Handbook of

Solar Cell and Photovoltaics Technology

Essence Schindler

Phoenix Mcintosh

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Email: info@wtbooks.com

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Chapter 1

Solar Cell

A **monocrystalline** solar cell

A **solar cell** made from a monocrystalline silicon wafer

A **solar cell** (also called **photovoltaic cell**) is a solid state device that converts the energy of sunlight directly into electricity by the **photovoltaic effect**. Assemblies of cells are used to make solar modules, also known as *solar panels*. The energy generated from these solar modules, referred to as *solar power*, is an example of *solar energy*.

Photovoltaics is the field of technology and research related to the practical application of photovoltaic cells in producing electricity from light, though it is often used specifically to refer to the generation of electricity from sunlight.

Cells are described as *photovoltaic cells* when the light source is not necessarily sunlight. These are used for detecting light or other electromagnetic radiation near the visible range, for example infrared detectors, or measurement of light intensity.

History of solar cells

The term "photovoltaic" comes from the Greek φῶς (*phōs*) meaning "light", and "voltaic", meaning electric, from the name of the Italian physicist Volta, after whom a unit of electro-motive force, the volt, is named. The term "photo-voltaic" has been in use in English since 1849.

The photovoltaic effect was first recognized in 1839 by French physicist A. E. Becquerel. However, it was not until 1883 that the first solar cell was built, by Charles Fritts, who coated the semiconductor selenium with an extremely thin layer of gold to form the junctions. The device was only around 1% efficient. In 1888 Russian physicist Aleksandr Stoletov built the first photoelectric cell (based on the outer photoelectric effect discovered by Heinrich Hertz earlier in 1887). Albert Einstein explained the photoelectric effect in 1905 for which he received the Nobel prize in Physics in 1921. Russell Ohl patented the modern junction semiconductor solar cell in 1946, which was discovered while working on the series of advances that would lead to the transistor.

Bell produces the first practical cell

The modern photovoltaic cell was developed in 1954 at Bell Laboratories. The highly efficient solar cell was first developed by Daryl Chapin, Calvin Souther Fuller and Gerald Pearson in 1954 using a diffused silicon p-n junction. At first, cells were developed for toys and other minor uses, as the cost of the electricity they produced was very high - in relative terms, a cell that produced 1 watt of electrical power in bright sunlight cost about $250, comparing to 2 to $3 for a coal plant.

Solar cells were rescued from obscurity by the suggestion to add them to the Vanguard I satellite. In the original plans, the satellite would be powered only by battery, and last a short time while this ran down. By adding cells to the outside of the fuselage, the mission time could be extended with no major changes to the spacecraft or its power systems. There was some skepticism at first, but in practice the cells proved to be a huge success, and solar cells were quickly designed into many new satellites, notably Bell's own Telstar.

Improvements were slow over the next two decades, and the only widespread use was in space applications where their power-to-weight ratio was higher than any competing technology. However, this success was also the reason for slow progress; space users were willing to pay anything for the best possible cells, there was no reason to invest in lower-cost solutions if this would reduce efficiency. Instead, the price of cells was determined largely by the semiconductor industry; their move to integrated circuits in the 1960s led to the availability of larger boules at lower relative prices. As their price fell, the price of the resulting cells did as well. However these effects were limited, and by 1971 cell costs were estimated to be $100 a watt.

Berman's price reductions

In the late 1960s, Elliot Berman was investigating a new method for producing the silicon feedstock in a ribbon process. However, he found little interest in the project and was unable to gain the funding needed to develop it. In a chance encounter, he was later introduced to a team at Exxon who were looking for projects 30 years in the future. The group had concluded that electrical power would be much more expensive by 2000, and felt that this increase in price would make new alternative energy sources more attractive, and solar was the most interesting among these. In 1969, Berman joined the Linden, New Jersey Exxon lab, Solar Power Corporation (SPC).

His first major effort was to canvas the potential market to see what possible uses for a new product were, and they quickly found that if the dollars per watt was reduced from then-current $100/watt to about $20/watt there was significant demand. Knowing that his ribbon concept would take years to develop, the team started looking for ways to hit the $20 price point using existing materials.

The first improvement was the realization that the existing cells were based on standard semiconductor manufacturing process, even though that was not ideal. This started with the boule, cutting it into disks called wafers, polishing the wafers, and then, for cell use, coating them with an anti-reflective layer. Berman noted that the rough-sawn wafers already had a perfectly suitable anti-reflective front surface, and by printing the electrodes directly on this surface, two major steps in the cell processing were eliminated. The team also explored ways to improve the mounting of the cells into arrays, eliminating the expensive materials and hand wiring used in space applications with a printed circuit board on the back, acrylic plastic on the front, and silicone based glue between the two potting the cells. But the largest improvement in price point was Berman's realization that existing silicon was effectively "too good" for solar cell use; the minor imperfections that would ruin a boule (or individual wafer) for electronics would have little effect in the solar application.

Putting all of these changes into practice, the company started buying up "reject" silicon from existing manufacturers at very low cost. By using the largest wafers available, thereby reducing the amount of wiring for a given panel area, and packaging them into panels using their new methods, by 1973 SPC was producing panels at $10 and selling them at $20, a five-fold decrease in prices in two years.

Navigation market

SPC approached companies making buoys as a natural market for their products, but found a curious situation. The primary company in the business was Automatic Power, a battery manufacturer. Realizing that solar cells might eat into their battery profits, Automatic purchased the rights to earlier solar cell designs and suppressed them. Seeing there was no interest there, SPC turned to Tideland Signal, another battery company formed by ex-Automatic managers. Tideland introduced a solar-powered buoy and was soon ruining Automatic's business.

The timing could not be better; the rapid increase in the number of offshore oil platforms and loading facilities produced an enormous market among the oil companies. As Tideland's fortunes improved, Automatic started looking for their own supply of solar panels. They found Bill Yerks of Solar Power International (SPI) in California, who was looking for a market. SPI was soon bought out by one of its largest customers, the ARCO oil giant, forming ARCO Solar. ARCO Solar's factory in Camarillo, California was the first dedicated to building solar panels, and has been in continual operation from its purchase by ARCO in 1977 to this day.

This market, combined with the 1973 oil crisis, led to a curious situation. Oil companies were now cash-flush due to their huge profits during the crisis, but were also acutely aware that their future success would depend on some other form of power. Over the next few years, the major oil companies started a number of solar firms, and were for decades the largest produces of solar panels. Exxon, ARCO, Shell, Amoco (later purchased by BP) and Mobil all had major solar divisions during the 1970s and 80s. Technology companies also had some investment, including General Electric, Motorola, IBM, Tyco and RCA.

Further improvements

In the time since Berman's work, improvements have brought production costs down under $1 a watt, with wholesale costs on the order of $2. "Balance of system" costs are now more than the panels themselves, with large commercial arrays falling to around $5 a watt, fully commissioned, in 2010.

As the semiconductor industry moved to ever-larger boules, older equipment became available at fire-sale prices. Cells have grown in size as older equipment became available on the surplus market; ARCO Solar's original panels used cells with 2 to 4 inch diameter. Panels in the 1990s and early 2000s generally used 5 inch wafers, and since 2008 almost all new panels use 6 inch cells. Another major change was the move to polycrystalline silicon. This material has less efficiency, but is less expensive to produce in bulk. The widespread introduction of flat screen televisions in the late 1990s and early 2000s led to the wide availability of large sheets of high-quality glass, used on the front of the panels.

Other technologies have also come to market. First Solar has grown to become the largest panel manufacturer, in terms of yearly power produced, using a thin-film cell sandwiched between two layers of glass. This was the first product to beat $1 a watt for production costs. Since then a glut of polycrystalline silicon has pushed prices of conventional panels into the same range.

Applications

Polycrystalline photovoltaic cells

Polycrystalline photovoltaic cells laminated to backing material in a module

Solar cells are often electrically connected and encapsulated as a **module**. Photovoltaic modules often have a sheet of glass on the front (sun up) side, allowing light to pass while protecting the semiconductor wafers from abrasion and impact due to wind-driven debris, rain, hail, et cetera. Solar cells are also usually connected in series in modules, creating an additive voltage. Connecting cells in parallel will yield a higher current. Modules are then interconnected, in series or parallel, or both, to create an **array** with the desired peak DC voltage and current.

To make practical use of the solar-generated energy, the electricity is most often fed into the electricity grid using inverters (grid-connected photovoltaic systems); in stand-alone systems, batteries are used to store the energy that is not needed immediately. Solar panels can be used to power or recharge portable devices.

Theory

The solar cell works in three steps:

1. Photons in sunlight hit the solar panel and are absorbed by semiconducting materials, such as silicon.
2. Electrons (negatively charged) are knocked loose from their atoms, allowing them to flow through the material to produce electricity. Due to the special composition of solar cells, the electrons are only allowed to move in a single direction.
3. An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity.

Efficiency

The efficiency of a solar cell may be broken down into reflectance efficiency, thermodynamic efficiency, charge carrier separation efficiency and conductive efficiency. The overall efficiency is the product of each of these individual efficiencies.

Due to the difficulty in measuring these parameters directly, other parameters are measured instead: thermodynamic efficiency, quantum efficiency, V_{OC} ratio, and fill factor. Reflectance losses are a portion of the quantum efficiency under "external quantum efficiency". Recombination losses make up a portion of the quantum efficiency, V_{OC} ratio, and fill factor. Resistive losses are predominantly categorized under fill factor, but also make up minor portions of the quantum efficiency, V_{OC} ratio.

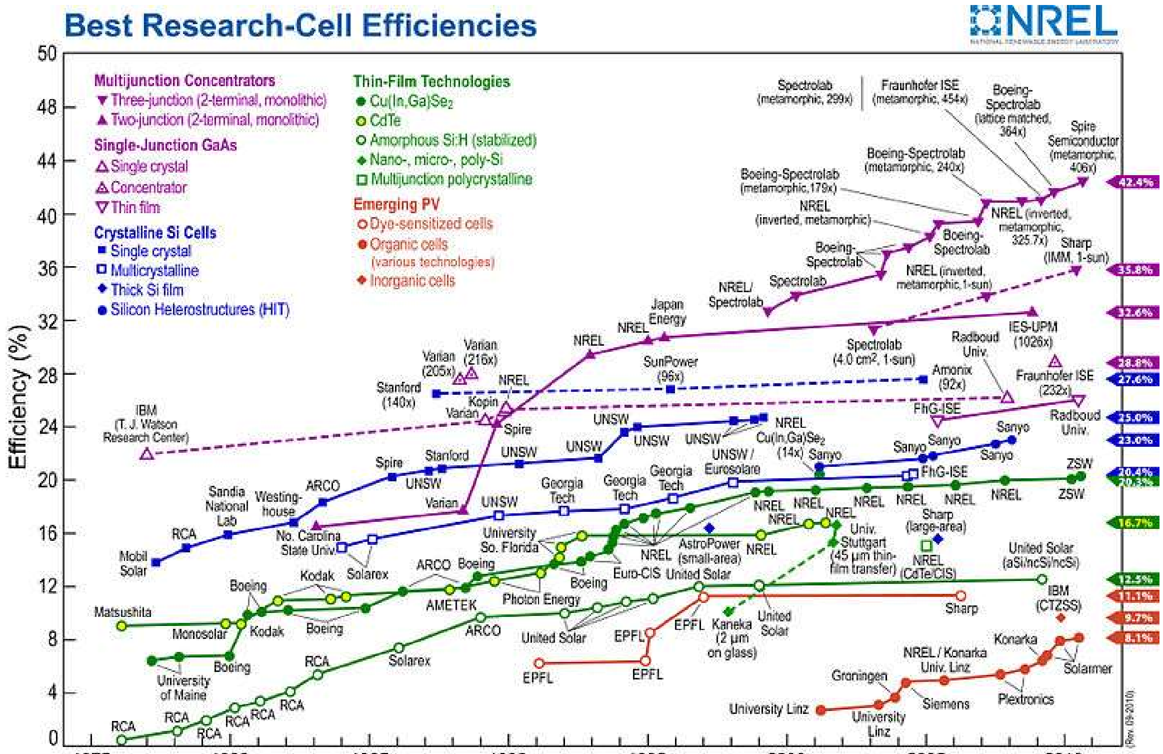
Crystalline silicon devices are now approaching the theoretical limiting efficiency of 29%.

Cost

The cost of a solar cell is given per unit of peak electrical power. Manufacturing costs necessarily including the cost of energy required for manufacture. Solar-specific feed in tariffs vary worldwide, and even state by state within various countries. Such feed-in tariffs can be highly effective in encouraging the development of solar power projects.

High-efficiency solar cells are of interest to decrease the cost of solar energy. Many of the costs of a solar power plant are proportional to the area of the plant; a higher efficiency cell may reduce area and plant cost, even if the cells themselves are more costly. Efficiencies of bare cells, to be useful in evaluating solar power plant economics, must be evaluated under realistic conditions. The basic parameters that need to be evaluated are the short circuit current, open circuit voltage.

The chart at the right illustrates the best laboratory efficiencies obtained for various materials and technologies, generally this is done on very small, i.e. one square cm, cells. Commercial efficiencies are significantly lower.



A **low-cost photovoltaic cell** is a thin-film cell intended to produce electrical energy at a price competitive with traditional (fossil fuels and nuclear power) energy sources. This includes second and third generation photovoltaic cells, that is cheaper than first generation (crystalline silicon cells, also called wafer or bulk cells).

Grid parity, the point at which photovoltaic electricity is equal to or cheaper than grid power, can be reached using low cost solar cells. It is achieved first in areas with abundant sun and high costs for electricity such as in California and Japan. Grid parity has been reached in Hawaii and other islands that otherwise use diesel fuel to produce electricity. George W. Bush had set 2015 as the date for grid parity in the USA. Speaking at a conference in 2007, General Electric's Chief Engineer predicted grid parity without subsidies in sunny parts of the United States by around 2015.

The price of solar panels fell steadily for 40 years, until 2004 when high subsidies in Germany drastically increased demand there and greatly increased the price of purified silicon (which is used in computer chips as well as solar panels). One research firm predicted that new manufacturing capacity began coming on-line in 2008 (projected to double by 2009) which was expected to lower prices by 70% in 2015. Other analysts warned that capacity may be slowed by economic issues, but that demand may fall because of lessening subsidies. Other potential bottlenecks which have been suggested are the capacity of ingot shaping and wafer slicing industries, and the supply of specialist chemicals used to coat the cells.

Materials

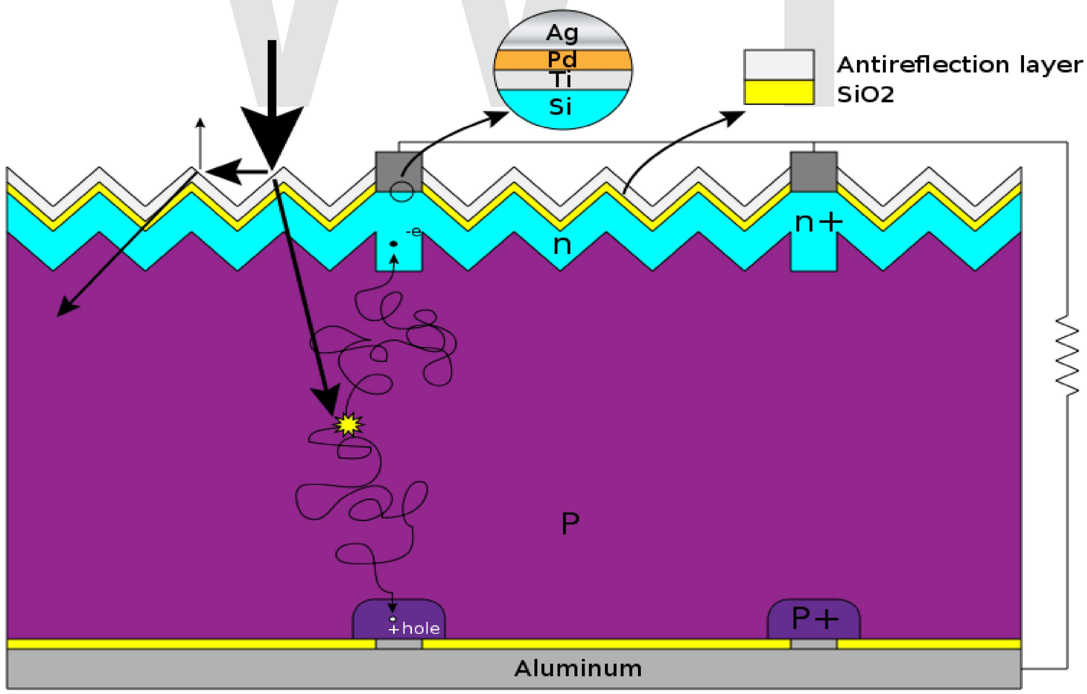
Different materials display different efficiencies and have different costs. Materials for efficient solar cells must have characteristics matched to the spectrum of available light. Some cells are designed to efficiently convert wavelengths of solar light that reach the Earth surface. However, some solar cells are optimized for light absorption beyond Earth's atmosphere as well. Light absorbing materials can often be used in *multiple physical configurations* to take advantage of different light absorption and charge separation mechanisms.

Materials presently used for photovoltaic solar cells include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium selenide/sulfide.

Many currently available solar cells are made from bulk material that are cut into wafers between 180 to 240 micrometers thick that are then processed like other semiconductors.

Other materials are made as thin-films layers, organic dyes, and organic polymers that are deposited on supporting substrates. A third group are made from nanocrystals and used as quantum dots (electron-confined nanoparticles). Silicon remains the only material that is well-researched in both *bulk* and *thin-film* forms.

Crystalline silicon



Basic structure of a silicon based solar cell and its working mechanism

By far, the most prevalent *bulk* material for solar cells is crystalline silicon (abbreviated as a group as *c-Si*), also known as "solar grade silicon". Bulk silicon is separated into multiple categories according to crystallinity and crystal size in the resulting ingot, ribbon, or wafer.

1. *monocrystalline silicon* (c-Si): often made using the Czochralski process. Single-crystal wafer cells tend to be expensive, and because they are cut from cylindrical ingots, do not completely cover a square solar cell module without a substantial waste of refined silicon. Hence most *c-Si* panels have uncovered gaps at the four corners of the cells.
2. *Poly- or multicrystalline silicon* (poly-Si or mc-Si): made from cast square ingots — large blocks of molten silicon carefully cooled and solidified. Poly-Si cells are less expensive to produce than single crystal silicon cells, but are less efficient. US DOE data shows that there were a higher number of multicrystalline sales than monocrystalline silicon sales.
3. *Ribbon silicon* is a type of multicrystalline silicon: it is formed by drawing flat thin films from molten silicon and results in a multicrystalline structure. These cells have lower efficiencies than poly-Si, but save on production costs due to a great reduction in silicon waste, as this approach does not require sawing from ingots.

Analysts have predicted that prices of polycrystalline silicon will drop as companies build additional polysilicon capacity quicker than the industry's projected demand. On the other hand, the cost of producing upgraded metallurgical-grade silicon, also known as UMG Si, can potentially be one-sixth that of making polysilicon.

Manufacturers of wafer-based cells have responded to thin-film lower prices with rapid reductions in silicon consumption. According to Jef Poortmans, director of IMEC's organic and solar department, current cells use between eight and nine grams of silicon per watt of power generation, with wafer thicknesses in the neighborhood of 0.200 mm. At 2008 spring's IEEE Photovoltaic Specialists' Conference (PVS'08), John Wohlgemuth, staff scientist at BP Solar, reported that his company has qualified modules based on 0.180 mm thick wafers and is testing processes for 0.16 mm wafers cut with 0.1 mm wire. IMEC's roadmap, presented at the organization's recent annual research review meeting, envisions use of 0.08 mm wafers by 2015.

Thin films

Thin-film technologies reduce the amount of material required in creating a solar cell. Though this reduces material cost, it may also reduce energy conversion efficiency. Thin-film silicon cells have become popular due to cost, flexibility, lighter weight, and ease of integration, compared to wafer silicon cells.

Cadmium telluride solar cell

A cadmium telluride solar cell use a cadmium telluride (CdTe) thin film, a semiconductor layer to absorb and convert sunlight into electricity. Solarbuzz has reported that the lowest quoted thin-film module price stands at US$1.76 per watt-peak, with the lowest crystalline silicon (c-Si) module at $2.48 per watt-peak.

