational on the Norwegian island of Utsira. The installation combines wind power and hydrogen power. In periods when there is surplus wind energy, the excess power is used for generating hydrogen by electrolysis. The hydrogen is stored, and is available for power generation in periods when there is little wind.

A joint venture between NREL and Xcel Energy is combining wind power and hydrogen power in the same way in Colorado.

Hydro in Newfoundland and Labrador are converting the current wind-diesel Power System on the remote island of Ramea into a Wind-Hydrogen Hybrid Power Systems facility.

A similar pilot project on Stuart Island uses solar power, instead of wind power, to generate electricity. When excess electricity is available after the batteries are full, hydrogen is generated by electrolysis and stored for later production of electricity by fuel cell.

The UK started a fuel cell pilot program in January 2004, the program ran two Fuel cell buses on route 25 in London until December 2005, and switched to route RV1 until January 2007.

The Hydrogen Expedition is currently working to create a hydrogen fuel cell-powered ship and using it to circumnavigate the globe, as a way to demonstrate the capability of hydrogen fuel cells.

Western Australia's Department of Planning and Infrastructure currently operates three Daimler Chrysler Citaro fuel cell buses as part of its Sustainable Transport Energy for Perth Fuel Cells Bus Trial in Perth. The buses are operated by Path Transit on regular Transperth public bus routes. The trial began in September 2004 and concluded in September 2006. The buses' fuel cells use a proton exchange membrane system and are supplied with raw hydrogen from a BP refinery in Kwinana, south of Perth. The hydrogen is a byproduct of the refinery's industrial process. The buses are refueled at a station in the northern Perth suburb of Malaga.

The United Nations Industrial Development Organization (UNIDO) and the Turkish Ministry of Energy and Natural Resources have signed in 2003 a $40M Trust Fund Agreement for the creation in Istanbul of the International Centre for Hydrogen Energy Technologies (UNIDO-ICHET), which started operation in 2004. A hydrogen forklift, a hydrogen cart and a mobile house powered by renewable energies are being demonstrated in UNIDO-ICHET's premises. An uninterruptible power supply system has been has been working since April 2009 in the headquarters of Istanbul Sea Buses company.

Hydrogen-using alternatives to a fully distributive hydrogen economy

Hydrogen is simply a method to store and transmit energy. Various alternative energy transmission and storage scenarios which begin with hydrogen production, but do not use it for all parts of the store and transmission infrastructure, may be more economic, in both near and far term. These include:

Ammonia economy

An alternative to gaseous hydrogen as an energy carrier is to bond it with nitrogen from the air to produce ammonia, which can be easily liquefied, transported, and used (directly or indirectly) as a clean and renewable fuel. The toxicity of ammonia is one of the main issues holding back an ammonia economy.

Hydrogen production of greenhouse-neutral alcohol

The methanol economy is a synfuel production energy plan which may begin with hydrogen production. Hydrogen in a full "hydrogen economy" was initially suggested as a way to make renewable energy in non-polluting form, available to automobiles which are not all-electric. However, a theoretical alternative to direct elemental hydrogen use in vehicles would address the same problem by using centrally produced hydrogen immediately, to make liquid fuels from a CO_2 source. Thus, hydrogen would be used captively to make fuel, and would not require expensive hydrogen transportation or storage. To be greenhouse-neutral, the source for CO_2 in such a plan would need to be from air, biomass, or from CO_2 which would otherwise be scheduled to be released into the air from non-carbon-capture fuel-burning power plants (of which there are likely to be many in the future, since economic carbon capture and storage is site-dependent and difficult to retrofit).

Captive hydrogen production to make more easily transportable and storable transportation fuels (such as alcohols or methane), using CO_2 input, can thus be seen as the artificial, or "non-biological green" analogue of biomass, biodiesel, and vegetable oil technologies. Green plants, in a sense, already use solar power to make captively produced hydrogen, which is then used to make easier-to-store-and-use fuels. In the plant leaf, solar energy is used to split water into hydrogen and oxygen, the latter gas being released. The hydrogen produced is then used "on-site" by the plant to reduce CO_2 from the air into various fuels, such as the cellulose in wood, and the seed oils which are the basis for vegetable oil, biodiesel, etc. Hydrogen-produced alcohols would thus act as a very similar, but non-biological greenhouse-neutral way of producing energy stores and carriers from locally produced hydrogen (solar or otherwise). By not requiring hydrogen to be produced entirely by plant leaves, they would save cropland. The fuels, however, would be used for purposes of transportation exactly as in plans to use "green fuels." Rather than be transported from its production site, hydrogen in such plans would instead be used centrally and immediately, to produce renewable liquid fuels which may be cycled into the present transportation infrastructure directly, requiring almost no infrastructure change. Moreover, methanol fuel cells are beginning to be demonstrated, so methanol may eventually compete directly with hydrogen in the fuel cell and hybrid market.

The electrical grid plus synthetic methanol fuel cells

Many of the hybrid strategies described above, using captive hydrogen to generate other more easily usable fuels, might be more effective than hydrogen-production alone. Short term energy storage (meaning the energy is used not long after it has been captured) may be best accomplished with battery or even ultracapacitor storage. Longer term energy storage (meaning the energy is used weeks or months after capture) may be better done with synthetic methane or alcohols, which can be stored indefinitely at relatively low cost, and even used directly in some type of fuel cells, for electric vehicles. These strategies dovetail well with the recent interest in Plug-in Hybrid Electric Vehicles, or PHEVs, which use a hybrid strategy of electrical and fuel storage for their energy needs. Hydrogen storage has been proposed by some to be optimal in a narrow range of energy storage time, probably somewhere between a few days and a few weeks. This range is subject to further narrowing with any improvements in battery technology. It is always possible that some kind of breakthrough in hydrogen storage or generation could occur, but this is unlikely given the physical and chemical limitations of the technical choices are fairly well understood.

Captive hydrogen synthetic methane production

In a similar way as with synthetic alcohol production, hydrogen can be used on-site to directly (nonbiologically) produce greenhouse-neutral gaseous fuels. Thus, captive-hydrogen-mediated production of greenhouse-neutral methane has been proposed (note that this is the reverse of the present method of acquiring hydrogen from natural methane, but one that does not require ultimate burning and release of fossil fuel carbon). Captive hydrogen (and carbon dioxide) may be used onsite to *synthesize* methane, using the Sabatier reaction. This process is about 80% efficient, reducing the round trip efficiency to about 20 to 30%, depending on the method of fuel utilization. This is even lower than hydrogen, but the storage costs drop by at least a factor of 3, because of methane's higher boiling point and higher energy density. Liquid methane has 3.2 times the energy density of liquid hydrogen and is easier to store. Additionally, the pipe infrastructure (natural gas pipelines) are already in place. Natural-gas-powered vehicles already exist, and are known to be easier to adapt from existing internal engine technology, than internal combustion autos running directly on hydrogen. Experience with natural gas powered vehicles shows that methane storage is inexpensive, once one has accepted the cost of conversion to store the fuel. However, the cost of alcohol storage is even lower, so this technology would need to produce methane at a considerable savings with regard to alcohol production. Ultimate mature prices of fuels in the competing technologies are not presently known, but both are expected to offer substantial infrastructural savings over attempts to transport and use hydrogen directly.