The cadmium present in the cells would be toxic if released. However, release is impossible during normal operation of the cells and is unlikely during fires in residential roofs. A square meter of CdTe contains approximately the same amount of Cd as a single C cell Nickel-cadmium battery, in a more stable and less soluble form.

Copper-Indium Selenide

Copper indium gallium selenide (CIGS) is a direct-bandgap material. It has the highest efficiency (~20%) among thin film materials. Traditional methods of fabrication involve vacuum processes including co-evaporation and sputtering. Recent developments at IBM and Nanosolar have been targeting to lower the cost by using non-vacuum solution processes.

Gallium arsenide multijunction

High-efficiency multijunction cells were originally developed for special applications such as satellites and space exploration, but at present, their use in terrestrial concentrators might be the lowest cost alternative in terms of $/kWh and $/W. These multijunction cells consist of multiple thin films produced using metalorganic vapour phase epitaxy. A triple-junction cell, for example, may consist of the semiconductors: GaAs, Ge, and $GaInP_2$. Each type of semiconductor will have a characteristic band gap energy which, loosely speaking, causes it to absorb light most efficiently at a certain color, or more precisely, to absorb electromagnetic radiation over a portion of the spectrum. The semiconductors are carefully chosen to absorb nearly all of the solar spectrum, thus generating electricity from as much of the solar energy as possible.

GaAs based multijunction devices are the most efficient solar cells to date. In October 2010, triple junction metamorphic cell reached a record high of 42.3%.

This technology is currently being utilized in the Mars Exploration Rover missions which have run far past their 90 day design life.

Tandem solar cells based on monolithic, series connected, gallium indium phosphide (GaInP), gallium arsenide GaAs, and germanium Ge pn junctions, are seeing demand rapidly rise. In just the past 12 months (12/2006 – 12/2007), the cost of 4N gallium metal has risen from about $350 per kg to $680 per kg. Additionally, germanium metal prices have risen substantially to $1000–$1200 per kg this year. Those materials include gallium (4N, 6N and 7N Ga), arsenic (4N, 6N and 7N) and germanium, pyrolitic boron nitride (pBN) crucibles for growing crystals, and boron oxide, these products are critical to the entire substrate manufacturing industry.

Triple-junction GaAs solar cells were also being used as the power source of the Dutch four-time World Solar Challenge winners Nuna in 2003, 2005 and 2007, and also by the Dutch solar cars Solutra (2005), Twente One (2007) and 21Revolution (2009).

The Dutch Radboud University Nijmegen set the record for thin film solar cell efficiency using a single junction GaAs to 25.8% in August 2008 using only 4 µm thick GaAs layer which can be transferred from a wafer base to glass or plastic film.

Light-absorbing dyes (DSSC)

Dye-sensitized solar cells (DSSCs) are made of low-cost materials and do not need elaborate equipment to manufacture, so they can be made in a DIY fashion, possibly allowing players to produce more of this type of solar cell than others. In bulk it should be significantly less expensive than older solid-state cell designs. DSSC's can be engineered into flexible sheets, and although its conversion efficiency is less than the best thin film cells, its price/performance ratio should be high enough to allow them to compete with fossil fuel electrical generation. The DSSC has been developed by Prof. Michael Grätzel in 1991 at the Swiss Federal Institute of Technology (EPFL) in Lausanne (CH).

Typically a ruthenium metalorganic dye (Ru-centered) is used as a monolayer of light-absorbing material. The dye-sensitized solar cell depends on a mesoporous layer of nanoparticulate titanium dioxide to greatly amplify the surface area (200–300 m^2/g TiO_2, as compared to approximately 10 m^2/g of flat single crystal). The photogenerated electrons from the *light absorbing dye* are passed on to the *n-type* TiO_2, and the holes are absorbed by an electrolyte on the other side of the dye. The circuit is completed by a redox couple in the electrolyte, which can be liquid or solid. This type of cell allows a more flexible use of materials, and is typically manufactured by screen printing and/or use of Ultrasonic Nozzles, with the potential for lower processing costs than those used for *bulk* solar cells. However, the dyes in these cells also suffer from degradation under heat and UV light, and the cell casing is difficult to seal due to the solvents used in assembly. In spite of the above, this is a popular emerging technology with some commercial impact forecast within this decade. The first commercial shipment of DSSC solar modules occurred in July 2009 from G24i Innovations.

Organic/polymer solar cells

Organic solar cells are a relatively novel technology, yet hold the promise of a substantial price reduction (over thin-film silicon) and a faster return on investment. These cells can be processed from solution, hence the possibility of a simple roll-to-roll printing process, leading to inexpensive, large scale production.

Organic solar cells and polymer solar cells are built from thin films (typically 100 nm) of organic semiconductors including polymers, such as polyphenylene vinylene and small-molecule compounds like copper phthalocyanine (a blue or green organic pigment) and carbon fullerenes and fullerene derivatives such as PCBM. Energy conversion efficiencies achieved to date using conductive polymers are low compared to inorganic materials. However, it improved quickly in the last few years and the highest NREL (National Renewable Energy Laboratory) certified efficiency has reached 6.77%. In addition, these cells could be beneficial for some applications where mechanical flexibility and disposability are important.

These devices differ from inorganic semiconductor solar cells in that they do not rely on the large built-in electric field of a PN junction to separate the electrons and holes created when photons are absorbed. The active region of an organic device consists of two materials, one which acts as an electron donor and the other as an acceptor. When a photon is converted into an electron hole pair, typically in the donor material, the charges tend to remain bound in the form of an exciton, and are separated when the exciton diffuses to the donor-acceptor interface. The short exciton diffusion lengths of most polymer systems tend to limit the efficiency of such devices. Nanostructured interfaces, sometimes in the form of bulk heterojunctions, can improve performance.

Silicon thin films

Silicon thin-film cells are mainly deposited by chemical vapor deposition (typically plasma-enhanced (PE-CVD)) from silane gas and hydrogen gas. Depending on the deposition parameters, this can yield:

1. Amorphous silicon (a-Si or a-Si:H)
2. Protocrystalline silicon or
3. Nanocrystalline silicon (nc-Si or nc-Si:H), also called microcrystalline silicon.

It has been found that protocrystalline silicon with a low volume fraction of nanocrystalline silicon is optimal for high open circuit voltage. These types of silicon present dangling and twisted bonds, which results in deep defects (energy levels in the bandgap) as well as deformation of the valence and conduction bands (band tails). The solar cells made from these materials tend to have lower *energy conversion efficiency* than *bulk* silicon, but are also less expensive to produce. The quantum efficiency of thin film solar cells is also lower due to reduced number of collected charge carriers per incident photon.

An amorphous silicon (a-Si) solar cell is made of amorphous or microcrystalline silicon and its basic electronic structure is the p-i-n junction. As the amorphous structure has a higher absorption rate of light than crystalline cells, the complete light spectrum can be absorbed with a very thin layer of photo-electrically active material. A film only 1 micron thick can absorb 90% of the usable solar energy. The production of a-Si thin film solar cells uses glass as a substrate and deposits a very thin layer of silicon by plasma-enhanced chemical vapor deposition (PECVD). A-Si manufacturers are working towards lower costs per watt and higher conversion efficiency with continuous research and development on Multijunction solar cells for solar panels. Anwell Technologies Limited recently announced its target for multi-substrate-multi-chamber PECVD, to lower the cost to USD0.5 per watt.

Amorphous silicon has a higher bandgap (1.7 eV) than crystalline silicon (c-Si) (1.1 eV), which means it absorbs the visible part of the solar spectrum more strongly than the infrared portion of the spectrum. As **nc-Si** has about the same bandgap as c-Si, the nc-Si and a-Si can advantageously be combined in thin layers, creating a layered cell called a **tandem cell**. The top cell in a-Si absorbs the visible light and leaves the infrared part of the spectrum for the bottom cell in nc-Si.

Recently, solutions to overcome the limitations of thin-film crystalline silicon have been developed. Light trapping schemes where the weakly absorbed long wavelength light is obliquely coupled into the silicon and traverses the film several times can significantly enhance the absorption of sunlight in the thin silicon films. Thermal processing techniques can significantly enhance the crystal quality of the silicon and thereby lead to higher efficiencies of the final solar cells.

Manufacture

Because solar cells are semiconductor devices, they share many of the same processing and manufacturing techniques as other semiconductor devices such as computer and memory chips. However, the stringent requirements for cleanliness and quality control of semiconductor fabrication are a little more relaxed for solar cells. Most large-scale commercial solar cell factories today make screen printed poly-crystalline silicon solar cells. Single crystalline wafers which are used in the semiconductor industry can be made into excellent high efficiency solar cells, but they are generally considered to be too expensive for large-scale mass production.

Poly-crystalline silicon wafers are made by wire-sawing block-cast silicon ingots into very thin (180 to 350 micrometer) slices or wafers. The wafers are usually lightly p-type doped. To make a solar cell from the wafer, a surface diffusion of n-type dopants is performed on the front side of the wafer. This forms a p-n junction a few hundred nanometers below the surface.

Antireflection coatings, to increase the amount of light coupled into the solar cell, are typically next applied. Silicon nitride has gradually replaced titanium dioxide as the antireflection coating because of its excellent surface passivation qualities. It prevents carrier recombination at the surface of the solar cell. It is typically applied in a layer several hundred nanometers thick using plasma-enhanced chemical vapor deposition (PECVD). Some solar cells have textured front surfaces that, like antireflection coatings, serve to increase the amount of light coupled into the cell. Such surfaces can usually only be formed on single-crystal silicon, though in recent years methods of forming them on multicrystalline silicon have been developed.

The wafer then has a full area metal contact made on the back surface, and a grid-like metal contact made up of fine "fingers" and larger "busbars" are screen-printed onto the front surface using a silver paste. The rear contact is also formed by screen-printing a metal paste, typically aluminium. Usually this contact covers the entire rear side of the cell, though in some cell designs it is printed in a grid pattern. The paste is then fired at several hundred degrees celsius to form metal electrodes in ohmic contact with the silicon. Some companies use an additional electro-plating step to increase the cell efficiency. After the metal contacts are made, the solar cells are interconnected in series (and/or parallel) by flat wires or metal ribbons, and assembled into modules or "solar panels". Solar panels have a sheet of tempered glass on the front, and a polymer encapsulation on the back.

Lifespan

Most commercially available solar cells are capable of producing electricity for at least twenty years without a significant decrease in efficiency. The typical warranty given by panel manufacturers is for a period of 25 – 30 years, wherein the output shall not fall below a specified percentage (around 80%) of the rated capacity.

Research topics

There are currently many research groups active in the field of photovoltaics in universities and research institutions around the world. This research can be divided into three areas: making current technology solar cells cheaper and/or more efficient to effectively compete with other energy sources; developing new technologies based on new solar cell architectural designs; and developing new materials to serve as light absorbers and charge carriers.

Manufacturers and certification

National Renewable Energy Laboratory tests and validates solar technologies. There are three reliable certifications of solar equipment: UL and IEEE (both U.S. standards) and IEC.

Solar cells are manufactured primarily in Japan, Germany, Mainland China, Taiwan and United States, though numerous other nations have or are acquiring significant solar cell production capacity. While technologies are constantly evolving toward higher efficiencies, the most effective cells for low cost electrical production are not necessarily those with the highest efficiency, but those with a balance between low-cost production and efficiency high enough to minimize area-related balance of systems cost. Those companies with large scale manufacturing technology for coating inexpensive substrates may, in fact, ultimately be the lowest cost net electricity producers, even with cell efficiencies that are lower than those of single-crystal technologies.

China

Backed by Chinese government's unprecedented plan to offer subsidies for utility-scale solar power projects that is likely to spark a new round of investment from Chinese solar panel makers. Chinese companies have already played a more important role in solar panels manufacturing in recent years. China produced solar cells/modules with an output of 1,180 MW in 2007 making it the largest producer in the world, according to statistics from China Photovoltaic Association. Some Chinese companies such as Suntech Power, Yingli, LDK Solar Co, JA Solar and ReneSola have already announced projects in cooperation with regional governments with hundreds of megawatts each after the 'Golden Sun' incentive program was announced by the government. The new development of solar module manufacturers with thin-film technology such as Veeco and Anwell Technologies Limited will further help to boost the domestic solar industry.

United States

New manufacturing facilities for solar cells and modules in Massachusetts, Michigan, New York, Ohio, Oregon, and Texas promise to add enough capacity to produce thousands of megawatts of solar devices per year within the next few years from 2008.

In late September 2008, Sanyo Electric Company, Ltd. announced its decision to build a manufacturing plant for solar ingots and wafers in Salem, Oregon. The plant will begin operating in October 2009 and will reach its full production capacity of 70 megawatts (MW) of solar wafers per year by April 2010.

In early October 2008, First Solar, Inc. broke ground on an expansion of its Perrysburg, Ohio, facility that will add enough capacity to produce another 57 MW per year of solar modules at the facility, bringing its total capacity to roughly 192 MW per year. The company expects to complete construction early next year and reach full production by mid-2010.

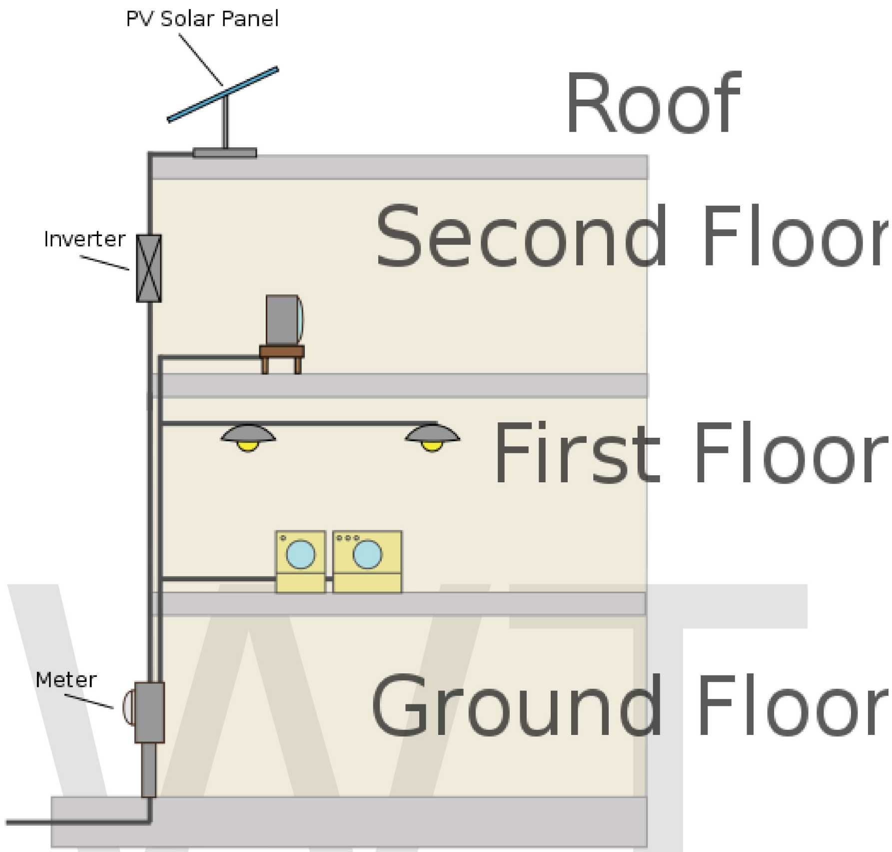
In mid-October 2008, SolarWorld AG opened a manufacturing plant in Hillsboro, Oregon, that is expected to produce 500 MW of solar cells per year when it reaches full production in 2011.

In March 2010, SpectraWatt, Inc. began production at its manufacturing plant in Hopewell Junction, NY, which is expected to produce 120 MW of solar cells per year when it reaches full production in 2011.

Chapter 2

Photovoltaic System

Solar Park



A PV-solar system

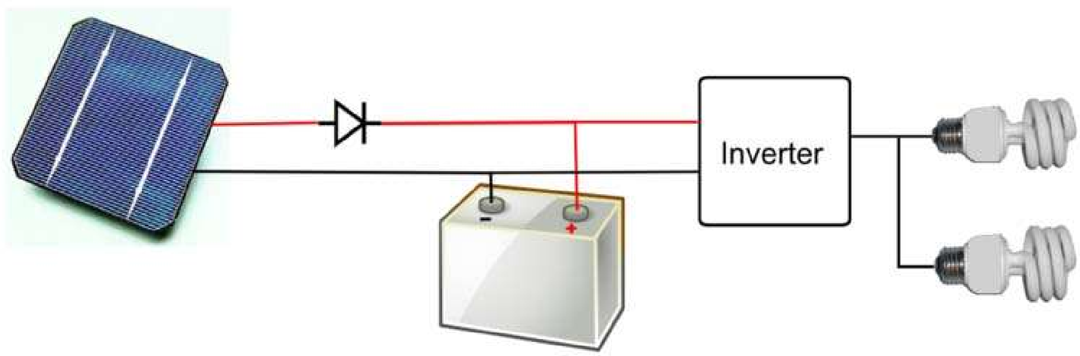
A **photovoltaic system** is a system which uses solar cells to convert light into electricity. A photovoltaic system consists of multiple components, including cells, mechanical and electrical connections and mountings and means of regulating and/or modifying the electrical output.

Due to the low voltage of an individual solar cell (typically ca. 0.5V), several cells are wired in series in the manufacture of a "laminate". The laminate is assembled into a protective weatherproof enclosure, thus making a photovoltaic module. "Modules" may then be strung together into an "array". The electricity generated can be either stored, used directly (island/standalone plant)or fed into a large electricity grid powered by central generation plants (grid-connected/grid-tied plant) or combined with one or many domestic electricity generators to feed into a small grid (hybrid plant). Depending on the type of application, the rest of the system ("balance of system" or "BOS") consists of different components. The BOS depends on the load profile and the system type. Systems are generally designed in order to ensure the highest energy yield for a given investment.

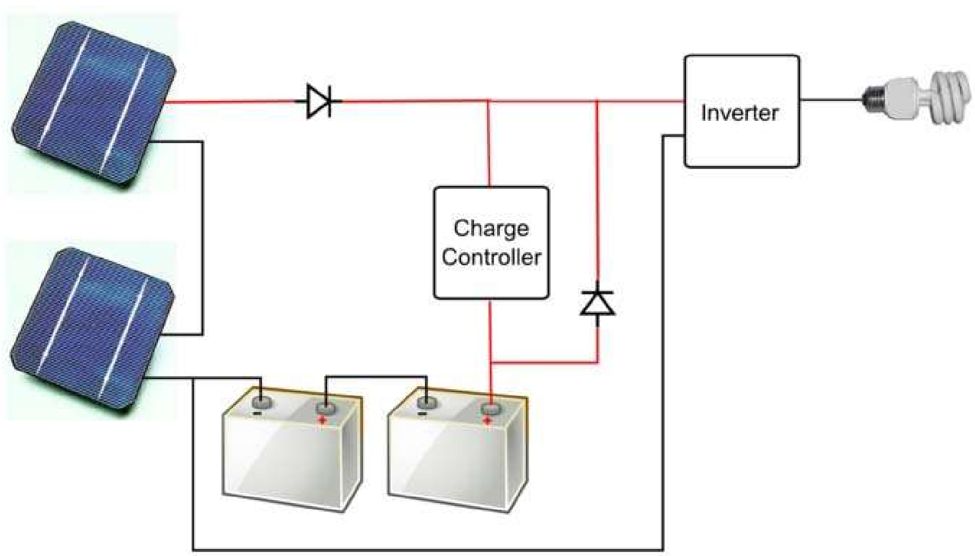
Standalone systems

Solar powered parking meter

A standalone system does not have a connection to the electricity "mains" (aka "grid"). Standalone systems vary widely in size and application from wristwatches or calculators to remote buildings or spacecraft. If the load is to be supplied independently of solar insolation, the generated power is stored and buffered with a battery. In non-portable applications where weight is not an issue, such as in buildings, lead acid batteries are most commonly used for their low cost. A charge controller may be incorporated in the system to: a) avoid battery damage by excessive charging or discharging and, b) optimizing the production of the cells or modules by maximum power point tracking (MPPT). However, in simple PV systems where the PV module voltage is matched to the battery voltage, the use of MPPT electronics is generally considered unnecessary, since the battery voltage is stable enough to provide near-maximum power collection from the PV module. In small devices (e.g. calculators, parking meters) only direct current (DC) is consumed. In larger systems (e.g. buildings, remote water pumps) AC is usually required. To convert the DC from the modules or batteries into AC, an inverter is used.



A schematic of a bare-bones off-grid system, consisting (from left to right) of photovoltaic module, a blocking-diode to prevent battery drain during low-insolation, a battery, an inverter, and an AC load such as a fluorescent lamp



off-grid PV system with battery charger

Grid-connected/Grid-tied System

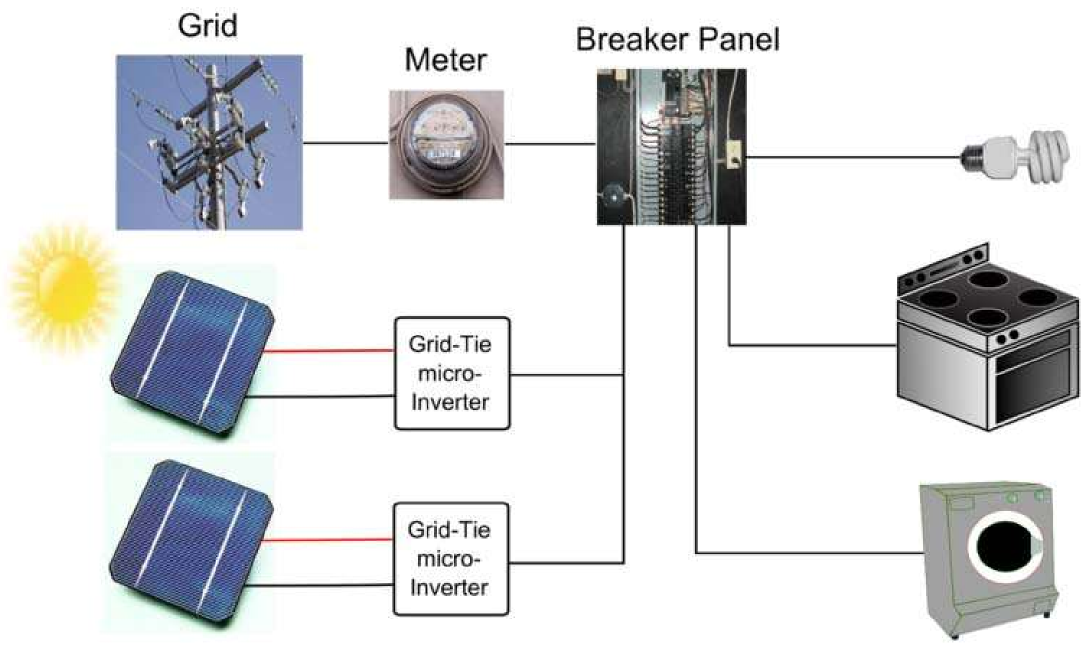


Diagram of a residential grid-connected PV system

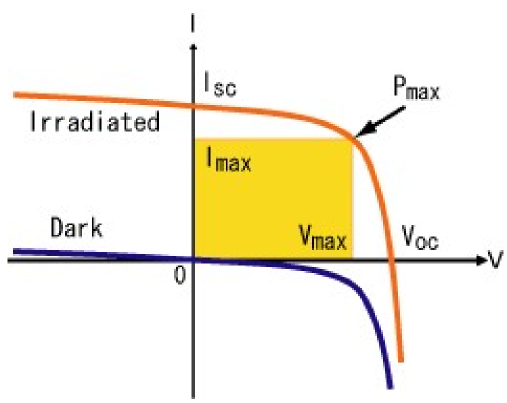
A grid connected system is connected to a large independent grid (typically the public electricity grid) and feeds power into the grid. Grid connected systems vary in size from residential (2-10kWp) to solar power stations (up to 10s of GWp). This is a form of decentralized electricity generation. In the case of residential or building mounted grid connected PV systems, the electricity demand of the building is met by the PV system. Only the excess is fed into the grid when there is an excess. The feeding of electricity into the grid requires the transformation of DC into AC by a special, grid-controlled inverter.

In kW sized installations the DC side system voltage is as high as permitted (typically 1000V except US residential 600V) to limit ohmic losses. Most modules (72 crystalline silicon cells) generate about 160W at 36 volts. It is sometimes necessary or desirable to connect the modules partially in parallel rather than all in series. One set of modules connected in series is known as a 'string'.

Grid connected inverters

Inverter for grid connected PV

On the AC side, these inverters must supply electricity in sinusoidal form, synchronized to the grid frequency, limit feed in voltage to no higher than the grid voltage including disconnecting from the grid if the grid voltage is turned off.



On the DC side, the power output of a module varies as a function of the voltage in a way that power generation can be optimized by varying the system voltage to find the 'maximum power point'. Most inverters therefore incorporate 'maximum power point tracking'.

The inverters are designed to connect to one or more strings.

For safety reasons a circuit breaker is provided both on the AC and DC side to enable maintenance. The AC output usually goes through across an electricity meter into the public grid.

The meter must be able to run in both directions.

In some countries, for installations over 30kWp a frequency and a voltage monitor with disconnection of all phases is required.

Connection to a DC grid

DC grids are only to be found in electric powered transport: railways trams and trolleybuses. A few pilot plants for such applications have been built, such as the tram depots in Hannover Leinhausen and Geneva (Bachet de Pesay). The 150 kW_p Geneva site feeds 600V DC directly into the tram/trolleybus electricity network provided about 15% of the electricity at its opening in 1999.

Small-scale PV solar systems

Small scale DIY solar systems

With a growing DIY-community and an increasing interest in environmentally friendly "green energy", some hobbyists have endeavored to build their own PV solar systems from kits or partly diy. Usually, the DIY-community uses inexpensive and/or high efficiency systems (such as those with solar tracking) to generate their own power. As a result, the DIY-systems often end up cheaper than their commercial counterparts. Often, the system is also hooked up unto the regular power grid to repay part of the investment via net metering. These systems usually generate power amount of ~2 kW or less. Through the internet, the community is now able to obtain plans to construct the system (at least partly DIY) and there is a growing trend toward building them for domestic requirements. The DIY-PV solar systems are now also being used both in developed countries and in developing countries, to power residences and small businesses.

Mounting systems

Ground mounted system

Modules are assembled into arrays on some kind of mounting system. For solar parks a large rack is mounted on the ground, and the modules mounted on the rack.

For buildings, many different racks have been devised for pitched roofs. For flat roofs, racks, bins and building integrated solutions are used.

Trackers

A solar tracker can substantially improve the amount of power produced by a system by enhancing morning and afternoon performance. It is only worth installing trackers for non-concentrating applications in regions with mostly direct sunlight. In diffuse light (i.e. under cloud or fog), tracking has no value. For concentrated photovoltaic systems a tracker is necessary.

Anti-reflective coatings for the glass covering of photovoltaic systems can provide most of the benefits of a tracking system without any extra power usage or maintenance. Some anti-reflective coatings use nanotechnology to improve their performance, providing virtually the same performance that a tracking system provides.

System performance

At high noon on a cloudless day at the equator, the power of the sun is about 1 kW/m², on the Earth's surface, to a plane that is perpendicular to the sun's rays. As such, PV arrays can track the sun through each day to greatly enhance energy collection. However, tracking devices add cost, and require maintenance, so it is more common for PV arrays to have fixed mounts that tilt the array and face due South in the Northern Hemisphere (in the Southern Hemisphere, they should point due North). The tilt angle, from horizontal, can be varied for season, but if fixed, should be set to give optimal array output during the peak electrical demand portion of a typical year.

For large systems, the energy gained by using tracking systems outweighs the added complexity (trackers can increase efficiency by 30% or more). PV arrays that approach or exceed one megawatt often use solar trackers. Accounting for clouds, and the fact that most of the world is not on the equator, and that the sun sets in the evening, the correct measure of solar power is insolation – the average number of kilowatt-hours per square meter per day.

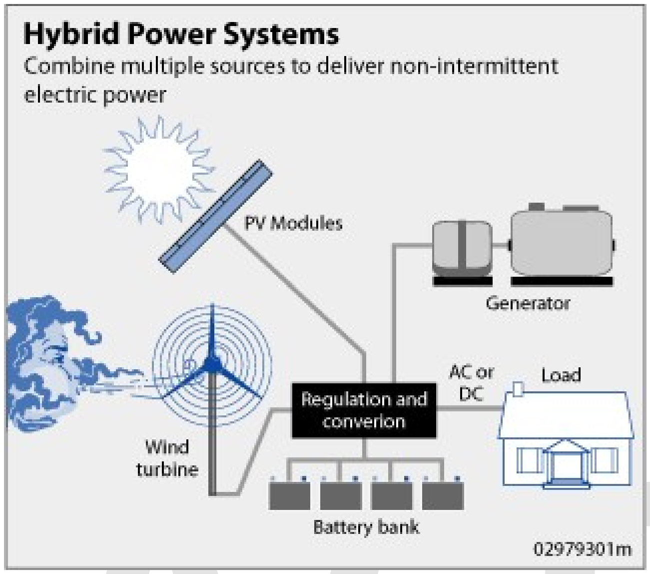
For the weather and latitudes of the United States and Europe, typical insolation ranges from 4 kWh/m²/day in northern climes to 6.5 kWh/m²/day in the sunniest regions. Typical solar panels have an average efficiency of 12%, with the best commercially available panels at 20%. Thus, a photovoltaic installation in the southern latitudes of Europe or the United States may expect to produce 1 kWh/m²/day. A typical "150 watt" solar panel is about a square meter in size. Such a panel may be expected to produce 1 kWh every day, on average, after taking into account the weather and the latitude.

In the Sahara desert, with less cloud cover and a better solar angle, one could ideally obtain closer to 8.3 kWh/m²/day provided the nearly ever present wind would not blow sand on the units. The unpopulated area of the Sahara desert is over 9 million km², which if covered with solar panels would provide 630 terawatts total power. The Earth's current energy consumption rate is around 13.5 TW at any given moment (including oil, gas, coal, nuclear, and hydroelectric).

Photovoltaic cells' electrical output is extremely sensitive to shading. When even a small portion of a cell, module, or array is shaded, while the remainder is in sunlight, the output falls dramatically due to internal 'short-circuiting' (the electrons reversing course through the shaded portion of the p-n junction). Therefore it is extremely important that a PV installation is not shaded at all by trees, architectural features, flag poles, or other obstructions. Sunlight can be absorbed by dust, fallout, or other impurities at the surface of the module. This can cut down the amount of light that actually strikes the cells by as much as half. Maintaining a clean module surface will increase output performance over the life of the module.

Module output and life are also degraded by increased temperature. Allowing ambient air to flow over, and if possible behind, PV modules reduces this problem. However, effective module lives are typically 25 years or more, so replacement costs should be considered as well.

Hybrid systems



A hybrid system combines PV with other forms of generation, usually a diesel generator. Biogas is also used. The other form of generation may be a type able to modulate power output as a function of demand. However more than one renewable form of energy may be used e.g. wind. The photovoltaic power generation serves to reduce the consumption of non renewable fuel. Hybrid systems are most often found on islands. Pellworm island in Germany and Kynthos island are notable examples (both are combined with wind). The Kynthos plant has diocane diesel consumption by 11.2%

There has also been recent work showing that the PV penetration limit can be increased by deploying a distributed network of PV+CHP hybrid systems in the U.S. The temporal distribution of solar flux, electrical and heating requirements for representative U.S. single family residences were analyzed and the results clearly show that hybridizing CHP with PV can enable additional PV deployment above what is possible with a conventional centralized electric generation system. This theory was reconfirmed with numerical simulations using per second solar flux data to determine that the necessary battery backup to provide for such a hybrid system is possible with relatively small and inexpensive battery systems. In addition, large PV+CHP systems are possible for institutional buildings, which again provide back up for intermittent PV and reduce CHP runtime.

Grid-Interactive Photovoltaic for Uninterruptible Power Supply(UPS)

A system to provide uninterrupted power which integrates PV, battery, battery charger & boost circuit, power factor correction & rectification, H-bridge inverter, protection, filtering based on dsPIC can be developed. The input power from grid will be filtered for common mode noise and will be protected from surges/spikes by input power protection circuitry. The power will go into the power factor correction (PFC) module which will force the input current to be sinusoidal for efficient utilization of power. The PFC module also will rectify the input AC power to produce voltage-regulated DC power which will be used by the rest of the functional modules. This rectified AC power will be OR'd through diodes with the DC voltage generated from the battery boost circuit. The dsPIC PWM will control a H-bridge inverter whose output, when filtered, will result a sinusoidal AC output waveform. The proposal presents a practical implementation of the grid interactive photovoltaic uninterruptible power supply (UPS) system using battery storage based on dsPIC controlled and monitoring.

Standardization

Increasing use of photovoltaic systems and integration of photovoltaic power into existing structures and techniques of supply and distribution increases the value of general standards and definitions for photovoltaic components and systems. The standards are compiled at the International Electrotechnical Commission (IEC) and apply to efficiency, durability and safety of cells, modules, simulation programs, plug connectors and cables, mounting systems, overall efficiency of inverters etc.

Chapter 3

Theory of Solar Cell

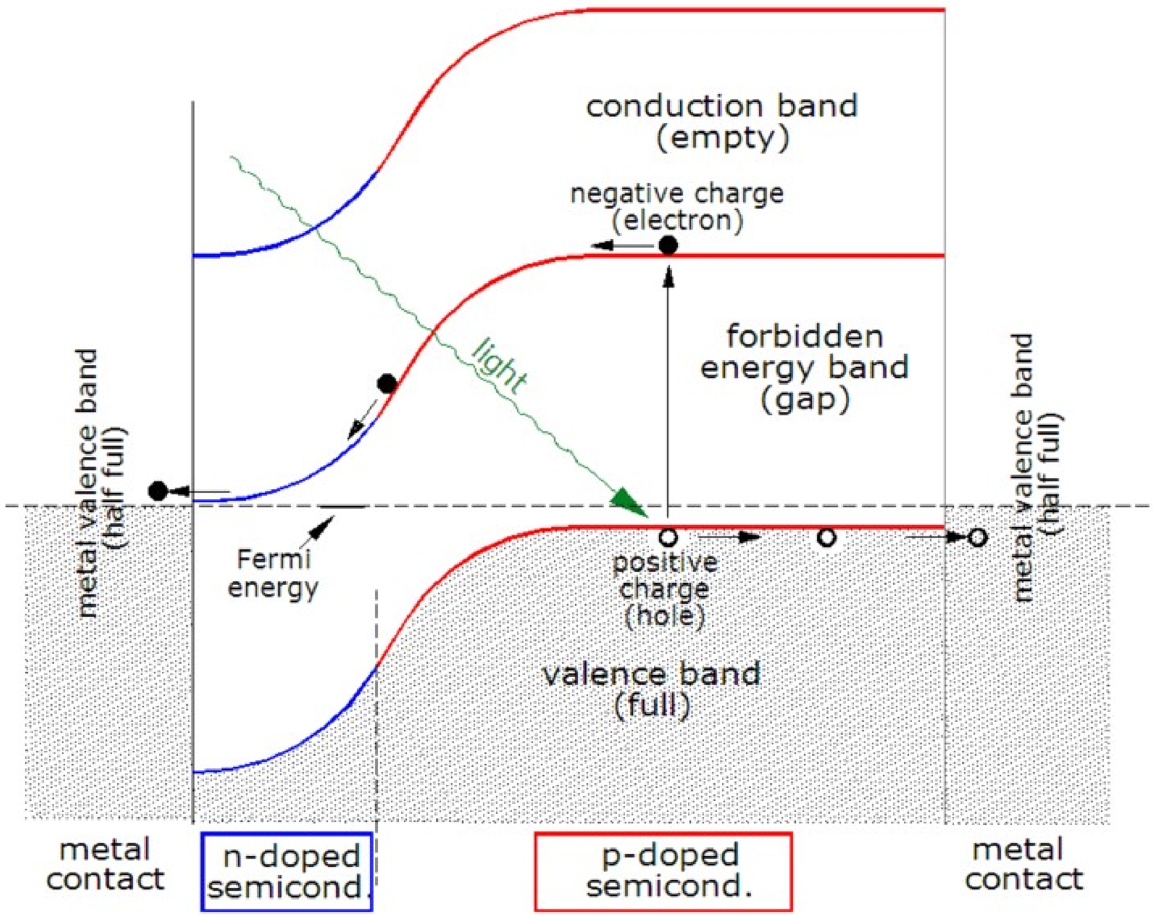
Simple explanation

1. Photons in sunlight hit the solar panel and are absorbed by semiconducting materials, such as silicon.
2. Electrons (negatively charged) are knocked loose from their atoms, allowing them to flow through the material to produce electricity. Due to the special composition of solar cells, the electrons are only allowed to move in a single direction.
3. An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity.

Photogeneration of charge carriers

When a photon hits a piece of silicon, one of three things can happen:

1. the photon can pass straight through the silicon — this (generally) happens for lower energy photons,
2. the photon can reflect off the surface,
3. the photon can be absorbed by the silicon, if the photon energy is higher than the silicon band gap value. This generates an electron-hole pair and sometimes heat, depending on the band structure.



Band diagram of a silicon solar cell

When a photon is absorbed, its energy is given to an electron in the crystal lattice. Usually this electron is in the valence band, and is tightly bound in covalent bonds between neighboring atoms, and hence unable to move far. The energy given to it by the photon "excites" it into the conduction band, where it is free to move around within the semiconductor. The covalent bond that the electron was previously a part of now has one fewer electron — this is known as a hole. The presence of a missing covalent bond allows the bonded electrons of neighboring atoms to move into the "hole," leaving another hole behind, and in this way a hole can move through the lattice. Thus, it can be said that photons absorbed in the semiconductor create mobile electron-hole pairs.

A photon need only have greater energy than that of the band gap in order to excite an electron from the valence band into the conduction band. However, the solar frequency spectrum approximates a black body spectrum at ~6000 K, and as such, much of the solar radiation reaching the Earth is composed of photons with energies greater than the band gap of silicon. These higher energy photons will be absorbed by the solar cell, but the difference in energy between these photons and the silicon band gap is converted into heat (via lattice vibrations — called phonons) rather than into usable electrical energy.

Charge carrier separation

There are two main modes for charge carrier separation in a solar cell:

1. **drift** of carriers, driven by an electric field established across the device
2. **diffusion** of carriers due to their random thermal motion, until they are captured by the electrical fields existing at the edges of the active region.

In thick solar cells there is no electric field in the active region, so the dominant mode of charge carrier separation is diffusion. In these cells the diffusion length of minority carriers (the length that photo-generated carries can travel before they recombine) must be large compared to the cell thickness. In thin film cells (such as amorphous silicon), the diffusion length of minority carriers is usually very short due to the existence of defects, and the dominant charge separation is therefore drift, driven by the electrostatic field of the junction, which extends to the whole thickness of the cell.

The p-n junction

The most commonly known solar cell is configured as a large-area p-n junction made from silicon. As a simplification, one can imagine bringing a layer of n-type silicon into direct contact with a layer of p-type silicon. In practice, p-n junctions of silicon solar cells are not made in this way, but rather by diffusing an n-type dopant into one side of a p-type wafer (or vice versa).

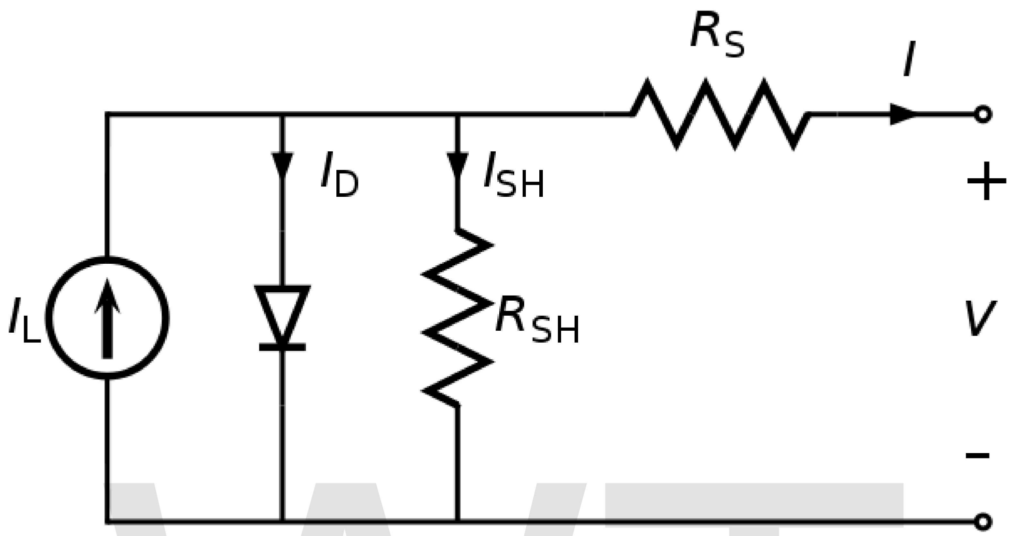
If a piece of p-type silicon is placed in intimate contact with a piece of n-type silicon, then a diffusion of electrons occurs from the region of high electron concentration (the n-type side of the junction) into the region of low electron concentration (p-type side of the junction). When the electrons diffuse across the p-n junction, they recombine with holes on the p-type side. The diffusion of carriers does not happen indefinitely, however, because charges build up on either side of the junction and create an electric field. The electric field creates a diode that promotes charge flow, known as drift current, that opposes and eventually balances out the diffusion of electrons and holes. This region where electrons and holes have diffused across the junction is called the depletion region because it no longer contains any mobile charge carriers. It is also known as the *space charge region*.