Chapter- 6

Electric Double-layer Capacitor and Nanowire Battery

Electric double-layer Capacitor

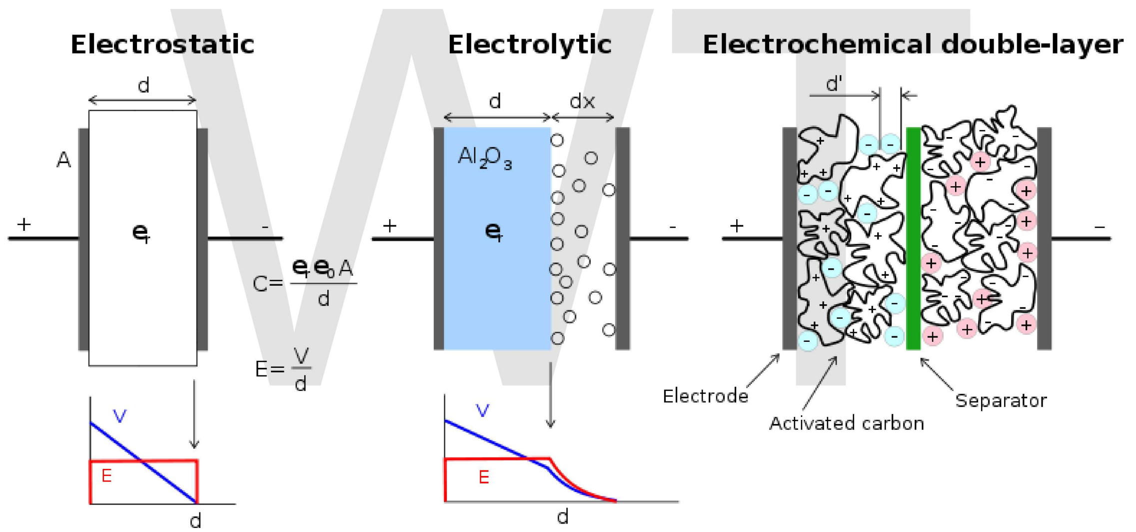
Maxwell Technologies "MC" and "BC" series supercapacitors (up to 3000 farad capacitance)

An **electric double-layer capacitor** (**EDLC**), also known as **supercapacitor**, **supercondenser**, **pseudocapacitor**, **electrochemical double layer capacitor**, or **ultracapacitor**, is an electrochemical capacitor with relatively high energy density. Compared to conventional electrolytic capacitors the energy density is typically on the order of thousands of times greater. In comparison with conventional batteries or fuel cells, EDLCs also have a much higher power density.

A typical D-cell sized electrolytic capacitor displays capacitance in the range of tens of millifarads. The same size EDLC might reach several farads, an improvement of two orders of magnitude. EDLCs usually yield a lower working voltage; as of 2010 larger double-layer capacitors have capacities up to 5,000 farads. Also in 2010, the highest available EDLC energy density is 30 Wh/kg (although 85 Wh/kg has been achieved at room temperature in the lab), lower than rapid-charging lithium-titanate batteries.

EDLCs have a variety of commercial applications, notably in "energy smoothing" and momentary-load devices. They have applications as energy-storage devices used in vehicles, and for smaller applications like home solar energy systems where extremely fast charging is a valuable feature.

Concept



Comparison of construction diagrams of three capacitors. Left: "normal" capacitor, middle: electrolytic, right: electric double-layer capacitor

In a conventional capacitor, energy is stored by the removal of charge carriers, typically electrons, from one metal plate and depositing them on another. This charge separation creates a potential between the two plates, which can be harnessed in an external circuit. The total energy stored in this fashion is proportional to both the amount of charge stored and the potential between the plates. The amount of charge stored per unit voltage is essentially a function of the size, the distance, and the material properties of the plates and the material in between the plates (the dielectric), while the potential between the plates is limited by breakdown of the dielectric. The dielectric controls the capacitor's voltage. Optimizing the material leads to higher energy density for a given size of capacitor.

EDLCs do not have a conventional dielectric. Rather than two separate plates separated by an intervening substance, these capacitors use "plates" that are in fact two layers of the same substrate, and their electrical properties, the so-called "electrical double layer", result in the effective separation of charge despite the vanishingly thin (on the order of nanometers) physical separation of the layers. The lack of need for a bulky layer of dielectric permits the packing of plates with much larger surface area into a given size, resulting in high capacitances in practical-sized packages.

In an electrical double layer, each layer by itself is quite conductive, but the physics at the interface where the layers are effectively in contact means that no significant current can flow between the layers. However, the double layer can withstand only a low voltage, which means that electric double-layer capacitors rated for higher voltages must be made of matched series-connected individual EDLCs, much like series-connected cells in higher-voltage batteries.

EDLCs have much higher power density than batteries. Power density combines the energy density with the speed that the energy can be delivered to the load. Batteries, which are based on the movement of charge carriers in a liquid electrolyte, have relatively slow charge and discharge times. Capacitors, on the other hand, can be charged or discharged at a rate that is typically limited by current heating of the electrodes. So while existing EDLCs have *energy* densities that are perhaps 1/10th that of a conventional battery, their *power* density is generally 10 to 100 times as great (see diagram, above).

History

General Electric engineers experimenting with devices using porous carbon electrodes first observed the EDLC effect in 1957. They believed that the energy was stored in the carbon pores and the device exhibited "exceptionally high capacitance", although the mechanism was unknown at that time.

General Electric did not immediately follow up on this work. In 1966 researchers at Standard Oil of Ohio developed the modern version of the devices, after they accidentally re-discovered the effect while working on experimental fuel cell designs. Their cell design used two layers of activated charcoal separated by a thin porous insulator, and this basic mechanical design remains the basis of most electric double-layer capacitors.

Standard Oil also failed to commercialize their invention, licensing the technology to NEC, who finally marketed the results as “supercapacitors” in 1978, to provide backup power for maintaining computer memory. The market expanded slowly for a time, but starting around the mid-1990s various advances in materials science and refinement of the existing systems led to rapidly improving performance and an equally rapid reduction in cost.

The first trials of supercapacitors in industrial applications were carried out for supporting the energy supply to robots.

In 2005 aerospace systems and controls company Diehl Luftfahrt Elektronik GmbH chose supercapacitors to power emergency actuation systems for doors and evacuation slides in airliners, including the new Airbus 380 jumbo jet. In 2005, the ultracapacitor market was between US $272 million and $400 million, depending on the source.

As of 2007 all solid state micrometer-scale electric double-layer capacitors based on advanced superionic conductors had been for low-voltage electronics such as deep-sub-voltage nanoelectronics and related technologies (the 22 nm technological node of CMOS and beyond).

Comparisons

Supercapacitors have several disadvantages and advantages relative to batteries, as described below.

Disadvantages

- The amount of energy stored per unit weight is generally lower than that of an electrochemical battery (3–5 W·h/kg for an standard ultracapacitor, although 85 W.h/kg has been achieved in the lab as of 2010 compared to 30-40 W·h/kg for a lead acid battery), and about 1/1,000th the volumetric energy density of gasoline.
- Typical of any capacitor, the voltage varies with the energy stored. Effective storage and recovery of energy requires complex electronic control and switching equipment, with consequent energy loss
- Has the highest dielectric absorption of any type of capacitor.
- High self-discharge - the rate is considerably higher than that of an electrochemical battery.
- Cells hold low voltages - serial connections are needed to obtain higher voltages. Voltage balancing is required if more than three capacitors are connected in series.
- Linear discharge voltage prevents use of the full energy spectrum.
- Due to rapid and large release of energy (albeit over short times), EDLC's have the potential to be deadly to humans.

Advantages

- Long life, with little degradation over hundreds of thousands of charge cycles. Due to the capacitor's high number of charge-discharge cycles (millions or more compared to 200 to 1000 for most commercially available rechargeable batteries) it will last for the entire lifetime of most devices, which makes the device environmentally friendly. Rechargeable batteries wear out typically over a few years, and their highly reactive chemical electrolytes present a disposal and safety hazard. Battery lifetime can be optimised by charging only under favorable conditions, at an ideal rate and, for some chemistries, as infrequently as possible. EDLCs can help in conjunction with batteries by acting as a charge conditioner, storing energy from other sources for load balancing purposes and then using any excess energy to charge the batteries at a suitable time.

- Low cost *per cycle*
- Good reversibility
- Very high rates of charge and discharge.
- Extremely low internal resistance (ESR) and consequent high cycle efficiency (95% or more) and extremely low heating levels
- High output power
- High specific power. According to ITS (Institute of Transportation Studies, Davis, California) test results, the specific power of electric double-layer capacitors can exceed 6 kW/kg at 95% efficiency
- Improved safety, no corrosive electrolyte and low toxicity of materials.
- Simple charge methods—no full-charge detection is needed; no danger of overcharging.

Materials

In general, EDLCs improve storage density through the use of a nanoporous material, typically activated charcoal, in place of the conventional insulating barrier. Activated charcoal is a powder made up of extremely small and very "rough" particles, which, in bulk, form a low-density heap with many holes that resembles a sponge. The overall surface area of even a thin layer of such a material is many times greater than a traditional material like aluminum, allowing many more charge carriers (ions or radicals from the electrolyte) to be stored in any given volume. The charcoal, which is not a good insulator, replaces the excellent insulators used in conventional devices, so in general EDLCs can only use low potentials on the order of 2 to 3 V.