Connection to an external load

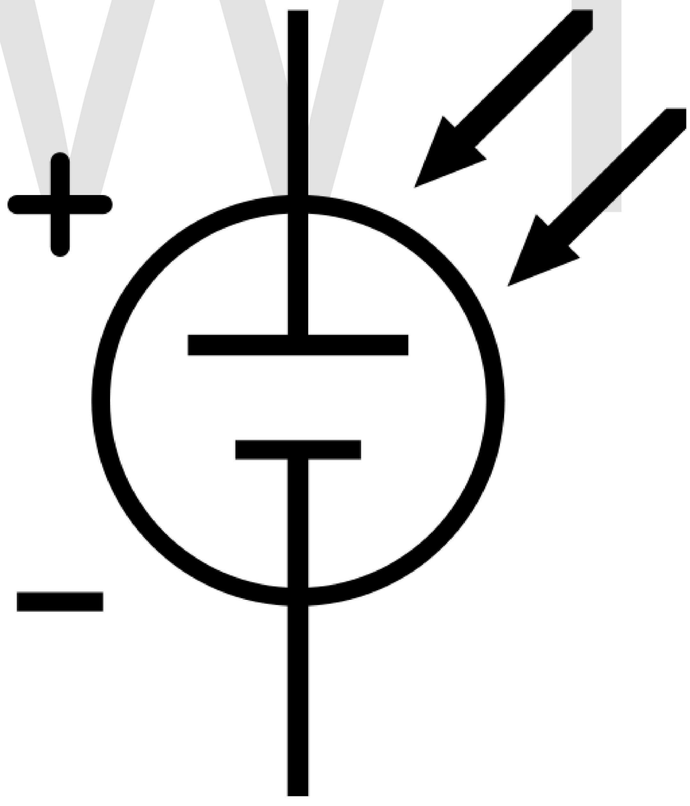
Ohmic metal-semiconductor contacts are made to both the n-type and p-type sides of the solar cell, and the electrodes connected to an external load. Electrons that are created on the n-type side, or have been "collected" by the junction and swept onto the n-type side, may travel through the wire, power the load, and continue through the wire until they reach the p-type semiconductor-metal contact. Here, they recombine with a hole that was either created as an electron-hole pair on the p-type side of the solar cell, or a hole that was swept across the junction from the n-type side after being created there.

The voltage measured is equal to the difference in the quasi Fermi levels of the minority carriers, i.e. electrons in the p-type portion and holes in the n-type portion.

Equivalent circuit of a solar cell



The equivalent circuit of a solar cell



The schematic symbol of a solar cell

To understand the electronic behavior of a solar cell, it is useful to create a model which is electrically equivalent, and is based on discrete electrical components whose behavior is well known. An ideal solar cell may be modelled by a current source in parallel with a diode; in practice no solar cell is ideal, so a shunt resistance and a series resistance component are added to the model. The resulting equivalent circuit of a solar cell is shown on the left. Also shown, on the right, is the schematic representation of a solar cell for use in circuit diagrams.

Characteristic equation

From the equivalent circuit it is evident that the current produced by the solar cell is equal to that produced by the current source, minus that which flows through the diode, minus that which flows through the shunt resistor:

$$I = I_L - I_D - I_{SH}$$

where

- I = output current (amperes)
- I_L = photogenerated current (amperes)
- I_D = diode current (amperes)
- I_{SH} = shunt current (amperes).

The current through these elements is governed by the voltage across them:

$$V_j = V + IR_S$$

where

- V_j = voltage across both diode and resistor R_{SH} (volts)
- V = voltage across the output terminals (volts)
- I = output current (amperes)
- R_S = series resistance (Ω).

By the Shockley diode equation, the current diverted through the diode is:

$$I_D = I_0 \left\{ \exp\left[\frac{qV_j}{nkT}\right] - 1 \right\}$$

where

- I_0 = reverse saturation current (amperes)
- n = diode ideality factor (1 for an ideal diode)
- q = elementary charge
- k = Boltzmann's constant
- T = absolute temperature

- At 25°C, $kT/q \approx 0.0259$ volts.

By Ohm's law, the current diverted through the shunt resistor is:

$$I_{SH} = \frac{V_j}{R_{SH}}$$

where

- R_{SH} = shunt resistance (Ω).

Substituting these into the first equation produces the characteristic equation of a solar cell, which relates solar cell parameters to the output current and voltage:

$$I = I_L - I_0 \left\{ \exp\left[\frac{q(V + IR_S)}{nkT}\right] - 1 \right\} - \frac{V + IR_S}{R_{SH}}.$$

An alternative derivation produces an equation similar in appearance, but with V on the left-hand side. The two alternatives are identities; that is, they yield precisely the same results.

In principle, given a particular operating voltage V the equation may be solved to determine the operating current I at that voltage. However, because the equation involves I on both sides in a transcendental function the equation has no general analytical solution. However, even without a solution it is physically instructive. Furthermore, it is easily solved using numerical methods. (A general analytical solution to the equation is possible using Lambert's W function, but since Lambert's W generally itself must be solved numerically this is a technicality.)

Since the parameters I_0, n, R_S, and R_{SH} cannot be measured directly, the most common application of the characteristic equation is nonlinear regression to extract the values of these parameters on the basis of their combined effect on solar cell behavior.

Open-circuit voltage and short-circuit current

When the cell is operated at open circuit, $I = 0$ and the voltage across the output terminals is defined as the *open-circuit voltage*. Assuming the shunt resistance is high enough to neglect the final term of the characteristic equation, the open-circuit voltage V_{OC} is:

$$V_{OC} \approx \frac{kT}{q} \ln\left(\frac{I_L}{I_0} + 1\right).$$

Similarly, when the cell is operated at short circuit, $V = 0$ and the current I through the terminals is defined as the *short-circuit current*. It can be shown that for a high-quality solar cell (low R_S and I_0, and high R_{SH}) the short-circuit current I_{SC} is:

$$I_{SC} \approx I_L.$$

Effect of physical size

The values of I_0, R_S, and R_{SH} are dependent upon the physical size of the solar cell. In comparing otherwise identical cells, a cell with twice the surface area of another will, in principle, have double the I_0 because it has twice the junction area across which current can leak. It will also have half the R_S and R_{SH} because it has twice the cross-sectional area through which current can flow. For this reason, the characteristic equation is frequently written in terms of current density, or current produced per unit cell area:

$$J = J_L - J_0 \left\{ \exp\left[\frac{q(V + Jr_S)}{nkT} \right] - 1 \right\} - \frac{V + Jr_S}{r_{SH}}$$

where

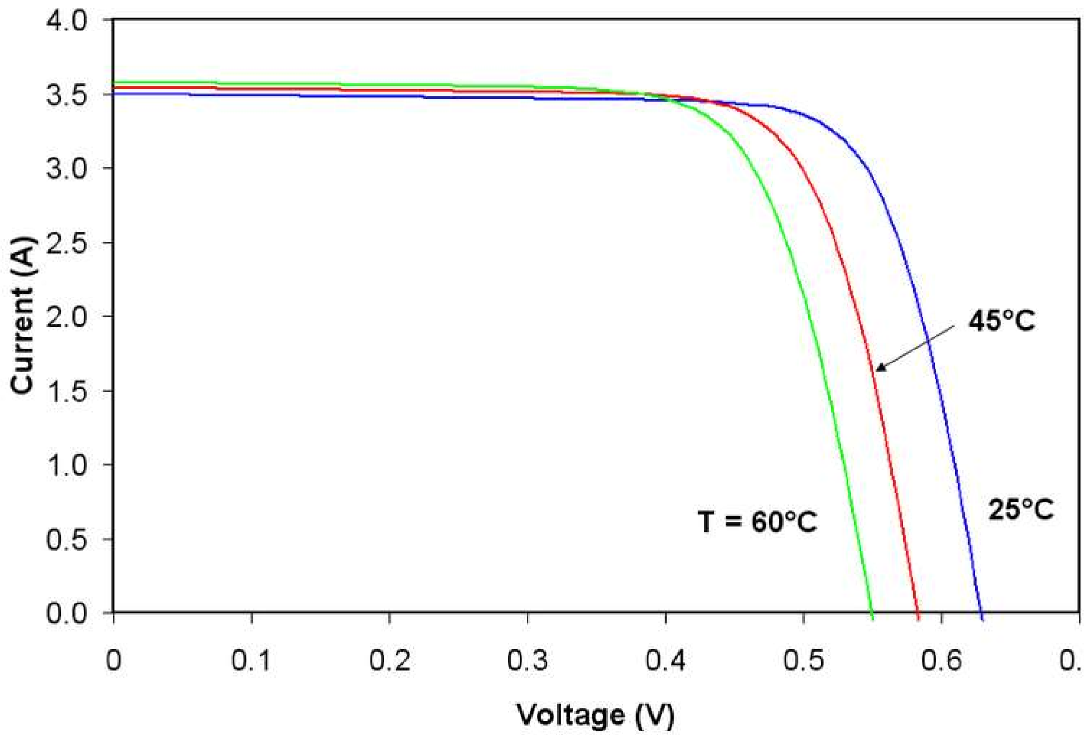
- J = current density (amperes/cm^2)
- J_L = photogenerated current density (amperes/cm^2)
- J_0 = reverse saturation current density (amperes/cm^2)
- r_S = specific series resistance (Ω-cm^2)
- r_{SH} = specific shunt resistance (Ω-cm^2).

This formulation has several advantages. One is that since cell characteristics are referenced to a common cross-sectional area they may be compared for cells of different physical dimensions. While this is of limited benefit in a manufacturing setting, where all cells tend to be the same size, it is useful in research and in comparing cells between manufacturers. Another advantage is that the density equation naturally scales the parameter values to similar orders of magnitude, which can make numerical extraction of them simpler and more accurate even with naive solution methods.

There are practical limitations of this formulation. For instance, certain parasitic effects grow in importance as cell sizes shrink and can affect the extracted parameter values. Recombination and contamination of the junction tend to be greatest at the perimeter of the cell, so very small cells may exhibit higher values of J_0 or lower values of R_{SH} than larger cells that are otherwise identical. In such cases, comparisons between cells must be made cautiously and with these effects in mind.

This approach should only be used for comparing solar cells with comparable layout. For instance, a comparison between primarily quadratical solar cells like typical crystalline silicon solar cells and narrow but long solar cells like typical thin film solar cells can lead to wrong assumptions caused by the different kinds of current paths and therefore the influence of for instance a distributed series resistance r_S.

Cell temperature



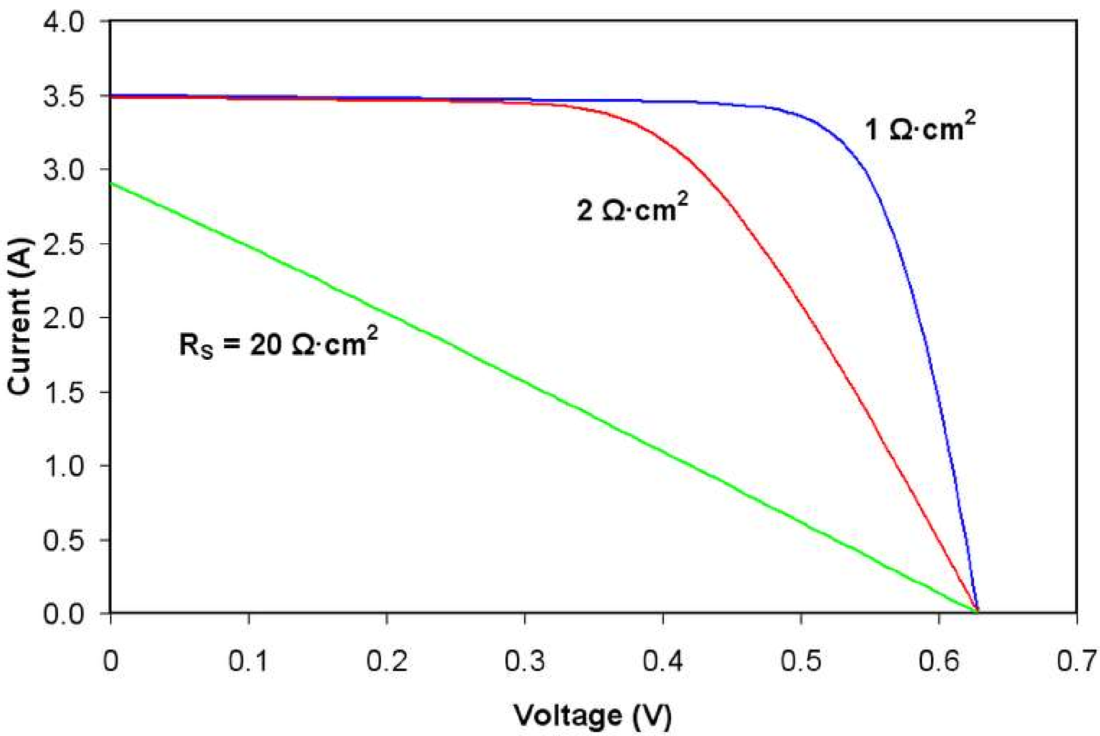
Effect of temperature on the current-voltage characteristics of a solar cell

Temperature affects the characteristic equation in two ways: directly, via T in the exponential term, and indirectly via its effect on I_0 (strictly speaking, temperature affects all of the terms, but these two far more significantly than the others). While increasing T reduces the magnitude of the exponent in the characteristic equation, the value of I_0 increases exponentially with T. The net effect is to reduce V_{OC} (the open-circuit voltage) linearly with increasing temperature. The magnitude of this reduction is inversely proportional to V_{OC}; that is, cells with higher values of V_{OC} suffer smaller reductions in voltage with increasing temperature. For most crystalline silicon solar cells the change in V_{OC} with temperature is about -0.50%/°C, though the rate for the highest-efficiency crystalline silicon cells is around -0.35%/°C. By way of comparison, the rate for amorphous silicon solar cells is -0.20%/°C to -0.30%/°C, depending on how the cell is made.

The amount of photogenerated current I_L increases slightly with increasing temperature because of an increase in the number of thermally generated carriers in the cell. This effect is slight, however: about 0.065%/°C for crystalline silicon cells and 0.09% for amorphous silicon cells.

The overall effect of temperature on cell efficiency can be computed using these factors in combination with the characteristic equation. However, since the change in voltage is much stronger than the change in current, the overall effect on efficiency tends to be similar to that on voltage. Most crystalline silicon solar cells decline in efficiency by 0.50%/°C and most amorphous cells decline by 0.15-0.25%/°C. The figure above shows I-V curves that might typically be seen for a crystalline silicon solar cell at various temperatures.

Series resistance

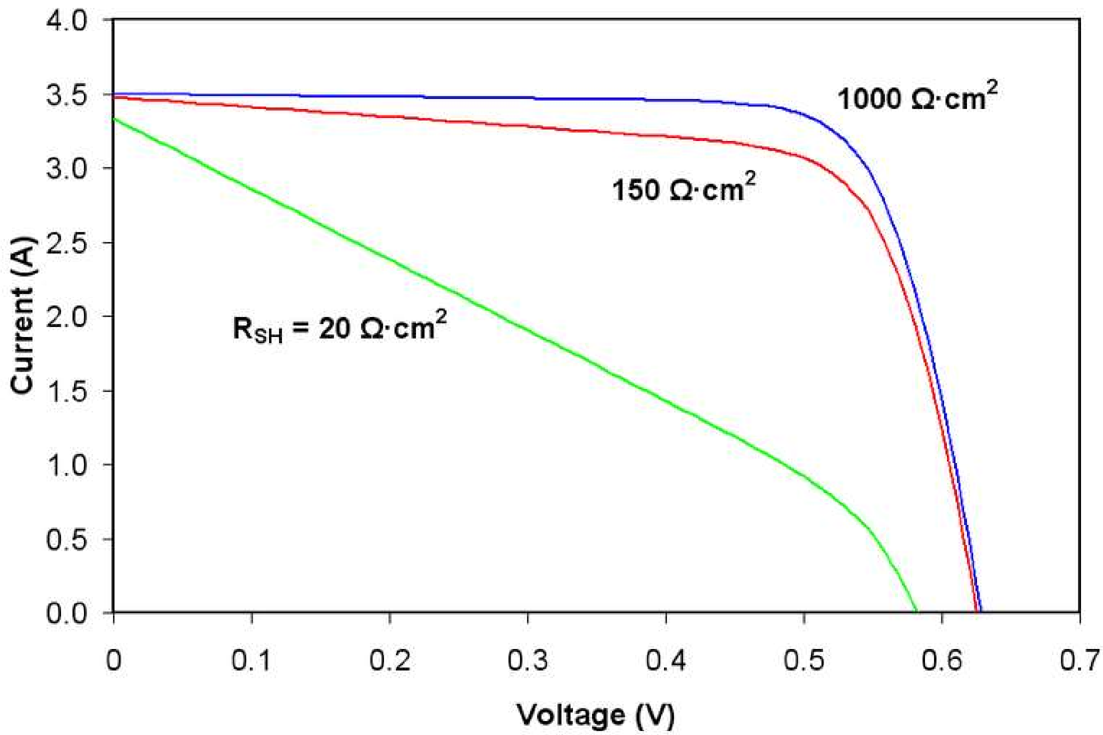


Effect of series resistance on the current-voltage characteristics of a solar cell

As series resistance increases, the voltage drop between the junction voltage and the terminal voltage becomes greater for the same flow of current. The result is that the current-controlled portion of the I-V curve begins to sag toward the origin, producing a significant decrease in the terminal voltage *V* and a slight reduction in I_{SC}, the short-circuit current. Very high values of R_S will also produce a significant reduction in I_{SC}; in these regimes, series resistance dominates and the behavior of the solar cell resembles that of a resistor. These effects are shown for crystalline silicon solar cells in the I-V curves displayed in the figure to the right.

Losses caused by series resistance are in a first approximation given by $P_{loss}=V_{Rs}I=I^2R_S$ and increase quadratically with (photo-)current. Series resistance losses are therefore most important at high illumination intensities.

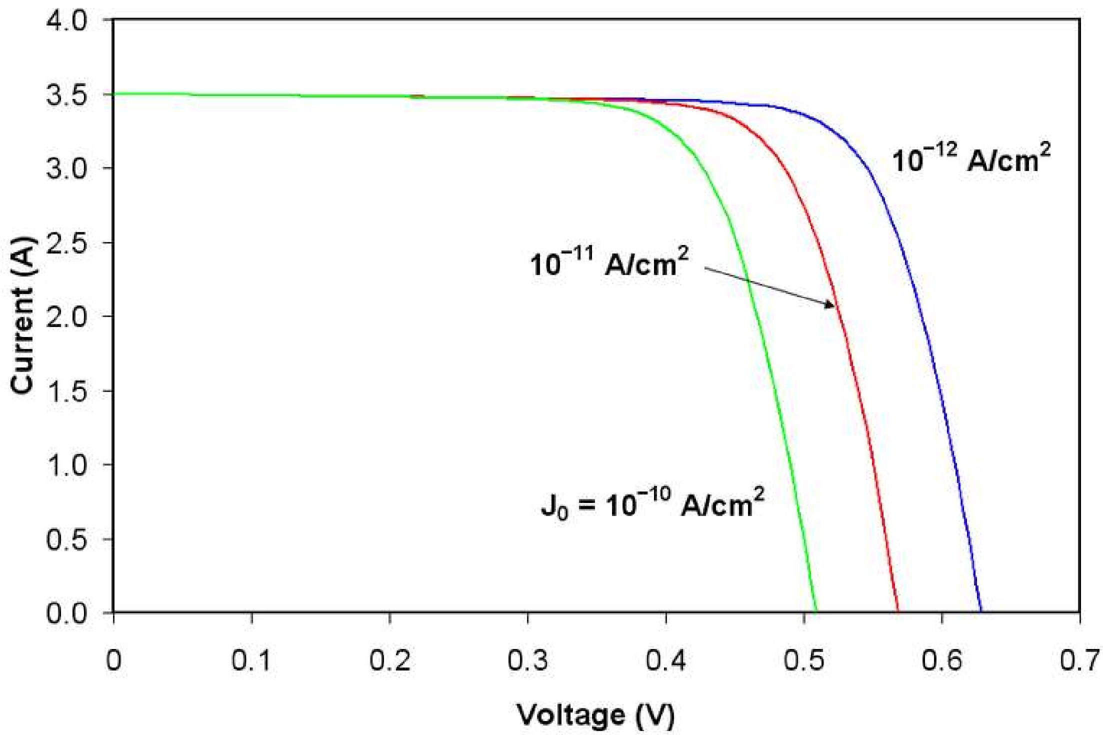
Shunt resistance



Effect of shunt resistance on the current–voltage characteristics of a solar cell

As shunt resistance decreases, the current diverted through the shunt resistor increases for a given level of junction voltage. The result is that the voltage-controlled portion of the I-V curve begins to sag toward the origin, producing a significant decrease in the terminal current *I* and a slight reduction in V_{OC}. Very low values of R_{SH} will produce a significant reduction in V_{OC}. Much as in the case of a high series resistance, a badly shunted solar cell will take on operating characteristics similar to those of a resistor. These effects are shown for crystalline silicon solar cells in the I-V curves displayed in the figure to the right.

Reverse saturation current



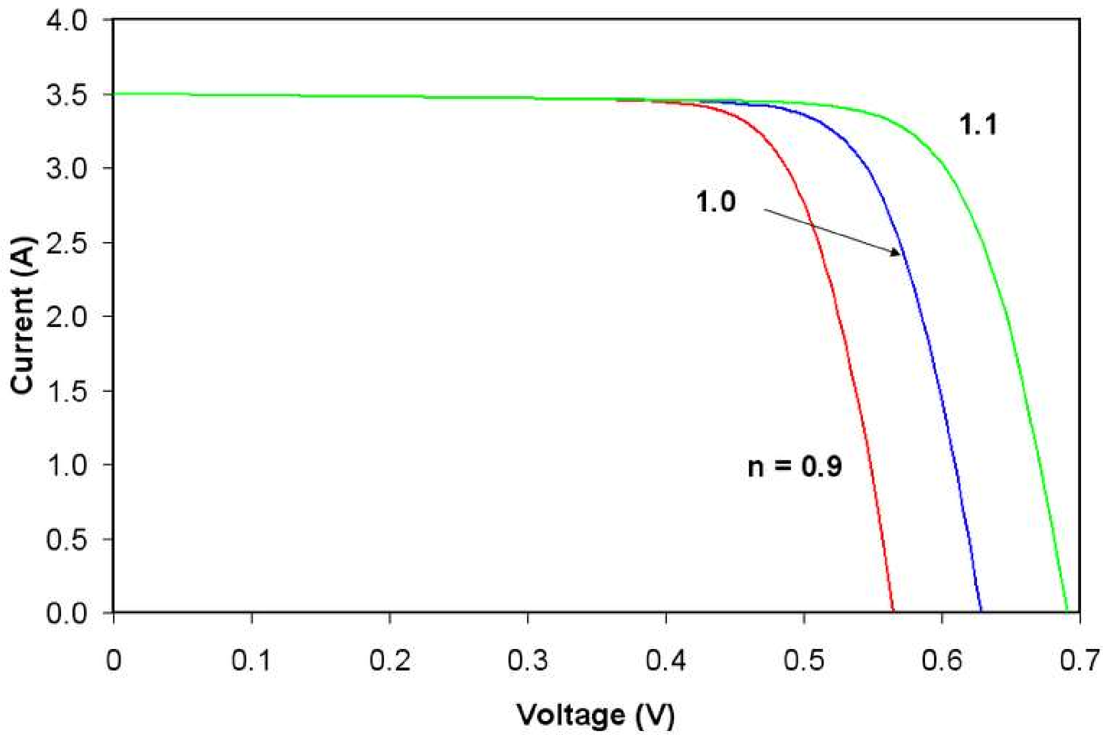
Effect of reverse saturation current on the current-voltage characteristics of a solar cell

If one assumes infinite shunt resistance, the characteristic equation can be solved for V_{OC}:

$$V_{OC} = \frac{kT}{q} \ln\left(\frac{I_{SC}}{I_0} + 1\right).$$

Thus, an increase in I_0 produces a reduction in V_{OC} proportional to the inverse of the logarithm of the increase. This explains mathematically the reason for the reduction in V_{OC} that accompanies increases in temperature described above. The effect of reverse saturation current on the I-V curve of a crystalline silicon solar cell are shown in the figure to the right. Physically, reverse saturation current is a measure of the "leakage" of carriers across the p-n junction in reverse bias. This leakage is a result of carrier recombination in the neutral regions on either side of the junction.

Ideality factor



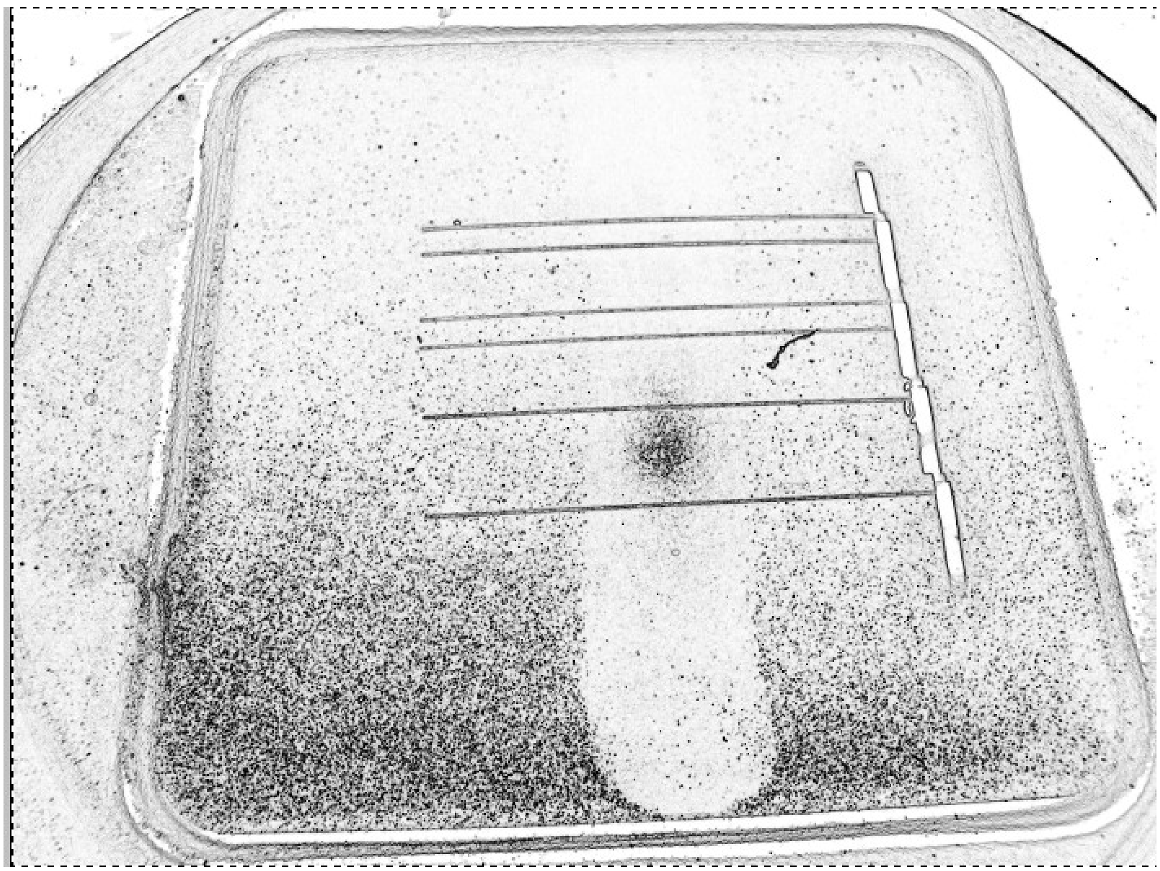
Effect of ideality factor on the current-voltage characteristics of a solar cell

The ideality factor (also called the emissivity factor) is a fitting parameter that describes how closely the diode's behavior matches that predicted by theory, which assumes the p-n junction of the diode is an infinite plane and no recombination occurs within the space-charge region. A perfect match to theory is indicated when $n = 1$. When recombination in the space-charge region dominate other recombination, however, $n = 2$. The effect of changing ideality factor independently of all other parameters is shown for a crystalline silicon solar cell in the I-V curves displayed in the figure to the right.

Most solar cells, which are quite large compared to conventional diodes, well approximate an infinite plane and will usually exhibit near-ideal behavior under Standard Test Condition ($n \approx 1$). Under certain operating conditions, however, device operation may be dominated by recombination in the space-charge region. This is characterized by a significant increase in I_0 as well as an increase in ideality factor to $n \approx 2$. The latter tends to increase solar cell output voltage while the former acts to erode it. The net effect, therefore, is a combination of the increase in voltage shown for increasing n in the figure to the right and the decrease in voltage shown for increasing I_0 in the figure above. Typically, I_0 is the more significant factor and the result is a reduction in voltage.

Chapter 4

Solar Cell Efficiency



Dust often accumulates on the glass of solar panels - seen here as black dots - which reduces the amount of available light.

The **efficiency** of a **solar cell** may be broken down into reflectance efficiency, thermodynamic efficiency, charge carrier separation efficiency and conductive efficiency. The overall efficiency is the product of each of these individual efficiencies.

Due to the difficulty in measuring these parameters directly, other parameters are measured instead: thermodynamic efficiency, quantum efficiency, V_{OC} ratio, and fill factor. Reflectance losses are a portion of the quantum efficiency under "external quantum efficiency". Recombination losses make up a portion of the quantum efficiency,

V_{OC} ratio, and fill factor. Resistive losses are predominantly categorized under fill factor, but also make up minor portions of the quantum efficiency, V_{OC} ratio.

Energy conversion efficiency factors

Energy conversion efficiency

A solar cell's *energy conversion efficiency* (η, "eta"), is the percentage of electric power converted from incident light. This is calculated at the maximum power point, P_m, divided by the input light *irradiance* (E, in W/m^2) under standard test conditions (STC) and the *surface area* of the solar cell (A_c in m^2).

$$\eta = \frac{P_m}{E \times A_c}$$

STC specifies a temperature of 25 °C and an irradiance of 1000 W/m^2 with an air mass 1.5 (AM1.5) spectrum. These correspond to the irradiance and spectrum of sunlight incident on a clear day upon a sun-facing 37°-tilted surface with the sun at an angle of 41.81° above the horizon. This condition approximately represents solar noon near the spring and autumn equinoxes in the continental United States with surface of the cell aimed directly at the sun. For example, under these test conditions a solar cell of 12% efficiency with a 100 cm^2 (0.01 m^2) surface area would produce 1.2 watts of power.

Thermodynamic efficiency limit

The absolute maximum theoretically possible conversion efficiency for sunlight is about 86% due to the Carnot limit, given the temperature of the photons emitted by the Sun's surface.

However, solar cells operate as quantum energy conversion devices, and are therefore subject to the "thermodynamic efficiency limit". Photons with an energy below the band gap of the absorber material cannot generate a hole-electron pair, and so their energy is not converted to useful output and only generates heat if absorbed. For photons with an energy above the band gap energy, only a fraction of the energy above the band gap can be converted to useful output. When a photon of greater energy is absorbed, the excess energy above the band gap is converted to kinetic energy of the carrier combination. The excess kinetic energy is converted to heat through phonon interactions as the kinetic energy of the carriers slows to equilibrium velocity.

Solar cells with multiple band gap absorber materials improve efficiency by dividing the solar spectrum into smaller bins where the thermodynamic efficiency limit is higher for each bin.

Quantum efficiency

As described above, when a photon is absorbed by a solar cell it can produce an electron-hole pair. One of the carriers may reach the p-n junction and contribute to the current produced by the solar cell; such a carrier is said to be *collected*. Or, the carriers recombine with no net contribution to cell current.

Quantum efficiency refers to the percentage of photons that are converted to electric current (i.e., collected carriers) when the cell is operated under short circuit conditions. Some of the light striking the cell is reflected, or passes throgh the cell; external quantum efficiency is the fraction of incident photons that are converted to electric current. Not all the photons captured by the cell contribute to electric current; internal quantum efficiency (IQE) is the fraction of *absorbed* photons that are converted to electric current. Thick cells let through little light.

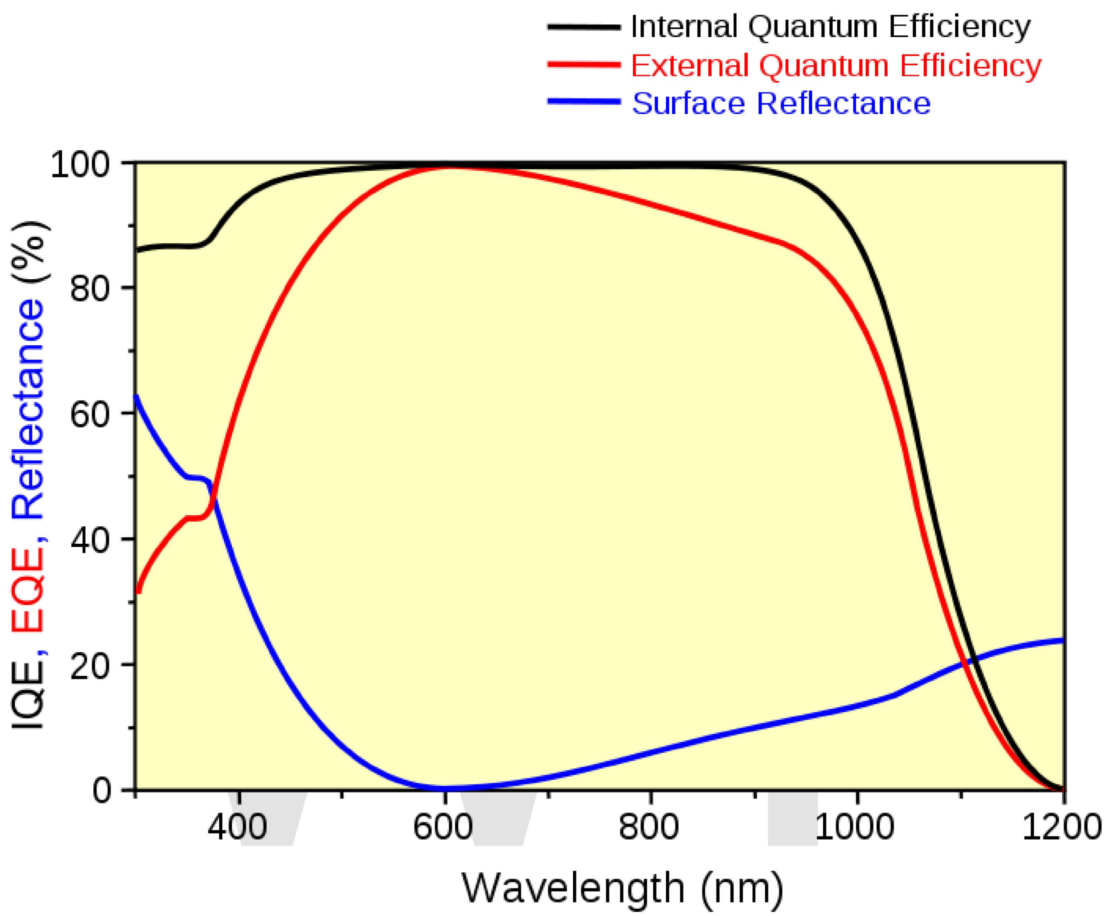
Quantum efficiency is most usefully expressed as a *spectral* measurement (that is, as a function of photon wavelength or energy). Since some wavelengths are absorbed more effectively than others, spectral measurements of quantum efficiency can yield valuable information about the quality of the semiconductor bulk and surfaces. Quantum efficiency alone is not the same as overall energy conversion efficiency, as it does not convey information about the fraction of power that is converted by the solar cell.

Quantum efficiency (QE**)** is the ratio of the number of *charge carriers* collected by the solar cell to the number of *photons* of a given energy shining on the solar cell. QE therefore relates to the response of a solar cell to the various wavelengths in the spectrum of light shining on the cell. The QE is given as a function of either wavelength or energy. If all the photons of a certain wavelength are absorbed and we collect the resulting minority carriers (for example, electrons in a p-type material), then the QE at that particular wavelength has a value of one. The QE for photons with energy below the bandgap is zero.

The quantum efficiency ideally has a square shape, where the QE value is fairly constant across the entire spectrum of wavelengths measured. However, the QE for most solar cells is reduced because of the effects of recombination, where charge carriers are not able to move into an external circuit. The same mechanisms that affect the collection probability also affect the QE. For example, modifying the front surface can affect carriers generated near the surface. And because high-energy (blue) light is absorbed very close to the surface, considerable recombination at the front surface will affect the "blue" portion of the QE. Similarly, lower energy (green) light is absorbed in the bulk of a solar cell, and a low diffusion length will affect the collection probability from the solar cell bulk, reducing the QE in the green portion of the spectrum. In somewhat technical terms, the quantum efficiency can be viewed as the collection probability due to the generation profile of a single wavelength, integrated over the device thickness and normalized to the number of incident photons.

"Quantum efficiency" is also sometimes called **IPCE**, which stands for **I**ncident-**P**hoton-to-electron **C**onversion **E**fficiency.

Types



A graph showing variation of internal quantum efficiency, external quantum efficiency, and reflectance with wavelength of a crystalline silicon solar cell.

Two types of **quantum efficiency (QE)** of a solar cell are often considered:

- **External Quantum Efficiency** (EQE) is the ratio of the number of charge carriers collected by the solar cell to the number of photons of a given energy *shining on the solar cell from outside* (incident photons).
- **Internal Quantum Efficiency** (IQE) is the ratio of the number of charge carriers collected by the solar cell to the number of photons of a given energy that shine on the solar cell from outside *and* is absorbed by the cell.

The IQE is always larger than the EQE. A low IQE indicates that the active layer of the solar cell is unable to make good use of the photons. A low EQE can indicate that, but it can also, instead, indicate that a lot of the light was reflected.

To measure the IQE, one first measures the EQE of the solar device, then measures its transmission and reflection, and combines these data to infer the IQE.

Energy conversion efficiency

A solar cell's *energy conversion efficiency* (η, "eta"), is the percentage of power converted (from absorbed light to electrical energy) and collected, when a solar cell is connected to an electrical circuit. This term is calculated using the ratio of the maximum power point, P_m, divided by the input light *irradiance* (E, in W/m²) under standard test conditions (STC) and the *surface area* of the solar cell (A_c in m²).

$$\eta = \frac{P_m}{E \times A_c}$$

STC specifies a temperature of 25°C and an irradiance of 1000 W/m² with an air mass 1.5 (AM1.5) spectrum. These correspond to the irradiance and spectrum of sunlight incident on a clear day upon a sun-facing 37°-tilted surface with the sun at an angle of 41.81° above the horizon. This condition approximately represents solar noon near the spring and autumn equinoxes in the continental United States with surface of the cell aimed directly at the sun. Thus, under these conditions a solar cell of 12% efficiency with a 100 cm^2 (0.01 m^2) surface area can be expected to produce approximately 1.2 watts of power. On June 16,2010, Sanyo Corporation announced the world's most efficient solar module, with a claimed energy conversion efficiency of 20.7%.

The losses of a solar cell may be broken down into reflectance losses, thermodynamic efficiency, recombination losses and resistive electrical loss. The overall efficiency is the product of each of these individual losses.

Due to the difficulty in measuring these parameters directly, other parameters are measured instead: Thermodynamic Efficiency, Quantum Efficiency, V_{OC} ratio, and Fill Factor. Reflectance losses are a portion of the Quantum Efficiency under "External Quantum Efficiency". Recombination losses make up a portion of the Quantum Efficiency, V_{OC} ratio, and Fill Factor. Resistive losses are predominantly categorized under Fill Factor, but also make up minor portions of the Quantum Efficiency, V_{OC} ratio.