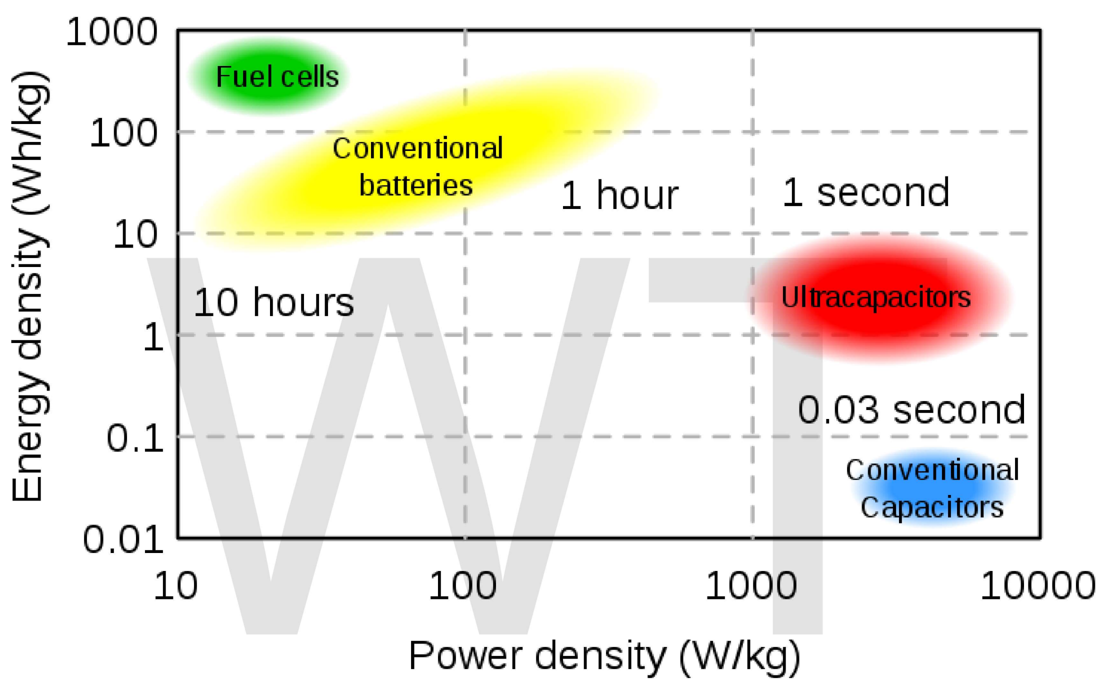
Activated charcoal is not the "perfect" material for this application. The charge carriers are actually (in effect) quite large—especially when surrounded by solventmolecules—and are often larger than the holes left in the charcoal, which are too small to accept them, limiting the storage.

As of 2010 virtually all commercial supercapacitors use powdered activated carbon made from coconut shells. Higher performance devices are available, at a significant cost increase, based on synthetic carbon precursors that are activated with potassium hydroxide (KOH).

Research in EDLCs focuses on improved materials that offer higher *usable* surface areas.

- Graphene has excellent surface area per unit of gravimetric or volumetric densities, is highly conductive and can now be produced in various labs, but is not available in production quantities. Specific energy density of 85.6 Wh/kg at room temperature and 136 Wh/kg at 80 °C (all based on the total electrode weight), measured at a current density of 1 A/g have been observed. These energy density values are comparable to that of the Nickel metal hydride battery. The device makes full utilization of the highest intrinsic surface capacitance and specific surface area of single-layer graphene by preparing curved graphene sheets that do not restack face-to-face. The curved shape enables the formation of mesopores accessible to and wettable by environmentally benign ionic liquids capable of operating at a voltage >4 V.

- Carbon nanotubes have excellent nanoporosity properties, allowing tiny spaces for the polymer to sit in the tube and act as a dielectric. Carbon nanotubes can store about the same charge as charcoal (which is almost pure carbon) per unit surface area but nanotubes can be arranged in a more regular pattern that exposes greater suitable surface area.



Ragone chart showing energy density vs.power density for various energy-storage devices

- Some polymers (eg. polyacenes) have a redox (reduction-oxidation) storage mechanism along with a high surface area.

- Carbon aerogel provides extremely high surface area gravimetric densities of about 400–1000 m²/g. The electrodes of aerogel supercapacitors are a composite material usually made of non-woven paper made from carbon fibers and coated with organic aerogel, which then undergoes pyrolysis. The carbon fibers provide structural integrity and the aerogel provides the required large surface area. Small aerogel supercapacitors are being used as backup electricity storage in microelectronics. Aerogel capacitors can only work at a few volts; higher voltages ionize the carbon and damage the capacitor. Carbon aerogel capacitors have achieved 325 J/g (90 W·h/kg) energy density and 20 W/g power density.

- Solid activated carbon, also termed *consolidated amorphous carbon* (CAC). It can have a surface area exceeding 2800 m^2/g and may be cheaper to produce than aerogel carbon.

- Tunable nanoporous carbon exhibits systematic pore size control. H_2 adsorption treatment can be used to increase the energy density by as much as 75% over what was commercially available as of 2005.

- Mineral-based carbon is a nonactivated carbon, synthesised from metal or metalloid carbides, e.g. SiC, TiC, Al_4C_3. The synthesised nanostructured porous carbon, often called Carbide Derived Carbon (CDC), has a surface area of about 400 m^2/g to 2000 m^2/g with a specific capacitance of up to 100 F/mL (in organic electrolyte). As of 2006 this material was used in a supercapacitor with a volume of 135 mL and 200 g weight having 1.6 kF capacitance. The energy density is more than 47 kJ/L at 2.85 V and power density of over 20 W/g.

- In August 2007 researchers combined a biodegradable paper battery with aligned carbon nanotubes, designed to function as both a lithium-ion battery and a supercapacitor (called *bacitor*). The device employed an ionic liquid, essentially a liquid salt, as the electrolyte. The paper sheets can be rolled, twisted, folded, or cut with no loss of integrity or efficiency, or stacked, like ordinary paper (or a voltaic pile), to boost total output. They can be made in a variety of sizes, from postage stamp to broadsheet. Their light weight and low cost make them attractive for portable electronics, aircraft, automobiles, and toys (such as model aircraft), while their ability to use electrolytes in blood make them potentially useful for medical devices such as pacemakers.

- Other teams are experimenting with custom materials made of activated polypyrrole, and nanotube-impregnated papers.

Density

The energy density of existing commercial EDLCs ranges from around 0.5 to 30 W·h/kg including lithium ion capacitors, known also as a "hybrid capacitor". Experimental electric double-layer capacitors have demonstrated densities of 30 W·h/kg and have been shown to be scalable to at least 136 W·h/kg, while others expect to offer energy densities of about 400 W·h/kg. For comparison, a conventional lead-acid battery stores typically 30 to 40 W·h/kg and modern lithium-ion batteries about 160 W·h/kg. Gasoline has a net calorific value (NCV) of around 12,000 W·h/kg; automobile applications operate at about 20% tank-to-wheel efficiency, giving an effective energy density of 2,400 W·h/kg.

Applications

Vehicles

Heavy and public transport

Some of the earliest uses were motor startup capacitors for large engines in tanks and submarines, and as the cost has fallen they have started to appear on diesel trucks and railroad locomotives. In the 00's they attracted attention in the green energy world, where their ability to charge much faster than batteries makes them particularly suitable for regenerative braking applications. New technology in development could potentially make EDLCs with high enough energy density to be an attractive replacement for batteries in all-electric cars and plug-in hybrids, as EDLCs charge quickly and are stable with respect to temperature.

China is experimenting with a new form of electric bus (capabus) that runs without powerlines using large onboard EDLCs, which quickly recharge whenever the bus is at any bus stop (under so-called **electric umbrellas**), and fully charge in the terminus. A few prototypes were being tested in Shanghai in early 2005. In 2006, two commercial bus routes began to use electric double-layer capacitor buses; one of them is route 11 in Shanghai.

In 2001 and 2002 VAG, the public transport operator in Nuremberg, Germany tested an hybrid bus that uses a diesel-electric battery drive system with electric double-layer capacitors. Since 2003 Mannheim Stadtbahn in Mannheim, Germany has operated a light-rail vehicle (LRV) that uses EDLCs to store braking energy.

Other public transport manufacturers are developing EDLC technology, including mobile storage and a stationary trackside power supply.

A triple hybrid forklift truck uses fuel cells and batteries as primary energy storage and EDLCs to supplement this energy storage solution.

Automotive

Ultracapacitors are used in some concept prototype vehicles, in order to keep batteries within resistive heating limits and extend battery life. The ultrabattery combines a supercapacitor and a battery in one unit, creating an electric vehicle battery that lasts longer, costs less and is more powerful than current plug-in hybrid electric vehicles (PHEVs).

Motor racing

The FIA, the governing body for many motor racing events, proposed in the *Power-Train Regulation Framework for Formula 1* version 1.3 of 23 May 2007 that a new set of power train regulations be issued that includes a hybrid drive of up to 200 kW input and output power using "superbatteries" made with both batteries and supercapacitors.

Consumer electronics

EDLCs can be used in PC Cards, flash photography devices in digital cameras, flashlights, portable media players, and in automated meter reading, particularly where extremely fast charging is desirable.

In 2007, a cordless electric screwdriver that uses an EDLC for energy storage was produced. It charges in 90 seconds, retains 85% of the charge after 3 months, and holds enough charge for about half the screws (22) a comparable screwdriver with a rechargeable battery will handle (37). Two LED flashlights using EDLCs were released in 2009. They charge in 90 seconds.

Alternative energy

The idea of replacing batteries with capacitors in conjunction with novel energy sources became a conceptual umbrella of the Green Electricity (GEL) Initiative, introduced by Dr. Alexander Bell. One successful GEL Initiative concept was a muscle-driven autonomous solution that employs a multi-farad EDLC as energy storage to power a variety of portable electrical and electronic devices such as MP3 players, AM/FM radios, flashlights, cell phones, and emergency kits.

Price

Costs have fallen quickly, with cost per kilojoule dropping faster than cost per farad. As of 2006 the cost of supercapacitors was 1 cent per farad and $2.85 per kilojoule, and was expected to drop further.

Market

According to Innovative Research and Products (iRAP), ultracapacitor market growth will continue during 2009 to 2014. Worldwide business, over US$275 million in 2009, will continue to grow at an AAGR of 21.4% through 2014.

Nanowire battery

A **nanowire battery** is a lithium-ion battery invented by a team led by Dr. Yi Cui at Stanford University in 2007. The team's invention consists of a stainless steel anode covered in silicon nanowires, to replace the traditional graphite anode. Silicon, which stores ten times more lithium than graphite, allows a far greater energy density on the anode, thus reducing the mass of the battery. The large surface area further allows for fast charging and discharging.

Design

Traditional silicon anodes were researched and dismissed due to the tendency of silicon to crack and become unusable because it swelled with lithium during operation. The nano-wires do not suffer from this flaw. According to Dr. Cui, the battery reached 10x density on the first charge and plateaued to 8x density on subsequent charges. In order to take advantage of this anode advancement, an equivalent cathode advancement is required to achieve the increased storage density.

Commercialization is expected to occur in 2012 with the batteries costing the same or less per watt hour than conventional lithium-ion batteries. The next milestone, life cycle testing, should be completed and the team expects to achieve at least one thousand charge cycles from nano-wire batteries.

In September 2010, Dr. Yi Cui's team demonstrated that 250 charge cycles are possible before the charge capacity drops below 80 percent of its initial storage capacity. The team expects to reach 3,000 charge cycles by 2012. Reaching this goal would make nano-wire batteries viable for use in electric vehicles. A prototype for use in cellular phones and other electronic devices is expected to be delivered by the first quarter of 2011.

Chapter- 7

Wireless Energy Transfer

Wireless energy transfer or **wireless power** is the transmission of electrical energy from a power source to an electrical load without interconnecting wires. Wireless transmission is useful in cases where interconnecting wires are inconvenient, hazardous, or impossible. The problem of wireless power transmission differs from that of wireless telecommunications, such as radio. In the latter the proportion of energy received becomes critical only if it is too low for the signal to be distinguished from the background noise. With wireless power, efficiency is the more significant parameter. A large part of the energy sent out by the generating plant must arrive at the receiver or receivers to make the system economical.

The most common form of wireless power transmission is carried out using direct induction followed by resonant magnetic induction. Other methods under consideration include electromagnetic radiation in the form of microwaves or lasers.

Electric energy transfer

An electric current flowing through a conductor carries electrical energy. When an electric current passes through a circuit there is an electric field in the dielectric surrounding the conductor; magnetic field lines around the conductor and lines of electric force radially about the conductor.

In a direct current circuit, if the current is continuous, the fields are constant; there is a condition of stress in the space surrounding the conductor, which represents stored electric and magnetic energy, just as a compressed spring or a moving mass represents stored energy. In an alternating current circuit, the fields also alternate; that is, with every half wave of current and of voltage, the magnetic and the electric field start at the conductor and run outwards into space with the velocity of light. Where these alternating fields impinge on another conductor a voltage and a current are induced.

Any change in the electrical conditions of the circuit, whether internal or external involves a readjustment of the stored magnetic and electric field energy of the circuit, that is, a so-called transient. A transient is of the general character of a condenser discharge through an inductive circuit. The phenomenon of the condenser discharge through an inductive circuit therefore is of the greatest importance to the engineer, as the foremost cause of high-voltage and high-frequency troubles in electric circuits.

Electromagnetic induction is proportional to the intensity of the current and voltage in the conductor which produces the fields and to the frequency. The higher the frequency the more intense the induction effect. Energy is transferred from a conductor that produces the fields (the primary) to any conductor on which the fields impinge (the secondary). Part of the energy of the primary conductor passes inductively across space into secondary conductor and the energy decreases rapidly along the primary conductor. A high frequency current does not pass for long distances along a conductor but rapidly transfers its energy by induction to adjacent conductors. Higher induction resulting from the higher frequency is the explanation of the apparent difference in the propagation of high frequency disturbances from the propagation of the low frequency power of alternating current systems. The higher the frequency the more preponderant become the inductive effects that transfer energy from circuit to circuit across space. The more rapidly the energy decreases and the current dies out along the circuit, the more local is the phenomenon.

The flow of electric energy thus comprises phenomena inside of the conductor and phenomena in the space outside of the conductor—the electric field—which, in a continuous current circuit, is a condition of steady magnetic and dielectric stress, and in an alternating current circuit is alternating, that is, an electric wave launched by the conductor to become far-field electromagnetic radiation traveling through space with the velocity of light.

In electric power transmission and distribution, the phenomena inside of the conductor are of main importance, and the electric field of the conductor is usually observed only incidentally. Inversely, in the use of electric power for *radio* telecommunications it is only the electric and magnetic fields outside of the conductor, that is electromagnetic radiation, which is of importance in transmitting the message. The phenomenon in the conductor, the current in the launching structure, is not used.

The electric charge displacement in the conductor produces a magnetic field and resultant lines of electric force. The magnetic field is a maximum in the direction concentric, or approximately so, to the conductor. That is, a ferromagnetic body tends to set itself in a direction at right angles to the conductor. The electric field has a maximum in a direction radial, or approximately so, to the conductor. The electric field component tends in a direction radial to the conductor and dielectric bodies may be attracted or repelled radially to the conductor.

The electric field of a circuit over which energy flows has three main axes at right angles with each other:

1. The *magnetic field*, concentric with the conductor.
2. The *lines of electric force*, radial to the conductor.
3. The *power gradient*, parallel to the conductor.

Where the electric circuit consists of several conductors, the electric fields of the conductors superimpose upon each other, and the resultant magnetic field lines and lines of electric force are not concentric and radial respectively, except *approximately in the immediate neighborhood* of the conductor. Between parallel conductors they are conjugate of circles. Neither the power consumption in the conductor, nor the magnetic field, nor the electric field, are proportional to the flow of energy through the circuit. However, the product of the intensity of the magnetic field and the intensity of the electric field is proportional to the flow of energy or the power, and the power is therefore resolved into a product of the two components **i** and **e**, which are chosen proportional respectively to the intensity of the magnetic field and of the electric field. The component called the current is defined as that factor of the electric power which is proportional to the magnetic field, and the other component, called the voltage, is defined as that factor of the electric power which is proportional to the electric field.

In *radio* telecommunications the electric field of the transmit antenna propagates through space as a radio wave and impinges upon the receive antenna where it is observed by its magnetic and electric effect. Radio waves, microwaves, infrared radiation, visible light, ultraviolet radiation, X rays and gamma rays are shown to be the same electromagnetic radiation phenomenon, differing one from the other only in frequency of vibration.