Generally, solar cells on the market today do not produce much electricity from ultraviolet light, instead it is either filtered out or absorbed by the cell, heating the cell. That heat is wasted energy and could even lead to damage to the cell.

Maximum-power point

A solar cell may operate over a wide range of voltages (V) and currents (I). By increasing the resistive load on an irradiated cell continuously from zero (a *short circuit*) to a very high value (an *open circuit*) one can determine the maximum-power point, the point that maximizes V×I; that is, the load for which the cell can deliver maximum electrical power at that level of irradiation. (The output power is zero in both the short circuit and open circuit extremes).

A high quality, monocrystalline silicon solar cell, at 25 °C cell temperature, may produce 0.60 volts open-circuit (V_{OC}). The cell temperature in full sunlight, even with 25 °C air temperature, will probably be close to 45 °C, reducing the open-circuit voltage to 0.55 volts per cell. The voltage drops modestly, with this type of cell, until the short-circuit current is approached (I_{SC}). Maximum power (with 45 °C cell temperature) is typically produced with 75% to 80% of the open-circuit voltage (0.43 volts in this case) and 90% of the short-circuit current. This output can be up to 70% of the V_{OC} x I_{SC} product. The short-circuit current (I_{SC}) from a cell is nearly proportional to the illumination, while the open-circuit voltage (V_{OC}) may drop only 10% with a 80% drop in illumination. Lower-quality cells have a more rapid drop in voltage with increasing current and could produce only 1/2 V_{OC} at 1/2 I_{SC}. The usable power output could thus drop from 70% of the V_{OC} x I_{SC} product to 50% or even as little as 25%. Vendors who rate their solar cell "power" only as V_{OC} x I_{SC}, without giving load curves, can be seriously distorting their actual performance.

The maximum power point of a photovoltaic varies with incident illumination. For systems large enough to justify the extra expense, a maximum power point tracker tracks the instantaneous power by continually measuring the voltage and current (and hence, power transfer), and uses this information to dynamically adjust the load so the maximum power is *always* transferred, regardless of the variation in lighting.

Fill factor

Another defining term in the overall behavior of a solar cell is the *fill factor* (*FF*). This is the ratio of the available *power* at the *maximum power point* (P_m) divided by the *open circuit voltage* (V_{OC}) and the *short circuit current* (I_{SC}):

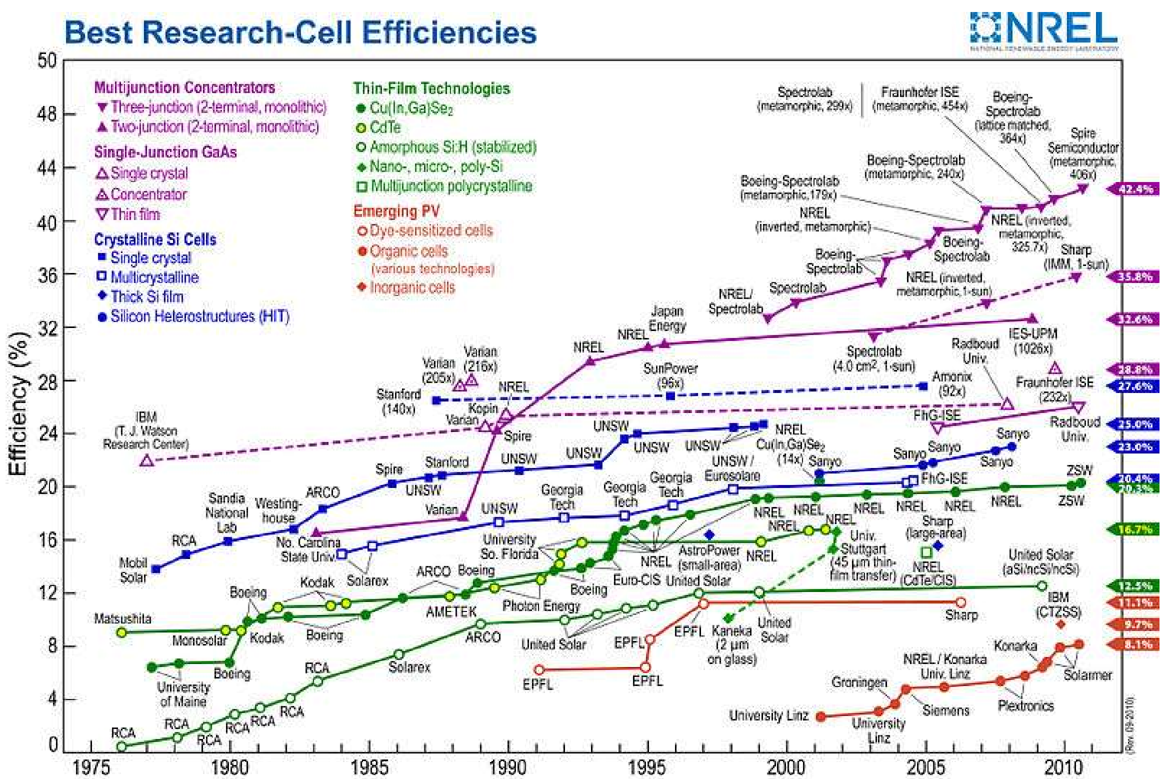
$$FF = \frac{P_m}{V_{OC} \times I_{SC}} = \frac{\eta \times A_c \times E}{V_{OC} \times I_{SC}}.$$

The fill factor is directly affected by the values of the cell's series and shunt resistances. Increasing the shunt resistance (R_{sh}) and decreasing the series resistance (R_s) lead to a higher fill factor, thus resulting in greater efficiency, and bringing the cell's output power closer to its theoretical maximum.

Comparison of energy conversion efficiencies

Energy conversion efficiency is measured by dividing the electrical power produced by the cell by the light power falling on the cell. Many factors influence the electrical power output, including spectral distribution, spatial distribution of power, temperature, and resistive load applied to the cell. IEC standard 61215 is used to compare the performance of cells and is designed around terrestrial, temperate conditions, using its standard temperature and conditions (STC): irradiance) of 1 kW/m^2, a spectral distribution close to solar radiation through AM (airmass) of 1.5 and a cell temperature 25 °C. The resistive load is varied until the peak or maximum power point (MPP) is achieved. The power at this point is recorded as Watt-peak (Wp). The same standard is used for measuring the power and efficiency of PV modules,

Air mass has an effect on power output. In space, where there is no atmosphere, the spectrum of the sun is relatively unfiltered. However, on earth, with air filtering the incoming light, the solar spectrum changes. To account for the spectral differences, a system was devised to calculate this filtering effect. Simply, the filtering effect ranges from Air Mass 0 (AM0) in space, to approximately Air Mass 1.5 on Earth. Multiplying the spectral differences by the quantum efficiency of the solar cell in question will yield the efficiency of the device. For example, a silicon solar cell in space might have an efficiency of 14% at AM0, but have an efficiency of 16% on earth at AM 1.5. Terrestrial efficiencies typically are greater than space efficiencies.



Solar cell efficiencies vary from 6% for amorphous silicon-based solar cells to 40.7% with multiple-junction research lab cells and 42.8% with multiple dies assembled into a hybrid package. Solar cell energy conversion efficiencies for commercially available *multicrystalline Si* solar cells are around 14-19%. The highest efficiency cells have not always been the most economical — for example a 30% efficient multijunction cell based on exotic materials such as gallium arsenide or indium selenide and produced in low volume might well cost one hundred times as much as an 8% efficient amorphous silicon cell in mass production, while only delivering about four times the electrical power.

However, there is a way to "boost" solar power. By increasing the light intensity, typically photogenerated carriers are increased, resulting in increased efficiency by up to 15%. These so-called "concentrator systems" have only begun to become cost-competitive as a result of the development of high efficiency GaAs cells. The increase in intensity is typically accomplished by using concentrating optics. A typical concentrator system may use a light intensity 6-400 times the sun, and increase the efficiency of a one sun GaAs cell from 31% at AM 1.5 to 35%.

A common method used to express economic costs of electricity-generating systems is to calculate a price per delivered kilowatt-hour (kWh). The solar cell efficiency in combination with the available irradiation has a major influence on the costs, but generally speaking the overall system efficiency is important. Using the commercially available solar cells (as of 2006) and system technology leads to system efficiencies between 5 and 19%. As of 2005, photovoltaic electricity generation costs ranged from ~0.60 US$/kWh (0.50 €/kWh) (central Europe) down to ~0.30 US$/kWh (0.25 €/kWh) in regions of high solar irradiation. This electricity is generally fed into the electrical grid on the customer's side of the meter. The cost can be compared to prevailing retail electric pricing (as of 2005), which varied from between 0.04 and 0.50 US$/kWh worldwide. (Note: in addition to solar irradiance profiles, these costs/kWh calculations will vary depending on assumptions for years of useful life of a system. Most c-Si panels are warranted for 25 years and should see 35+ years of useful life.)

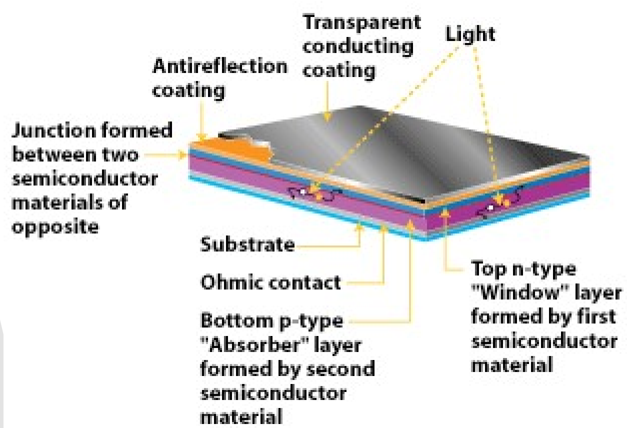
Solar cells and energy payback

The energy payback time, defined as the recovery time required for generating the energy spent for manufacturing a modern photovoltaic module is typically from 1 to 4 years depending on the module type and location. Generally, thin-film technologies - despite having comparatively low conversion efficiencies - achieve significantly shorter energy payback times than conventional systems (often < 1 year). With a typical lifetime of 20 to 30 years, this means that modern solar cells are net energy producers, i.e. they generate significantly more energy over their lifetime than the energy expended in producing them.

Crystalline silicon devices are approaching the theoretical limiting efficiency of 29% and achieve an energy payback period of 1–2 years.

Chapter 5

Thin Film Solar Cell



Cross-section of thin film polycrystalline solar cell

A **thin-film solar cell** (TFSC), also called a **thin-film photovoltaic cell** (TFPV), is a solar cell that is made by depositing one or more thin layers (thin film) of photovoltaic material on a substrate. The thickness range of such a layer is wide and varies from a few nanometers to tens of micrometers.

Many different photovoltaic materials are deposited with various deposition methods on a variety of substrates. Thin-film solar cells are usually categorized according to the photovoltaic material used:

- Amorphous silicon (a-Si) and other thin-film silicon (TF-Si)
- Cadmium Telluride (CdTe)
- Copper indium gallium selenide (CIS or CIGS)
- Dye-sensitized solar cell (DSC) and other organic solar cells

$$\begin{pmatrix} \mathrm{Cu} \\ \mathrm{Ag} \\ \mathrm{Au} \end{pmatrix} \begin{pmatrix} \mathrm{Al} \\ \mathrm{Ga} \\ \mathrm{In} \end{pmatrix} \begin{pmatrix} \mathrm{S} \\ \mathrm{Se} \\ \mathrm{Te} \end{pmatrix}_2$$

Possible combinations of Group-(I, III, VI) elements in the periodic table that yield a compound showing photovoltaic effect (*Cu, Ag, Au | Al, Ga, In | S, Se, Te*).

History

Initially appearing as small strips powering hand-held calculators, thin-film PV is now available in very large modules used in sophisticated building-integrated installations and vehicle charging systems. GBI Research projects thin film production to grow 24% from 2009 levels and to reach 22,214 MW in 2020. "Expectations are that in the long-term, thin-film solar PV technology would surpass dominating conventional solar PV technology, thus enabling the long sought-after grid parity objective."

Thin-film silicon

A silicon thin-film cell is a thin-film cell that uses amorphous (a-Si or a-Si:H), protocrystalline, nanocrystalline (nc-Si or nc-Si:H) or black silicon. Thin-film silicon is opposed to *wafer* (or *bulk*) silicon (monocrystalline or polycrystalline).

Design and fabrication

The silicon is mainly deposited by chemical vapor deposition, typically plasma-enhanced (PE-CVD), from silane gas and hydrogen gas. Other deposition techniques being investigated include sputtering and hot wire techniques.

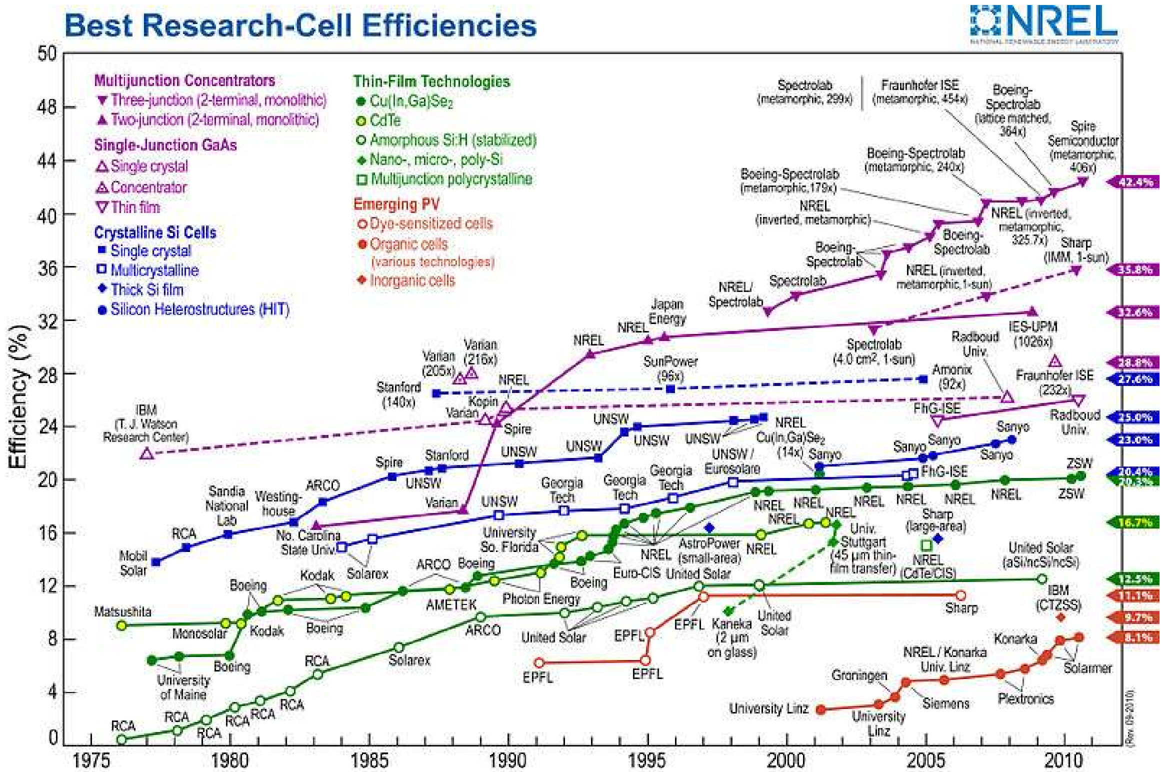
The silicon is deposited on glass, plastic or metal which has been coated with a layer of transparent conducting oxide (TCO).

A p-i-n structure is usually used, as opposed to an n-i-p structure. This is because the mobility of electrons in a-Si:H is roughly 1 or 2 orders of magnitude larger than that of holes, and thus the collection rate of electrons moving from the p- to n-type contact is better than holes moving from p- to n-type contact. Therefore, the p-type layer should be placed at the top where the light intensity is stronger, so that the majority of the charge carriers crossing the junction would be electrons.

Micromorphous silicon

Micromorphous silicon module technology combines two different types of silicon, amorphous and microcrystalline, in a top and a bottom photovoltaic cell. Use of protocrystalline silicon for the intrinsic layer has shown to optimize the open circuit voltage of an a-Si photovoltaic cell.

Efficiency



Solar Cell Efficiencies

These types of silicon present dangling and twisted bonds, which results in deep defects (energy levels in the bandgap) as well as deformation of the valence and conduction bands (band tails). The solar cells made from these materials tend to have lower energy conversion efficiency than bulk silicon (also called crystalline or wafer silicon), but are also less expensive to produce. The quantum efficiency of thin-film solar cells is also lower due to reduced number of collected charge carriers per incident photon.

Amorphous silicon has a higher bandgap (1.7 eV) than crystalline silicon (c-Si) (1.1 eV), which means it absorbs the visible part of the solar spectrum more strongly than the infrared portion of the spectrum. As nc-Si has about the same bandgap as c-Si, the nc-Si and a-Si can advantageously be combined in thin layers, creating a layered cell called a *tandem cell*. The top cell in a-Si absorbs the visible light and leaves the infrared part of the spectrum for the bottom cell in nc-Si.

Recently, solutions to overcome the limitations of thin-film silicon have been developed. Light trapping schemes where the incoming light is obliquely coupled into the silicon and the light traverses the film several times enhance the absorption of sunlight in the films. Thermal processing techniques enhance the crystallinity of the silicon and pacify electronic defects.

Building integrated photovoltaics

Thin film photovoltaic panels being installed onto a roof

Thin film solar panels are commercially available for installation onto the roofs of buildings, either applied onto the finished roof, or integrated into the roof covering. The advantage over tradition PV panels is that they are very low in weight, are not subject to wind lifting, and can be walked on (with care). The comparable disadvantages are increased cost and reduced efficiency.

A silicon thin film technology is being developed for building integrated photovoltaics (BIPV) in the form of semitransparent solar cells which can be applied as window glazing. These cells function as window tinting while generating electricity.

Organic solar cells

The Organic solar cell is another alternative to the more conventional materials used to make photovoltaics. Although a very novel technology it is promising since it offers a very low cost solution.

Efficiencies, volumes and prices

Since the invention of the first modern silicon solar cell in 1954, incremental improvements have resulted in modules capable of converting 12 to 18 percent of solar radiation into electricity. The performance and potential of thin-film materials are high, reaching cell efficiencies of 12%-20%; prototype module efficiencies of 7%-13%; and production modules in the range of 9%. Future module efficiencies are expected to climb close to the state-of-the-art of today's best cells, or to about 10-16%.

Annual manufacturing volume in the United States has grown from about 12 megawatts (MW) per year in 2003 to more than 20 MW/yr in 2004; 40-50 MW/yr production levels are expected in 2005 with continued rapid growth in the years after that.

Costs are expected to drop to below $100/m^2$ in volume production, and could reach even lower levels—well under $50/m^2$, the DOE/NREL goal for thin films—when fully optimized. At these levels, thin-film modules will cost less than fifty cents per watt to manufacture, opening new markets such as cost-effective distributed power and utility production to thin-film electricity generation.

As crystalline silicon price rose, the production cost of silicon-based solar cell module in 2008 was at some point 4-5 times higher than that of thin film modules. Thin-film producers still enjoy in 2009 price advantage as its production cost is 20% less than that of silicon modules.It is expected that the production cost of thin-film will continue dropping (40% less than silicon), as Chinese producers are now putting more resources into R&D and partnering with manufacturing equipment suppliers

Production, cost and market

In recent years, the manufacturers of thin-film solar modules are bringing costs down and gaining in competitive strength through advanced thin film technology. However, the traditional crystalline silicon technologies will not give up their market positions for a few years because they still hold considerable development potential in terms of the cost. Efficiency of thin film solar is considerably lower and thin film solar manufacturing equipment suppliers intend to score costs of below USD 1/W, and Anwell Technologies Limited claimed that they intend to bring it down further to USD 0.5/W. Those equipment suppliers have been doing R&D for micro-morphous silicon modules since 2008. This technology represents a development based on the thin-film panels made of ordinary amorphous silicon marketed at present that brings higher cell efficiency by depositing an additional absorber layer made of micro crystalline silicon on the amorphous layer. Some equipment suppliers even claim that there will be machinery in market to manufacture these new modules at $0.70. With such potential of further development of thin film solar technology, the European Photovoltaic Industry Association (EPIA) expects that manufacturing capacities for these technologies will double to over 4GW by 2010 representing a market share of around 20%.