Electromagnetic induction

Energy transfer by electromagnetic induction is typically magnetic but capacitive coupling can also be achieved.

Electrodynamic induction method

The electrodynamic induction wireless transmission technique is near field over distances up to about one-sixth of the wavelength used. Near field energy itself is non-radiative but some radiative losses do occur. In addition there are usually resistive losses. With electrodynamic induction, electric current flowing through a primary coil creates a magnetic field that acts on a secondary coil producing a current within it. Coupling must be tight in order to achieve high efficiency. As the distance from the primary is increased, more and more of the magnetic field misses the secondary. Even over a relatively short range the inductive coupling is grossly inefficient, wasting much of the transmitted energy.

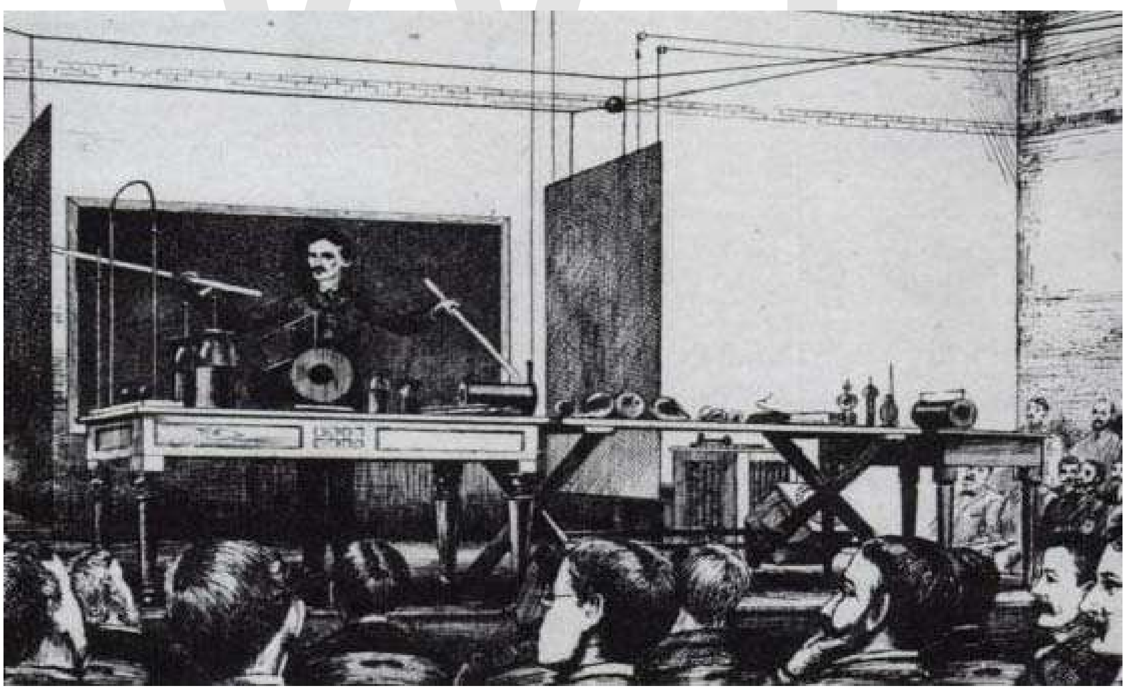
This action of an electrical transformer is the simplest form of wireless power transmission. The primary and secondary circuits of a transformer are not directly connected. Energy transfer takes place through a process known as mutual induction. Principal functions are stepping the primary voltage either up or down and electrical isolation. Mobile phone and electric toothbrush battery chargers, and electrical power distribution transformers are examples of how this principle is used. Induction cookers use this method. The main drawback to this basic form of wireless transmission is short range. The receiver must be directly adjacent to the transmitter or induction unit in order to efficiently couple with it.

The application of resonance improves the situation somewhat. When resonant coupling is used the transmitter and receiver inductors are tuned to a mutual frequency and the drive current is modified from a sinusoidal to a nonsinusoidal transient waveform. Pulse power transfer occurs over multiple cycles. In this way significant power may be transmitted over a distance of up to a few times the size of the primary coil. Transmitting and receiving coils are usually single layer solenoids or flat spirals with series capacitors, which, in combination, allow the receiving element to be tuned to the transmitter frequency.

Common uses of resonance-enhanced electrodynamic induction are charging the batteries of portable devices such as laptop computers and cell phones, medical implants and electric vehicles. A localized charging technique selects the appropriate transmitting coil in a multilayer winding array structure. Resonance is used in both the wireless charging pad (the transmitter circuit) and the receiver module (embedded in the load) to maximize energy transfer efficiency. This approach is suitable for universal wireless charging pads for portable electronics such as mobile phones. It has been adopted as part of the Qi wireless charging standard.

It is also used for powering devices having no batteries, such as RFID patches and contactless smartcards, and to couple electrical energy from the primary inductor to the helical resonator of Tesla coil wireless power transmitters.

Electrostatic induction method



The **Tesla effect**. is the illumination of two exhausted tubes by means of a powerful, rapidly alternating electrostatic field created between two vertical metal sheets suspended from the ceiling on insulating cords. It exploits the physics of electrostatic induction.

Electrostatic or capacitive coupling is the passage of electrical energy through a dielectric. In practice it is an electric field gradient or differential capacitance between two or more insulated terminals, plates, electrodes, or nodes that are elevated over a conducting ground plane. The electric field is created by an alternating current of high potential and high frequency. The capacitance between fixed plates and the powered device form a voltage divider.

The electric energy transmitted through the atmosphere can be utilized by receiving devices. Tesla demonstrated the illumination of wireless lamps by energy that was coupled to them through an alternating electric field.

"Instead of depending on *electrodynamic induction* at a distance to light the tube . . . [the] ideal way of lighting a hall or room would . . . be to produce such a condition in it that an illuminating device could be moved and put anywhere, and that it is lighted, no matter where it is put and without being electrically connected to anything. I have been able to produce such a condition by creating in the room a powerful, *rapidly alternating electrostatic field*. For this purpose I suspend a sheet of metal a distance from the ceiling on insulating cords and connect it to one terminal of the induction coil, the other terminal being preferably connected to the ground. Or else I suspend two sheets . . . each sheet being connected with one of the terminals of the coil, and their size being carefully determined. An exhausted tube may then be carried in the hand anywhere between the sheets or placed anywhere, even a certain distance beyond them; it remains always luminous."

The principle of electrostatic induction is applicable to the electrical conduction wireless transmission method.

Electromagnetic radiation

Far field methods achieve longer ranges, often multiple kilometer ranges, where the distance is much greater than the diameter of the device(s). The main reason for longer ranges with radio wave and optical devices is the fact that electromagnetic radiation in the far-field can be made to match the shape of the receiving area (using high directivity antennas or well-collimated Laser Beam) thereby delivering almost all emitted power at long ranges. The maximum directivity for antennas is physically limited by diffraction.

Beamed power, size, distance, and efficiency

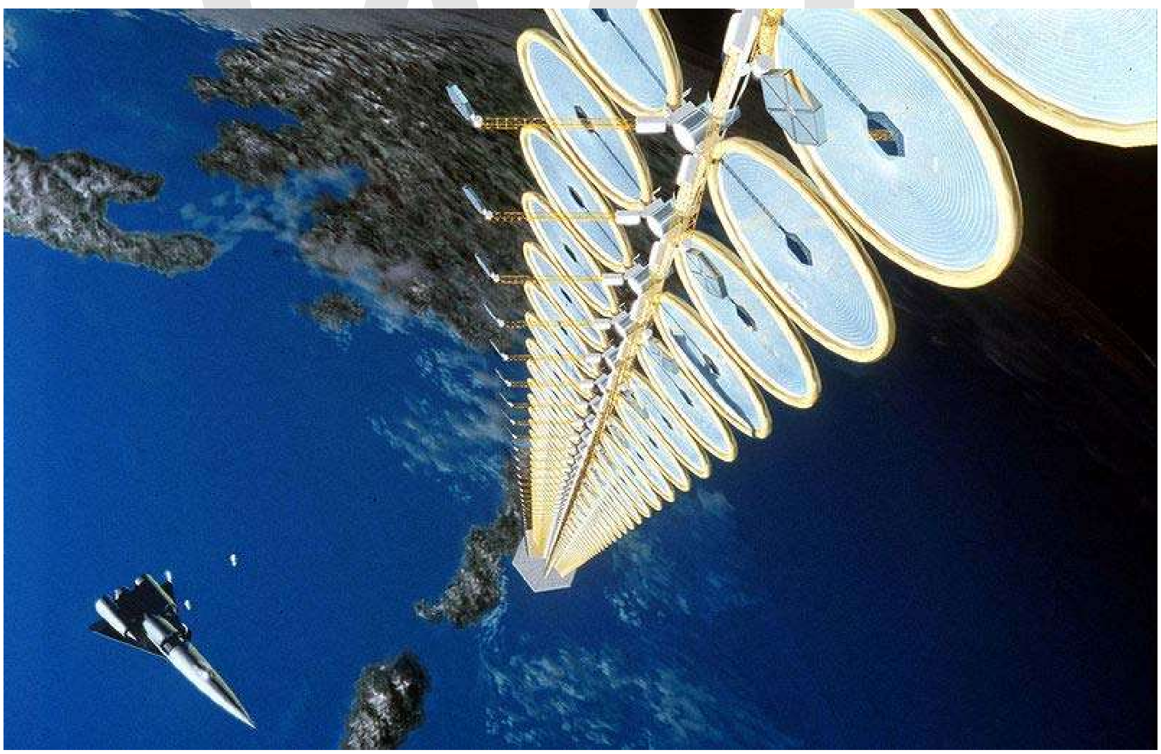
The size of the components may be dictated by the distance from transmitter to receiver, the wavelength and the Rayleigh criterion or diffraction limit, used in standard radio frequency antenna design, which also applies to lasers. In addition to the Rayleigh criterion Airy's diffraction limit is also frequently used to determine an approximate spot size at an arbitrary distance from the aperture.

The Rayleigh criterion dictates that any radio wave, microwave or laser beam will spread and become weaker and diffuse over distance; the larger the transmitter antenna or laser aperture compared to the wavelength of radiation, the tighter the beam and the less it will spread as a function of distance (and vice versa). Smaller antennae also suffer from excessive losses due to side lobes. However, the concept of laser aperture considerably differs from an antenna. Typically, a laser aperture much larger than the wavelength induces multi-moded radiation and mostly collimators are used before emitted radiation couples into a fiber or into space.

Ultimately, beamwidth is physically determined by diffraction due to the dish size in relation to the wavelength of the electromagnetic radiation used to make the beam. Microwave power beaming can be more efficient than lasers, and is less prone to atmospheric attenuation caused by dust or water vapor losing atmosphere to vaporize the water in contact.

Then the power levels are calculated by combining the above parameters together, and adding in the gains and losses due to the antenna characteristics and the transparency and dispersion of the medium through which the radiation passes. That process is known as calculating a link budget.

Microwave method



An artist's depiction of a solar satellite that could send electric energy by microwaves to a space vessel or planetary surface.

Power transmission via radio waves can be made more directional, allowing longer distance power beaming, with shorter wavelengths of electromagnetic radiation, typically in the microwave range. A rectenna may be used to convert the microwave energy back into electricity. Rectenna conversion efficiencies exceeding 95% have been realized. Power beaming using microwaves has been proposed for the transmission of energy from orbiting solar power satellites to Earth and the beaming of power to spacecraft leaving orbit has been considered.

Power beaming by microwaves has the difficulty that for most space applications the required aperture sizes are very large due to diffraction limiting antenna directionality. For example, the 1978 NASA Study of solar power satellites required a 1-km diameter transmitting antenna, and a 10 km diameter receiving rectenna, for a microwave beam at 2.45 GHz. These sizes can be somewhat decreased by using shorter wavelengths, although short wavelengths may have difficulties with atmospheric absorption and beam blockage by rain or water droplets. Because of the "thinned array curse," it is not possible to make a narrower beam by combining the beams of several smaller satellites.

For earthbound applications a large area 10 km diameter receiving array allows large total power levels to be used while operating at the low power density suggested for human electromagnetic exposure safety. A human safe power density of 1 mW/cm^2 distributed across a 10 km diameter area corresponds to 750 megawatts total power level. This is the power level found in many modern electric power plants.

Following World War II, which saw the development of high-power microwave emitters known as cavity magnetrons, the idea of using microwaves to transmit power was researched. By 1964 a miniature helicopter propelled by microwave power had been demonstrated.

Japanese researcher Hidetsugu Yagi also investigated wireless energy transmission using a directional array antenna that he designed. In February 1926, Yagi and Uda published their first paper on the tuned high-gain directional array now known as the Yagi antenna. While it did not prove to be particularly useful for power transmission, this beam antenna has been widely adopted throughout the broadcasting and wireless telecommunications industries due to its excellent performance characteristics.

Wireless high power transmission using microwaves is well proven. Experiments in the tens of kilowatts have been performed at Goldstone in California in 1975 and more recently (1997) at Grand Bassin on Reunion Island. These methods achieve distances on the order of a kilometer.

Laser method

In the case of electromagnetic radiation closer to visible region of spectrum (10s of microns (um) to 10s of nm), power can be transmitted by converting electricity into a laser beam that is then pointed at a solar cell receiver. This mechanism is generally known as "powerbeaming" because the power is beamed at a receiver that can convert it to usable electrical energy.

Advantages of laser based energy transfer compared with other wireless methods are:

1. collimated monochromatic wavefront propagation allows narrow beam cross-section area for energy transmission over large ranges.
2. compact size of solid state lasers-photovoltaics semiconductor diodes fit into into small products.
3. no radio-frequency interference to existing radio communication such as Wi-fi and cell phones.
4. control of access; only receivers illuminated by the laser receive power.

Its drawbacks are:

1. Conversion to light, such as with a laser, is inefficient
2. Conversion back into electricity is inefficient, with photovoltaic cells achieving 40%-50% efficiency. (Note that conversion efficiency is rather higher with monochromatic light than with insolation of solar panels).
3. Atmospheric absorption causes losses.
4. As with microwave beaming, this method requires a direct line of sight with the target.

The laser "powerbeaming" technology has been mostly explored in military weapons and aerospace applications and is now being developed for commercial and consumer electronics Low-Power applications. Wireless energy transfer system using laser for consumer space has to satisfy Laser safety requirements standardized under IEC 60825.

To develop an understanding of the trade-offs of Laser ("a special type of light wave"-based system):

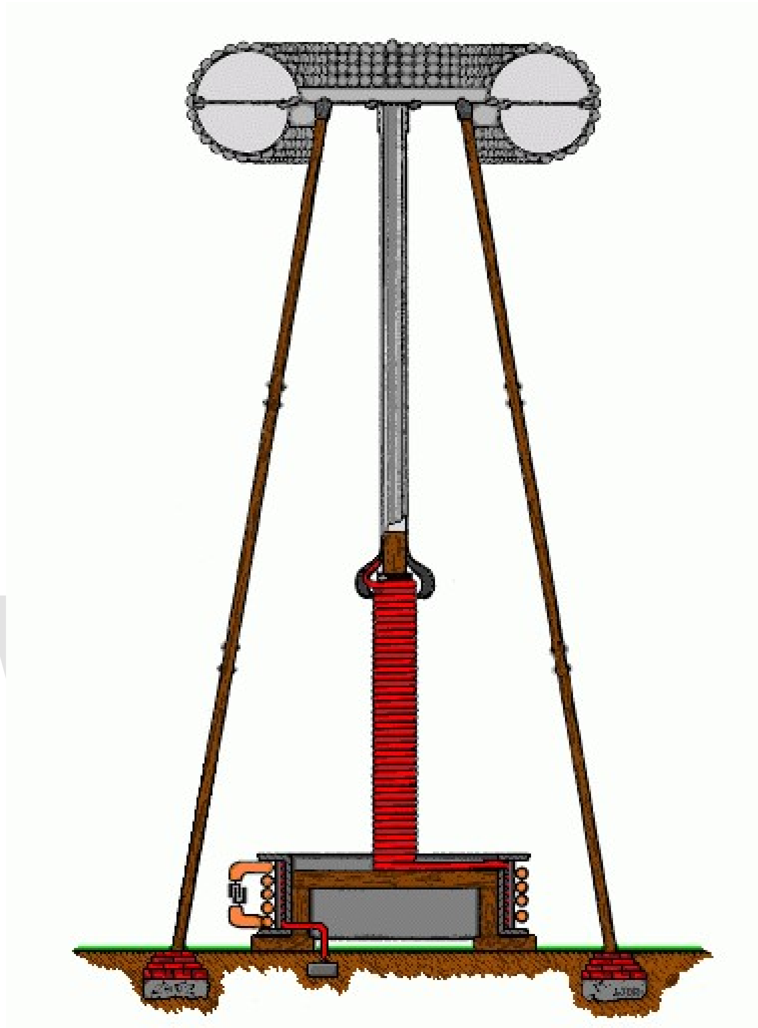
1. Propagation of a laser beam (on how Laser beam propagation is much less affected by diffraction limits)
2. Coherence and the range limitation problem (on how spatial and spectral coherence characteristics of Lasers allows better distance-to-power capabilities)
3. Airy disk (on how wavelength fundamentally dictates the size of a disk with distance)
4. Applications of laser diodes (on how the laser sources are utilized in various industries and their sizes are reducing for better integration)

Geoffrey Landis is one of the pioneers of solar power satellite and laser-based transfer of energy especially for space and lunar missions. The continuously increasing demand for safe and frequent space missions has resulted in serious thoughts on a futuristic space elevator that would be powered by lasers. NASA's space elevator would need wireless power to be beamed to it for it to climb a tether.