Installations

First Solar, the CdTe thin-film manufacturer stated that "at the end of 2007, over 300 MW of First Solar PV modules had been installed worldwide." Below is a list of several recent installations:

- Since 16 October 2008, Germany's largest thin-film pitched roof system, constructed by Riedel Recycling, has been in operation and producing solar power in Moers near Duisburg. Over eleven thousand cadmium telluride modules, from First Solar, deliver a total of 837 kW.
- First Solar recently completed a 2.4 MW rooftop installation as part of Southern California Edison program to install 250 MW of rooftop solar panels throughout Southern California over by 2013.
- First Solar announced a 7.5 MW system to be installed in Blythe, CA, where the California Public Utilities Commission has accepted a 12 ¢/kWh power purchase agreement with First Solar (after the application of all incentives).
- Construction of a 10 MW plant in the Nevada desert began in July 2008. First Solar is partnering with Sempra Generation, which will own and operate the PV power-plant, being built next to their natural gas plant.
- Stadtwerke Trier (SWT) in Trier, Germany is expected to produce over 9 GWh annually
- A 40 MW system is being installed by Juwi in Waldpolenz Solar Park, Germany. At the time of its announcement, it was both the largest planned and lowest cost PV system in the world. The price of 3.25 euros translated then (when the euro was equal to US$1.3) to $4.2 per installed watt.
- 4.8KW of thin film flexible solar panels manufactured by Uni-Solar Ovonic installed on a South Beach hurricane-prone residence in 2008.

Denver-based Conergy Americas and officials at California's South San Joaquin Irrigation District (SSJID) have installed what is believed to be the world's first single-axis solar tracking system featuring thin-film photovoltaic cells.

Chapter 6

Copper Indium Gallium Selenide and Multijunction Photovoltaic Cell

Copper indium gallium selenide

Copper indium gallium (di)selenide (**CIGS**) (CAS NO. 12018-95-0) is a I-III-VI_2 compound semiconductor material composed of copper, indium, gallium, and selenium. The material is a solid solution of copper indium selenide (often abbreviated "CIS") and copper gallium selenide, with a chemical formula of $CuIn_xGa_{(1-x)}Se_2$, where the value of x can vary from 1 (pure copper indium selenide) to 0 (pure copper gallium selenide). It is a tetrahedrally bonded semiconductor, with the chalcopyrite crystal structure, and a bandgap varying continuously with *x* from about 1.0 eV (for copper indium selenide) to about 1.7 eV (for copper gallium selenide). It is used as light absorber material for thin-film solar cells.

CIGS photovoltaic cells

$$\begin{pmatrix}\mathrm{Cu}\\\mathrm{Ag}\\\mathrm{Au}\end{pmatrix}\begin{pmatrix}\mathrm{Al}\\\mathrm{Ga}\\\mathrm{In}\end{pmatrix}\begin{pmatrix}\mathrm{S}\\\mathrm{Se}\\\mathrm{Te}\end{pmatrix}_2$$

Possible combinations of (I, III, VI) elements in the periodic table that have photovoltaic effect

The materials based on $CuInSe_2$ that are of interest for photovoltaic applications include several elements from groups I, III and VI in the periodic table. These semiconductors are especially attractive for thin film solar cell application because of their high optical absorption coefficients and versatile optical and electrical characteristics which can in principle be manipulated and tuned for a specific need in a given device.

CIS is an abbreviation for general chalcopyrite films of copper indium selenide (**Cu****In****Se**$_2$), CIGS mentioned below is a variation of CIS. CIS films (no Ga) achieved greater than 14% efficiency. Manufacturing costs of CIS solar cells are high compared with amorphous silicon solar cells. Work continues on reducing cost. The first large-scale production of CIS modules was started in 2006 in Germany by Würth Solar.

When gallium is substituted for some of the indium in CIS, the material is referred to as CIGS, or copper indium/gallium diselenide, a solid mixture of the semiconductors $CuInSe_2$ and $CuGaSe_2$, often abbreviated by the chemical formula $CuIn_xGa_{(1-x)}Se_2$. Unlike the conventional silicon based solar cell, which can be modelled as a simple p-n junction, these cells are best described by a more complex heterojunction model. The best efficiency of a thin-film solar cell as of March 2008 was 19.9% with CIGS absorber layer. Higher efficiencies (around 30%) can be obtained by using optics to concentrate the incident light or by using multi-junction tandem solar cells.

The use of gallium increases the optical bandgap of the CIGS layer as compared to pure CIS, thus increasing the open-circuit voltage, but decreasing the short circuit current. In another point of view, gallium is added to replace indium due to gallium's relative availability to indium. Approximately 70% of indium currently produced is used by the flat-screen monitor industry. However, the atomic ratio for Ga in the >19% efficient CIGS solar cells is ~7%, which corresponds to a bandgap of ~1.15 eV. CIGS solar cells with higher Ga amounts have lower efficiency. For example, CGS solar cells (which have a bandgap of ~1.7 eV have a record efficiency of 9.5% for pure CGS and 10.2% for surface-modified CGS. Some investors in solar technology worry that production of CIGS cells will be limited by the availability of indium. Producing 2 GW of CIGS cells (roughly the amount of silicon cells produced in 2006) would use about 10% of the indium produced in 2004. For comparison, silicon solar cells used up 33% of the world's electronic grade silicon production in 2006.

Se allows for better uniformity across the layer and so the number of recombination sites in the film are reduced which benefits the quantum efficiency and thus the conversion efficiency.

Conversion efficiency

CIGS is mainly used in photovoltaic cells (CIGS cells), in the form of polycrystalline thin films. The best efficiency achieved as of December 2005 was 19.5%. A team at the National Renewable Energy Laboratory achieved 19.9% new world record efficiency by modifying the CIGS surface and making it look like CIS.

These efficiencies are different from module conversion efficiencies. Two of the leading manufacturers of CIGS thin-film PV have hit new record highs in module conversion efficiencies. The U.S. National Renewable Energy Laboratory has confirmed 13.8% efficiency of MiaSolé's large-area (meter-square) production panels, while Fraunhofer ISE said that Q-Cells' subsidiary Solibro has hit 13% total-area (and 14.2% aperture-area) efficiency with its newly rebranded Q.SMART production module.

Higher efficiencies (around 30%) can be obtained by using optics to concentrate the incident light. The use of gallium increases the optical band gap of the CIGS layer as compared to pure CIS, thus increasing the open-circuit voltage. In another point of view, gallium is added to replace as much indium as possible due to gallium's relative availability to indium.

Deposition

CIGS films can be manufactured by several different methods:

- The most common vacuum-based process co-evaporates or co-sputters copper, gallium, and indium, then anneals the resulting film with a selenide vapor to form the final CIGS structure. An alternative is to directly co-evaporate copper, gallium, indium and selenium onto a heated substrate.
- A non-vacuum-based alternative process deposits nanoparticles of the precursor materials on the substrate and then sinters them in situ. Electroplating is another low cost alternative to apply the CIGS layer.

With record CIGS efficiency at just below 20% for several years, new trend of CIGS research has shifted to investigation on lower-cost deposition methods that could be an alternative to expensive vacuum processes. Non-vacuum solution processes progressed quickly and efficiencies of 10%-15% have been achieved by many parties, such as ISET, Nanosolar and IBM.

CIGS and silicon

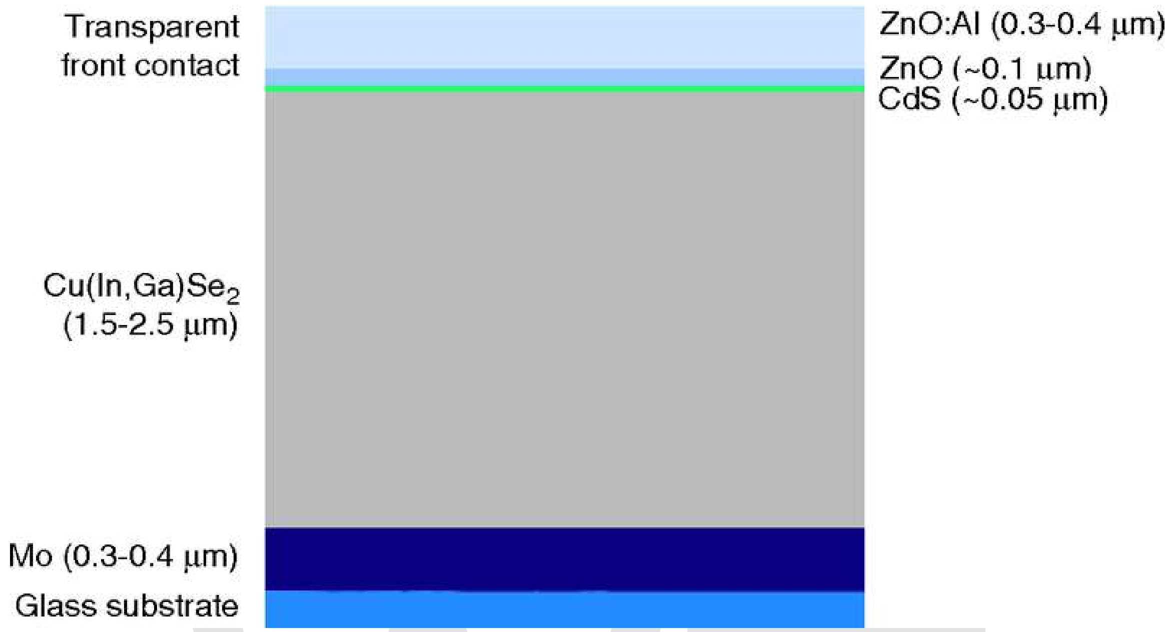
Unlike the silicon cells based on a homojunction, the structure of CIGS cells is a more complex heterojunction system. CIGS solar cells are not as efficient as crystalline silicon solar cells, for which the record efficiency lies at 24.7%, but they are expected to be substantially cheaper due to the much lower material cost and potentially lower fabrication cost. Being a direct bandgap material, CIGS has very strong light absorption and only 1-2 micrometers of CIGS is enough to absorb most of the sunlight. A much greater thickness of crystalline silicon is required for the same absorption.

The active layer (CIGS) can be deposited in a polycrystalline form directly onto molybdenum coated glass sheets or steel bands. This uses less energy than growing large crystals, which is a necessary step in the manufacture of crystalline silicon solar cells. Also unlike crystalline silicon, these substrates can be flexible.

CIGS and other thin films

CIGS belongs in the category of thin film solar cells (TFSC). The semiconductors used as absorber layer in thin-film photovoltaics exhibit direct bandgaps allowing the cells to be a few micrometers thin; hence, the term thin-film solar cells is used. Other materials in this group of TFSC include CdTe and amorphous Si. Their record efficiencies are slightly lower than that of CIGS for lab-scale top performance cells. The 19.9% efficiency is by far the highest compared with those achieved by other thin film technologies such as Cadmium Telluride (CdTe) or amorphous silicon (a-Si). As for CIS, and CGS solar cells, the world record total area efficiencies are 15.0% and 9.5% respectively. Another advantage of CIGS compared to CdTe is smaller amount of toxic material cadmium are present in CIGS cells.

Structure of a CIGS thin-film solar cell



Cross-section of an $Cu(In,Ga)Se_2$ solar cell

The basic structure of a $Cu(In,Ga)Se_2$ thin-film solar cell is depicted in the image to the right. The most common substrate is soda-lime glass of 1–3 mm thickness. This is coated on one side with molybdenum (Mo) that serves as metal back contact. The heterojunction is formed between the semiconductors CIGS and ZnO, buffered by a thin layer of CdS and a layer of intrinsic ZnO. The CIGS is doped p-type from intrinsic defects, while the ZnO is doped n-type to a much larger extent through the incorporation of aluminum (Al). This asymmetric doping causes the space-charge region to extend much further into the CIGS than into the ZnO. Matched to this are the layer thicknesses and the bandgaps of the materials: the wide CIGS layer serves as absorber with a bandgap between 1.02 eV ($CuInSe_2$) and 1.65 eV ($CuGaSe_2$). Absorption is minimized in the upper layers, called window, by the choice of larger bandgaps: $E_{g,ZnO}$=3.2 eV and $E_{g,CdS}$=2.4 eV. The doped ZnO also serves as front contact for current collection. Laboratory scale devices, typically 0.5 cm^2 large, are provided with a Ni/Al-grid deposited onto the front side to contact the ZnO.

For the production of modules, individual cells are divided and monolithically interconnected by a series of scribing steps between the layer depositions. Additionally, susceptibility to dampness makes module encapsulation a requisite for long lifetimes.

Multijunction photovoltaic cell

Multijunction photovoltaic cells are a sub-class of solar cell or photovoltaic cell developed for higher efficiency. These multijunction cells consist of multiple thin films produced using molecular beam epitaxy and / or metalorganic vapour phase epitaxy. Each type of semiconductor will have a characteristic band gap energy which, loosely speaking, causes it to absorb light most efficiently at a certain color, or more precisely, to absorb electromagnetic radiation over a portion of the spectrum. The semiconductors are carefully chosen to absorb nearly all of the solar spectrum, thus generating electricity from as much of the solar energy as possible.

In short, in the multijunction structure, several layers each capture part of the sunlight passing through the cell. These layers allow the cell to capture more of the solar spectrum and convert it into electricity.

History

Multijunction solar cells first were developed and deployed for satellite power applications where the high cost was offset by the weight savings offered by the higher efficiency.

Multijunction cells have recently seen application in terrestrial applications in concentrated photovoltaics. The combination of the higher efficiency and concentration has resulted in a price competitive with silicon flat panel arrays.

This technology is currently being utilized in the Mars rover missions.

Tandem solar cells based on monolithic, series connected, gallium indium phosphide (GaInP), gallium arsenide (GaAs), and germanium (Ge) pn junctions, are seeing demand rapidly rise. In the year 2006 – 2007, the cost of 4N gallium metal rose from about $350 per kg to $680 per kg. Additionally, germanium metal prices rose substantially to $1,000–$1,200 per kg in the same year. Those materials include gallium (4N, 6N and 7N Ga), arsenic (4N, 6N and 7N) and germanium, pyrolitic boron nitride (pBN) crucibles for growing crystals, and boron oxide, these products are critical to the entire substrate manufacturing industry.

Triple-junction GaAs solar cells were also being used as the power source of the Dutch four-time World Solar Challenge winners Nuna in 2005 and 2007.

Scientists at the Spire Semiconductor have set a world record in solar cell efficiency with a photovoltaic device that converts 42.3 percent of the light that hits it into electricity. This is the highest confirmed efficiency of any photovoltaic device to date. The metamorphic triple-junction solar cell was designed, fabricated and independently measured at NREL.

Theory of operation

In a single band gap solar cell, efficiency is limited due to the inability to efficiently convert the broad range of energy that photons possess in the solar spectrum. Photons below the band gap of the cell material are lost; they either pass through the cell or are converted to only heat within the material. Energy in the photons above the band gap energy is also lost, since only the energy necessary to generate the hole-electron pair is utilized, and the remaining energy is converted into heat.

By utilizing multiple junctions with several band gaps, different portions of the solar spectrum may be converted by each junction at a greater efficiency.

Device description

Multijunction photovoltaic cells use many layers of epitaxially deposited films. By using differing alloys of III-V Semiconductors, the band-gap of each layer may be tuned to absorb a specific band of the solar electromagnetic radiation. The ability to optimize the respective band gaps of the various junctions is hampered by the requirement that each layer must be lattice matched to all other layers.

Each layer is optically in series, with the highest band gap material at the top. The first junction receives all of the spectrum. Photons above the band gap of the first junction are absorbed in the first layer. Photons below the band gap of the first layer pass through to the lower layers to be absorbed there.

All currently commercialized cells utilize tandem electrical connection. This means that they are electrically connected in series and the composite cell has two terminals. A major constraint placed upon tandem cells is that because of the series connection, the current through each junction will be the same. If the maximum power point current of each junction is not the same, then efficiency suffers. Current match of each junction is a very important design consideration for multijunction cells.

Material classification

Multijunction cells may be categorized by the substrate used for cell manufacture. Cells on Gallium arsenide and Germanium have been commercialized. Research into Indium Phosphide based cells for lower band gaps is ongoing.

Gallium arsenide substrate

Twin junction cells with Indium gallium phosphide and Gallium arsenide can be made on Gallium arsenide wafers. Alloys of $In_{.5}Ga_{.5}P$ through $In_{.53}Ga_{.47}P$ may be used as the high band gap alloy. This alloy range provides for the ability to have band gaps in the range of 1.92eV to 1.87eV. The lower GaAs junction has a band gap of 1.42eV.

The considerable quantity of photons in the solar spectrum with energies below the band gap of GaAs results in a considerable limitation on the achievable efficiency of GaAs substrate cells.

In spacecraft applications, the cells have a poor current match due to a greater photon flux of photons above 1.87eV vs. those between 1.87eV and 1.42eV. This results in too little current in the GaAs junction, and hampers the overall efficiency since the InGaP junction operates below MPP current and the GaAs junction operates above MPP current. To improve current match, the InGaP layer is intentionally thinned to allow additional photons to penetrate to the lower GaAs layer.

In terrestrial concentrating applications, the scatter of blue light by the atmosphere reduces the photon flux above 1.87eV, better balancing the junction currents.

Germanium substrate

Triple junction cells consisting of Indium gallium phosphide, Gallium arsenide or Indium gallium arsenide and Germanium can be fabricated on germanium wafers. Early cells used straight gallium arsenide in the middle junction. Later cells have utilized $In_{0.015}Ga_{0.985}As$, due to the better lattice match to Ge, resulting in a lower defect density.

Due to the huge band gap difference between GaAs (1.42eV), and Ge (0.66eV), the current match is very poor, with the Ge junction operated significantly current limited.

Current efficiencies for InGaP/GaAs/Ge cells are in the mid 30% range.

Research into methods to produce band gaps in the range between the Ge and GaAs is ongoing. Lab cells using additional junctions between the GaAs and Ge junction have demonstrated efficiencies above 40%.

Indium phosphide substrate

Indium phosphide may be used as a substrate to fabricate cells with band gaps between 1.35eV and 0.74eV. Indium Phosphide has a band gap of 1.35eV. Indium gallium arsenide ($In_{0.53}Ga_{0.47}As$) is lattice matched to Indium Phosphide with a band gap of 0.74eV. A quaternary alloy of Indium gallium arsenide phosphide can be lattice matched for any band gap in between the two.

Indium phosphide-based cells are being researched as a possible companion to gallium arsenide cells. The two differing cells may be either optically connected in series (with the InP cell below the GaAs cell), or through the use of spectra splitting using a Dichroic filter.

Efficiency

Spire Semiconductor has developed a new multijunction concentrator solar cell with a sunlight-to-electricity conversion efficiency of 42.4 percent, a new world record in solar cell efficiency, costing as little as $3 per watt to install and producing electricity at a cost of 8 to 10 cents per kilowatt-hour. In the 1980s, multijunction solar cells achieved about 16 percent efficiency, and USDOE's National Renewable Energy Laboratory broke the 30 percent barrier in 1994.

Chapter 7

Dye-sensitized Solar Cell

A selection of dye-sensitized solar cells

A **dye-sensitized solar cell** (**DSSC**, **DSC** or **DYSC**) is a class of low-cost solar cell belonging to the group of thin film solar cells. It is based on a semiconductor formed between a photo-sensitized anode and an electrolyte; a *photoelectrochemical* system. This cell was invented by Michael Grätzel and Brian O'Regan at the École Polytechnique Fédérale de Lausanne in 1991 and are also known as **Grätzel cells**. Michael Grätzel won the 2010 Millennium Technology Prize for the invention of the Grätzel cell.

Because it is made of low-cost materials and does not require elaborate apparatus to manufacture, this cell is technically attractive. Likewise, manufacture can be significantly less expensive than older solid-state cell designs. It can also be engineered into flexible sheets and is mechanically robust, requiring no protection from minor events like hail or tree strikes. Although its conversion efficiency is less than the best thin-film cells, in theory its price/performance ratio (kWh/(m^2·annum·dollar)) should be high enough to allow them to compete with fossil fuel electrical generation by achieving grid parity. Commercial applications, which were held up due to chemical stability problems, are now forecast in the European Union Photovoltaic Roadmap to significantly contribute to renewable electricity generation by 2020.