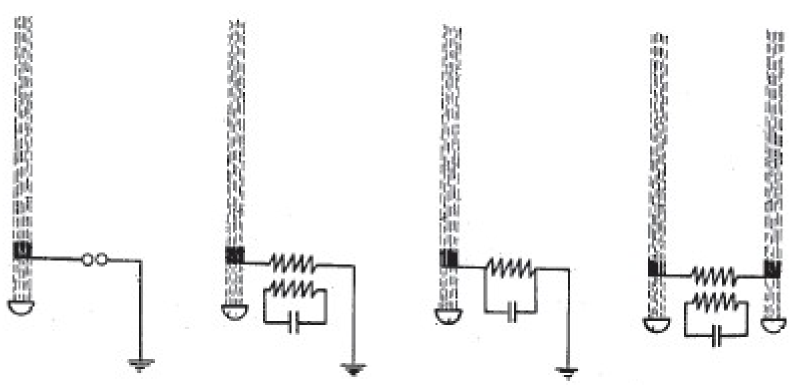
NASA's Dryden Flight Research Center has demonstrated flight of a lightweight unmanned model plane powered by a laser beam. This proof-of-concept demonstrates the feasibility of periodic recharging using the laser beam system and the lack of need to return to ground.

"Lasermotive" demonstrated laser powerbeaming at one kilometer during NASA's 2009 powerbeaming contest. Also "Lighthouse DEV" (a spin off of NASA Power Beaming Team) along with "University of Maryland" is developing an eye safe laser system to power a small UAV. Since 2006, "PowerBeam" which originally invented the eye-safe technology and holds all crucial patents in this technology space, is developing commercially ready units for various consumer and industrial electronic products.

Electrical conduction



The Tesla coil wireless power transmitter
U.S. Patent 1,119,732



Means for long conductors of electricity forming part of an electric circuit and electrically connecting said ionized beam to an electric circuit. Hettinger 1917 -(U.S. Patent 1,309,031)

Disturbed charge of ground and air method

Single wire with Earth return electrical power transmission systems rely on current flowing through the earth plus a single wire insulated from the earth to complete the circuit. In emergencies high-voltage direct current power transmission systems can also operate in the 'single wire with earth return' mode. Elimination of the raised insulated wire, and transmission of high-potential, high-frequency alternating current through the earth with an atmospheric return circuit has been investigated as a method of wireless electrical power transmission. Transmission of electrical energy through the earth alone, eliminating the second conductor is also being investigated.

Low frequency alternating current can be transmitted through the inhomogeneous earth with low loss because the net resistance between earth antipodes is considerably less than 1 ohm. The electrical displacement takes place predominantly by electrical conduction through the oceans, and metallic ore bodies and similar subsurface structures. The electrical displacement is also by means of electrostatic induction through the more dielectric regions such as quartz deposits and other non-conducting minerals.

Alternating current can be transmitted through atmospheric strata having a barometric pressure of less than 135 millimeters of mercury. Current flows by means of electrostatic induction through the lower atmosphere up to about two or three miles above the plants (this is the middle part in a three-space model) and the flow of ions, that is to say, electrical conduction through the ionized region above three miles. Intense vertical beams of ultraviolet light may be used to ionize the atmospheric gasses directly above the two elevated terminals resulting in the formation of plasma high-voltage electrical transmission lines leading up to the conducting atmospheric strata. The end result is a flow electrical current between the two elevated terminals by a path up to and through the troposphere and back down to the other facility. Electrical conduction through atmospheric strata is made possible by the creation of capacitively coupled discharge plasma through the process of atmospheric ionization.

Terrestrial transmission line with atmospheric return

Tesla discovered that electrical energy can be transmitted through the earth and the atmosphere. In the course of his research he successfully lit lamps at moderate distances and was able to detect the transmitted energy at much greater distances. The Wardenclyffe Tower project was a commercial venture for trans-Atlantic wireless telephony and proof-of-concept demonstrations of global wireless power transmission. The facility was not completed because of insufficient funding.

Earth is a naturally conducting body and forms one conductor of the system. A second path is established through the upper troposphere and lower stratosphere starting at an elevation of approximately 4.5 miles (7.2 km).

A global system for "the transmission of electrical energy without wires" called the World Wireless System, dependent upon the high electrical conductivity of plasma and the high electrical conductivity of the earth, was proposed as early as 1904.

Terrestrial single-conductor surface wave transmission line

The same transmitter used for the atmospheric conduction method is used for the terrestrial single-conductor earth resonance method.

The fundamental earth resonance frequency is claimed to be approximately 11.78 Hz. With the earth resonance method some harmonic of this fundamental frequency is used. "I would say that the frequency should be smaller then twenty thousand per second, through shorter waves might be practicable" and on the low end, "a frequency of nine hundred and twenty-five per second" is used, "when it is indispensable to operate motors of the ordinary kind."

Observations have been made that may be inconsistent with a basic tenet of physics related to the scalar derivatives of the electromagnetic potentials that are presently considered to be *nonphysical.*

Timeline of wireless power

- **1820**: André-Marie Ampère develops Ampere's law showing that electric current produces a magnetic field.
- **1831**: Michael Faraday develops Faraday's law of induction describing the electromagnetic force induced in a conductor by a time-varying magnetic flux.
- **1836**: Nicholas Callan invents the electrical transformer.
- **1864**: James Clerk Maxwell synthesizes the previous observations, experiments and equations of electricity, magnetism and optics into a consistent theory and mathematically models the behavior of electromagnetic radiation.
- **1888**: Heinrich Rudolf Hertz confirms the existence of electromagnetic radiation. Hertz's "*apparatus for generating electromagnetic waves*" was a VHF or UHF "radio wave" spark gap transmitter.
- **1891**: Tesla improves Hertz-wave wireless transmitter RF power supply or exciter in his patent No. 454,622, "System of Electric Lighting."
- **1893**: Tesla demonstrates the wireless illumination of phosphorescent lamps of his design at the World's Columbian Exposition in Chicago.
- **1893**: Tesla publicly demonstrates wireless power before a meeting of the National Electric Light Association in St. Louis.
- **1894**: Tesla lights incandescent lamps wirelessly at the 35 South Fifth Avenue laboratory in New York City by means of "electro-dynamic induction" or resonant inductive coupling.
- **1894**: Hutin & LeBlanc, espouse long held view that inductive energy transfer should be possible, they received U.S. Patent # 527,857 describing a system for power transmission at 3 kHz.

- **1894**: Jagdish Chandra Bose ignites gunpowder and rings a bell at a distance using electromagnetic waves, showing that communications signals can be sent without using wires.
- **1896**: Tesla demonstrates wireless transmission over a distance of about 48 kilometres (30 mi).
- **1897**: Tesla files his first patent application dealing specifically with wireless transmission.
- **1899**: Tesla continues his wireless power transmission research in Colorado Springs and writes, "the inferiority of the induction method would appear immense as compared with the *disturbed charge of ground and air method*."
- **1902**: Nikola Tesla vs. Reginald Fessenden **-** U.S. Patent Interference No. 21,701, System of Signaling (wireless); wireless power transmission, time and frequency domain spread spectrum telecommunications, electronic logic gates in general.
- **1904**: At the St. Louis World's Fair, a prize is offered for a successful attempt to drive a 0.1 horsepower (75 W) airship motor by energy transmitted through space at a distance of at least 100 feet (30 m).
- **1916**: Tesla states, "In my [*disturbed charge of ground and air*] system, you should free yourself of the idea that there is [electromagnetic] radiation, that energy is radiated. It is not radiated; it is conserved."
- **1917**: Tesla's Wardenclyffe tower is demolished. . . .

- **1926**: Shintaro Uda and Hidetsugu Yagi publish their first paper on Uda's *"tuned high-gain directional array"* better known as the Yagi antenna.

- **1961**: William C. Brown publishes an article exploring possibilities of microwave power transmission.
- **1964**: Brown demonstrates on CBS News with Walter Cronkite a model helicopter that receives all of the power needed for flight from a microwave beam. Between 1969 and 1975, Brown is technical director of a JPL Raytheon program that beams 30 kW over a distance of 1 mile at 84% efficiency.
- **1968**: Peter Glaser proposes wirelessly transmitting solar energy captured in space using "Powerbeaming" technology. This is usually recognized as the first description of a solar power satellite.
- **1971**: Prof. Don Otto develops a small trolley powered by induction at The University of Auckland, in New Zealand.
- **1973**: The world's first passive RFID system is demonstrated at Los-Alamos National Lab.
- **1975**: Goldstone Deep Space Communications Complex does experiments in the tens of kilowatts.
- **1988**: A power electronics group led by Prof. John Boys at The University of Auckland in New Zealand, develops an inverter using novel engineering materials and power electronics and conclude that power transmission by means of electrodynamic induction should be achievable. A first prototype for a contact-less power supply is built. Auckland Uniservices, the commercial company of The University of Auckland, patents the technology.

- **1989**: Daifuku, a Japanese company, engages Auckland Uniservices Ltd. to develop technology for car assembly plants and materials handling providing challenging technical requirements including multiplicity of vehicles.
- **1990**: Prof. John Boys team develops novel technology enabling multiple vehicles to run on the same inductive power loop and provide independent control of each vehicle. Auckland UniServices Patents the technology.
- **1996**: Auckland Uniservices develops an Electric Bus power system using electrodynamic induction to charge (30-60 kW) opportunistically commencing implementation in New Zealand. Prof John Boys Team commission 1st commercial IPT Bus in the world at Whakarewarewa, in New Zealand.
- **1998**: RFID tags are powered by electrodynamic induction over a few feet.
- **1999**: Dr. Herbert L. Becker powers a lamp and a hand held fan from a distance of 30 feet.
- **1999**: Prof. Shu Yuen (Ron) Hui and Mr. S.C. Tang of the City University of Hong Kong file a patent on "Coreless Printed-Circuit-Board (PCB) transformers and operating techniques", which form the basis for future planar charging surface with "vertical flux" leaving the planar surface. The circuit uses resonant circuits for wireless power transfer. EP(GB)0935263B
- **2000**: Prof. Shu Yuen (Ron) Hui invent a planar wireless charging pad using the "vertical flux" approach and resonant power transfer for charging portable consumer electronic products. A patent is filed on "Apparatus and method of an inductive battery charger," PCT Patent PCT/AU03/00 721, 2000.
- **2000**: Based on the coreless PCB transformer developed by Prof. Ron Hui, Prof. B. Choi and his team at Kyungpook National University publish a paper on "A new contactless battery charger for portable telecommunication/computing electronics," in Proc. ICCE'00 Int. Conf. Consumer Electron., 2000, pp. 58–59. The coreless PCB transformer is used to wirelessly charge a mobile phone.
- **2001** Prof. Shu Yuen (Ron) Hui and Dr. S.C. Tang file a patent on "Planar Printed-Circuit-Board Transformers with Effective Electromagnetic Interference (EMI) Shielding". The EM shield consists of a thin layer of ferrite and a thin layer of copper sheet. It enables the underneath of the future wireless charging pads to be shielded with a thin EM shield structure with thickness of typically 0.7mm or less. Patent: US6,501,364.
- **2001**: Prof. Ron Hui's team demonstrate that the coreless PCB transformer can transmit power close to 100W in 'A low-profile low-power converter with coreless PCB isolation transformer, IEEE Transactions on Power Electronics, Volume: 16 Issue: 3, May 2001. A team of Philips Research Center Aachen, led by Dr. Eberhard Waffenschmidt, use it to power an 100W lighting device in their paper "Size advantage of coreless transformers in the MHz range" in the European Power Electronics Conference in Graz.
- **2001**: Splashpower formed in the UK. Uses coupled resonant coils in a flat "pad" style to transfer tens of watts into a variety of consumer devices, including lamp, phone, PDA, iPod etc.
- **2002**: Prof. Shu Yuen (Ron) Hui extends the planar wireless charging pad concept using the vertical flux approach to incorporate free-positioning feature for multiple loads. This is achieved by using a multilayer planar winding array

structure. Patent were granted as "Planar Inductive Battery Charger", GB2389720 and GB 2389767.

- **2004**: Electrodynamic induction used by 90 percent of the US$1 billion clean room industry for materials handling equipment in semiconductor, LCD and plasma screen manufacture.
- **2005**: Prof. Shu Yuen (Ron) Hui and Dr. W.C. Ho of City University of Hong Kong publish their work in the IEEE Transactions on a planar wireless charging platform with free-positioning feature. The planar wireless charging pad is able to charge several loads simultaneously on a flat surface.
- **2005**: Prof Boys' team at The University of Auckland, refines 3-phase IPT Highway and pick-up systems allowing transmission of power to moving vehicles in the lab.
- **2007**: A localized charging technique is reported by Dr. Xun Liu and Prof. Ron Hui for the wireless charging pad with free-positioning feature. With the aid of the double-layer EM shields enclosing the transmitter and receiver coils, the localized charging selects the right transmitter coil so as to minimize flux leakage and human exposure to radiation.
- **2007**: Using electrodynamic induction a physics research group, led by Prof. Marin Soljacic, at MIT, wirelessly power a 60W light bulb with 40% efficiency at a 2 metres (6.6 ft) distance with two 60 cm-diameter coils.
- **2008**: Bombardier offers a new wireless power transmission product PRIMOVE, a system for use on trams and light-rail vehicles.
- **2008**: Industrial designer Thanh Tran, at Brunel University make a wireless lamp incorporating a high efficiency 3W LED.
- **2008**: Intel reproduces Tesla's original 1894 implementation of electrodynamic induction and Prof. John Boys group's 1988 follow-up experiments by wirelessly powering a nearby light bulb with 75% efficiency.
- **2008**: Greg Leyh and Mike Kennan of the Nevada Lightning Laboratory publish a paper on Tesla's *disturbed charge of ground and air method* of wireless power transmission with circuit simulations and test results showing an efficiency greater than can be obtained using the electrodynamic induction method.
- **2009**: A Consortium of interested companies called the Wireless Power Consortium announce they are nearing completion for a new industry standard for low-power inductive charging
- **2009**: Palm (now a division HP) launches the Palm Pre smartphone with the Palm Touchstone wireless charger.
- **2009**: An Ex approved Torch and Charger aimed at the offshore market is introduced. This product is developed by Wireless Power & Communication, a Norway based company.
- **2009**: A simple analytical electrical model of electrodynamic induction power transmission is proposed and applied to a wireless power transfer system for implantable devices.
- **2009**: Lasermotive uses diode laser to win $900k NASA prize in power beaming, breaking several world records in power and distance, by transmitting over a kilowatt more than several hundred meters.

- **2009**: Sony shows a wireless electrodynamic-induction powered TV set, 60 W over 50 cm
- **2010**: Haier Group debuts “the world's first” completely wireless LCD television at CES 2010 based on Prof. Marin Soljacic's follow-up research on Tesla's electrodynamic induction wireless energy transmission method and the Wireless Home Digital Interface (WHDI).
- **2010**: System On Chip (SoC) group in University of British Columbia develops an optimization tool for the design of highly efficient wireless power transmission systems using multiple coils. The design is optimized for implantable applications and power transfer efficiency of 82% is achieved.
- **2010**: The Wireless Power Consortium launches the world's first wireless power transfer standard "Qi", that governs wireless power transfer applications up to 5W.
- **2010**: The US company Energizer launches the first Qi-certified wireless charging pad with free-positioning and localized charging features in October 2010.