Current technology: semiconductor solar cells

In a traditional solid-state semiconductor, a solar cell is made from two doped crystals, one doped with n-type impurities (n-type semiconductor), which has "extra free" electrons, and the other doped with p type impurities (p-type semiconductor), which is lacking free electrons. When placed in contact, some of the electrons in the n-type portion flow into the p-type to "fill in" the missing electrons, also known as electron holes. Eventually enough electrons will flow across the boundary to equalize the Fermi levels of the two materials. The result is a region at the interface, the p-n junction, where charge carriers are depleted and/or accumulated on each side of the interface. In silicon, this transfer of electrons produces a potential barrier of about 0.6 to 0.7 V.

When placed in the sun, photons of the sunlight can excite electrons on the n-type side of the semiconductor, a process known as photoexcitation. In silicon, sunlight can provide enough energy to push an electron out of the lower-energy valence band into the higher-energy conduction band. As the name implies, electrons in the conduction band are free to move about the silicon. When a load is placed across the cell as a whole, these electrons will flow out of the n-type side into the p-type side, lose energy while moving through the external circuit, and then back into the n-type material where they can once again re-combine with the valence-band hole they left behind. In this way, sunlight creates an electrical current.

In any semiconductor, the band gap means that only photons with that amount of energy, or more, will contribute to producing a current. In the case of silicon, the majority of visible light from red to violet has sufficient energy to make this happen. Unfortunately higher energy photons, those at the blue and violet end of the spectrum, have more than enough energy to cross the band gap; although some of this extra energy is transferred into the electrons, the majority of it is wasted as heat. Another issue is that in order to have a reasonable chance of capturing a photon, the n-type layer has to be fairly thick. This also increases the chance that a freshly ejected electron will meet up with a previously created hole in the material before reaching the p-n junction. These effects produce an upper limit on the efficiency of silicon solar cells, currently around 12 to 15% for common examples and up to 25% for the best laboratory modules.

By far the biggest problem with the conventional approach is cost; solar cells require a relatively thick layer of doped silicon in order to have reasonable photon capture rates, and silicon processing is expensive. There have been a number of different approaches to reduce this cost over the last decade, notably the thin-film approaches, but to date they have seen limited application due to a variety of practical problems. Another line of research has been to dramatically improve efficiency through the multi-junction approach, although these cells are very high cost and suitable only for large commercial deployments. In general terms the types of cells suitable for rooftop deployment have not changed significantly in efficiency, although costs have dropped somewhat due to increased supply.

Dye-sensitized solar cells

Grätzel's cell is composed of a porous layer of titanium dioxide nanoparticles, covered with a molecular dye that absorbs sunlight, like the chlorophyll in green leaves. The titanium dioxide is immersed under an electrolyte solution, above which is a platinum-based catalyst. As in a conventional alkaline battery, an anode (the titanium dioxide) and a cathode (the platinum) are placed on either side of a liquid conductor (the electrolyte).

Sunlight passes through the transparent electrode into the dye layer where it can excite electrons that then flow into the titanium dioxide. The electrons flow toward the transparent electrode where they are collected for powering a load. After flowing through the external circuit, they are re-introduced into the cell on a metal electrode on the back, flowing into the electrolyte. The electrolyte then transports the electrons back to the dye molecules.

Dye-sensitized solar cells separate the two functions provided by silicon in a traditional cell design. Normally the silicon acts as both the source of photoelectrons, as well as providing the electric field to separate the charges and create a current. In the dye-sensitized solar cell, the bulk of the semiconductor is used solely for charge transport, the photoelectrons are provided from a separate photosensitive dye. Charge separation occurs at the surfaces between the dye, semiconductor and electrolyte.

The dye molecules are quite small (nanometer sized), so in order to capture a reasonable amount of the incoming light the layer of dye molecules needs to be made fairly thick, much thicker than the molecules themselves. To address this problem, a nanomaterial is used as a scaffold to hold large numbers of the dye molecules in a 3-D matrix, increasing the number of molecules for any given surface area of cell. In existing designs, this scaffolding is provided by the semiconductor material, which serves double-duty.

Construction

In the case of the original Grätzel design, the cell has 3 primary parts. On top is a transparent anode made of fluoride-doped tin dioxide (SnO_2:F) deposited on the back of a (typically glass) plate. On the back of this conductive plate is a thin layer of titanium dioxide (TiO_2), which forms into a highly porous structure with an extremely high surface area. TiO_2 only absorbs a small fraction of the solar photons (those in the UV). The plate is then immersed in a mixture of a photosensitive ruthenium-polypyridine dye (also called molecular sensitizers) and a solvent. After soaking the film in the dye solution, a thin layer of the dye is left covalently bonded to the surface of the TiO_2.

A separate plate is then made with a thin layer of the iodide electrolyte spread over a conductive sheet, typically platinum metal. The two plates are then joined and sealed together to prevent the electrolyte from leaking. The construction is simple enough that there are hobby kits available to hand-construct them. Although they use a number of "advanced" materials, these are inexpensive compared to the silicon needed for normal cells because they require no expensive manufacturing steps. TiO_2, for instance, is already widely used as a paint base.

Operation

Sunlight enters the cell through the transparent SnO_2:F top contact, striking the dye on the surface of the TiO_2. Photons striking the dye with enough energy to be absorbed create an excited state of the dye, from which an electron can be "injected" directly into the conduction band of the TiO_2. From there it moves by diffusion (as a result of an electron concentration gradient) to the clear anode on top.

Meanwhile, the dye molecule has lost an electron and the molecule will decompose if another electron is not provided. The dye strips one from iodide in electrolyte below the TiO_2, oxidizing it into triiodide. This reaction occurs quite quickly compared to the time that it takes for the injected electron to recombine with the oxidized dye molecule, preventing this recombination reaction that would effectively short-circuit the solar cell.

The triiodide then recovers its missing electron by mechanically diffusing to the bottom of the cell, where the counter electrode re-introduces the electrons after flowing through the external circuit.

Efficiency

Several important measures are used to characterize solar cells. The most obvious is the total amount of electrical power produced for a given amount of solar power shining on the cell. Expressed as a percentage, this is known as the *solar conversion efficiency*. Electrical power is the product of current and voltage, so the maximum values for these measurements are important as well, J_{sc} and V_{oc} respectively. Finally, in order to understand the underlying physics, the "quantum efficiency" is used to compare the chance that one photon (of a particular energy) will create one electron.

In quantum efficiency terms, DSSCs are extremely efficient. Due to their "depth" in the nanostructure there is a very high chance that a photon will be absorbed, and the dyes are very effective at converting them to electrons. Most of the small losses that do exist in DSSC's are due to conduction losses in the TiO_2 and the clear electrode, or optical losses in the front electrode. The overall quantum efficiency for green light is about 90%, with the "lost" 10% being largely accounted for by the optical losses in top electrode. The quantum efficiency of traditional designs vary, depending on their thickness, but are about the same as the DSSC.

In theory, the maximum voltage generated by such a cell is simply the difference between the (*quasi*-)Fermi level of the TiO_2 and the redox potential of the electrolyte, about 0.7 V under solar illumination conditions (V_{oc}). That is, if an illuminated DSSC is connected to a voltmeter in an "open circuit", it would read about 0.7 V. In terms of voltage, DSSCs offer slightly higher V_{oc} than silicon, about 0.7 V compared to 0.6 V. This is a fairly small difference, so real-world differences are dominated by current production, J_{sc}.

Although the dye is highly efficient at converting absorbed photons into free electrons in the TiO_2, only photons absorbed by the dye ultimately produce current. The rate of photon absorption depends upon the absorption spectrum of the sensitized TiO_2 layer and upon the solar flux spectrum. The overlap between these two spectra determines the maximum possible photocurrent. Typically used dye molecules generally have poorer absorption in the red part of the spectrum compared to silicon, which means that fewer of the photons in sunlight are usable for current generation. These factors limit the current generated by a DSSC, for comparison, a traditional silicon-based solar cell offers about 35 mA/cm^2, whereas current DSSCs offer about 20 mA/cm^2.

Combined with a fill factor of about 45%, overall peak power production efficiency for current DSSCs is about 11%.

Degradation

DSSCs degrade when exposed to ultraviolet radiation. The barrier layer may include UV stabilizers and/or UV absorbing luminescent chromophores (which emit at longer wavelengths) and antioxidants to protect and improve the efficiency of the cell.

Advantages and drawbacks

DSSCs are currently the most efficient third-generation (2005 Basic Research Solar Energy Utilization 16) solar technology available. Other thin-film technologies are typically between 5% and 13%, and traditional low-cost commercial silicon panels operate between 12% and 15%. This makes DSSCs attractive as a replacement for existing technologies in "low density" applications like rooftop solar collectors, where the mechanical robustness and light weight of the glass-less collector is a major advantage. They may not be as attractive for large-scale deployments where higher-cost higher-efficiency cells are more viable, but even small increases in the DSSC conversion efficiency might make them suitable for some of these roles as well.

There is another area where DSSCs are particularly attractive. The process of injecting an electron directly into the TiO_2 is qualitatively different to that occurring in a traditional cell, where the electron is "promoted" within the original crystal. In theory, given low rates of production, the high-energy electron in the silicon could re-combine with its own hole, giving off a photon (or other form of energy) and resulting in no current being generated. Although this particular case may not be common, it is fairly easy for an electron generated in another molecule to hit a hole left behind in a previous photoexcitation.

In comparison, the injection process used in the DSSC does not introduce a hole in the TiO_2, only an extra electron. Although it is energetically possible for the electron to recombine back into the dye, the rate at which this occurs is quite slow compared to the rate that the dye regains an electron from the surrounding electrolyte. Recombination directly from the TiO_2 to species in the electrolyte is also possible although, again, for optimized devices this reaction is rather slow. On the contrary, electron transfer from the platinum coated electrode to species in the electrolyte is necessarily very fast.

As a result of these favorable "differential kinetics", DSSCs work even in low-light conditions. DSSCs are therefore able to work under cloudy skies and non-direct sunlight, whereas traditional designs would suffer a "cutout" at some lower limit of illumination, when charge carrier mobility is low and recombination becomes a major issue. The cutoff is so low they are even being proposed for indoor use, collecting energy for small devices from the lights in the house.

A practical advantage, one DSSCs share with most thin-film technologies, is that the cell's mechanical robustness indirectly leads to higher efficiencies in higher temperatures. In any semiconductor, increasing temperature will promote some electrons into the conduction band "mechanically". The fragility of traditional silicon cells requires them to be protected from the elements, typically by encasing them in a glass box similar to a greenhouse, with a metal backing for strength. Such systems suffer noticeable decreases in efficiency as the cells heat up internally. DSSCs are normally built with only a thin layer of conductive plastic on the front layer, allowing them to radiate away heat much easier, and therefore operate at lower internal temperatures.

The major disadvantage to the DSSC design is the use of the liquid electrolyte, which has temperature stability problems. At low temperatures the electrolyte can freeze, ending power production and potentially leading to physical damage. Higher temperatures cause the liquid to expand, making sealing the panels a serious problem. Another major drawback is the electrolyte solution, which contains volatile organic solvents and must be carefully sealed. This, along with the fact that the solvents permeate plastics, has precluded large-scale outdoor application and integration into flexible structure.

Replacing the liquid electrolyte with a solid has been a major ongoing field of research. Recent experiments using solidified melted salts have shown some promise, but currently suffer from higher degradation during continued operation, and are not flexible.

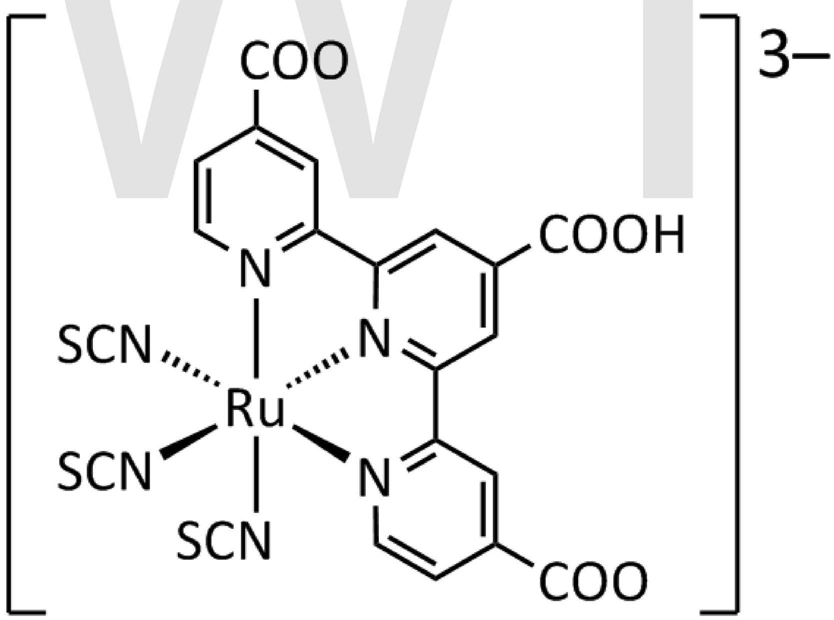
Photocathodes and tandem cells

Grätzel’s cell operates as a photoanode (n-DSC), where photocurrent result from electron injection by the sensitized dye. Photocathodes (p-DSCs)operate in an inverse mode compared to the conventional n-DSC, where dye-excitation is followed by rapid electron transfer from a p-type semiconductor to the dye (dye-sensitized hole injection, instead of electron injection). Such p-DSCs and n-DSCs can be combined to construct tandem solar cells (pn-DSCs) and the theoretical efficiency of tandem DSCs is well beyond that of single-junction DSCs.

A standard tandem cell consists of one n-DSC and one p-DSC in a simple sandwich configuration with an intermediate electrolyte layer. n-DSC and p-DSC are connected in series, which implies that the resulting photocurrent will be controlled by the weakest photoelectrode, whereas photovoltages are additive. Thus, Photocurrent matching is very important for the construction of highly efficient tandem pn-DSCs. However, unlike n-DSCs, fast charge recombination following dye-sensitized hole injection usually resulted in low photocurrents in p-DSC and thus hampered the efficiency of the overall device.

Researchers have found that using dyes comprising a perylenemonoimid (PMI) as the acceptor and an oligothiophene coupled to triphenylamine as the donor greatly improve the performance of p-DSC by reducing charge recombination rate following dye-sensitized hole injection. The researchers constructed a tandem DSC device with NiO on the p-DSC side and TiO_2 on the n-DSC side. Photocurrent matching was achieved through adjustment of NiO and TiO_2 film thicknesses to control the optical absorptions and therefore match the photocurrents of both electrodes. The energy conversion efficiency of the device is 1.91%, which exceeds the efficiency of its individual components, but is still much lower than that of high performance n-DSC devices (6%–11%). The results are still promising since the tandem DSC was in itself rudimentary. The dramatic improvement in performance in p-DSC can eventually lead to tandem devices with much greater efficiency than lone n-DSCs.

Development



"Black Dye", an anionic Ru-terpyridine complex

The dyes used in early experimental cells (circa 1995) were sensitive only in the high-frequency end of the solar spectrum, in the UV and blue. Newer versions were quickly introduced (circa 1999) that had much wider frequency response, notably "triscarboxy-ruthenium terpyridine" [Ru(4,4',4"-$(COOH)_3$-terpy)$(NCS)_3$], which is efficient right into the low-frequency range of red and IR light. The wide spectral response results in the dye having a deep brown-black color, and is referred to simply as "black dye". The dyes have an excellent chance of converting a photon into an electron, originally around 80% but improving to almost perfect conversion in more recent dyes, the overall efficiency is about 90%, with the "lost" 10% being largely accounted for by the optical losses in top electrode.

A solar cell must be capable of producing electricity for at least twenty years, without a significant decrease in efficiency (life span). The "black dye" system was subjected to 50 million cycles, the equivalent of ten years' exposure to the sun in Switzerland. No discernible performance decrease was observed. However the dye is subject to breakdown in high-light situations. Over the last decade an extensive research program has been carried out to address these concerns. The newer dyes included 1-ethyl-3 methylimidazolium tetrocyanoborate [EMIB(CN)$_4$] which is extremely light- and temperature-stable, copper-diselenium [Cu(In,GA)Se$_2$] which offers higher conversion efficiencies, and others with varying special-purpose properties.

DSSCs are still at the start of their development cycle. Efficiency gains are possible and have recently started more widespread study. These include the use of quantum dots for conversion of higher-energy (higher frequency) light into multiple electrons, using solid-state electrolytes for better temperature response, and changing the doping of the TiO_2 to better match it with the electrolyte being used.

New developments

2003

A group of researchers at the Swiss Federal Institute of Technology has reportedly increased the thermostability of DSC by using amphiphilic ruthenium sensitizer in conjunction with quasi-solid-state gel electrolyte. The stability of the device matches that of a conventional inorganic silicon based solar cells. The cell sustained heating for 1,000 h at 80 °C.

The group has previously prepared an ruthenium amphiphilic dye Z-907 (cis-Ru(H$_2$dcbpy)(dnbpy)(NCS)$_2$,where the ligand H$_2$dcbpy is 4,4′-dicarboxylic acid-2,2′-bipyridine and dnbpy is 4,4′-dinonyl-2,2′-bipyridine) to increase dye tolerance to water in the electrolytes. In addition, the group also prepared a quasi-solid-state gel electrolye with a 3-methoxypropionitrile (MPN)-based liquid electrolyte that was solidified by a photochemically stable fluorine polymer, poly(vinylidenefluoride-co-hexafluoropropylene (PVDF-HFP).

The use of the amphiphilic Z-907 dye in conjunction with the polymer gel electrolyte in DSC achieved an energy conversion efficiency of 6.1%. More importantly, the device was stable under thermal stress and soaking with light. The high conversion efficiency of the cell was sustained after heating for 1,000 h at 80 °C, maintaining 94% of its initial value. After accelerated testing in a solar simulator for 1,000 h of light-soaking at 55 °C

(100 mW cm^{-2}) the efficiency had decreased by less than 5% for cells covered with an ultraviolet absorbing polymer film. These results are well within the limit for that of traditional inorganic silicon solar cells.

The enhanced performance may arise from a decrease in solvent permeation across the sealant due to the application of the polymer gel electrolyte. The polymer gel electrolyte is quasi-solid at room temperature, and becomes a viscous liquid (viscosity: 4.34 mPa·s) at 80 °C compared with the traditional liquid electrolyte (viscosity: 0.91 mPa·s). The much improved stabilities of the device under both thermal stress and soaking with light has never before been seen in DSCs, and they match the durability criteria applied to solar cells for outdoor use, which makes these devices viable for practical application.

2006

The first successful solid-hybrid dye-sensitized solar cells were reported.

To improve electron transport in these solar cells, while maintaining the high surface area needed for dye adsorption, two researchers have designed alternate semiconductor morphologies, such as arrays of nanowires and a combination of nanowires and nanoparticles, to provide a direct path to the electrode via the semiconductor conduction band. Such structures may provide a means to improve the quantum efficiency of DSSCs in the red region of the spectrum, where their performance is currently limited.

On August 2006, to prove the chemical and thermal robustness of the 1-ethyl-3 methylimidazolium tetracyanoborate solar cell, the researchers subjected the devices to heating at 80 °C in the dark for 1000 hours, followed by light soaking at 60 °C for 1000 hours. After dark heating and light soaking, 90% of the initial photovoltaic efficiency was maintained – the first time such excellent thermal stability has been observed for a liquid electrolyte that exhibits such a high conversion efficiency. Contrary to silicon solar cells, whose performance declines with increasing temperature, the dye-sensitized solar-cell devices were only negligibly influenced when increasing the operating temperature from ambient to 60 °C.

April 2007

Wayne Campbell at Massey University, New Zealand, has experimented with a wide variety of organic dyes based on porphyrin. In nature, porphyrin is the basic building block of the hemoproteins, which include chlorophyll in plants and hemoglobin in animals. He reports efficiency on the order of 5.6% using these low-cost dyes.

June 2008

An article published in *Nature Materials* demonstrated cell efficiencies of 8.2% using a new solvent-free liquid redox electrolyte consisting of a melt of three salts, as an alternative to using organic solvents as an electrolyte solution. Although the efficiency with this electrolyte is less than the 11% being delivered using the existing iodine-based solutions, the team is confident the efficiency can be improved.

2009

A group of researchers at Georgia Tech made dye-sensitized solar cells with a higher effective surface area by wrapping the cells around a quartz optical fiber. The researchers removed the cladding from optical fibers, grew zinc oxide nanowires along the surface, treated them with dye molecules, surrounded the fibers by an electrolyte and a metal film that carries electrons off the fiber. The cells are six times more efficient than a zinc oxide cell with the same surface area. Photons bounce inside the fiber as they travel, so there are more chances to interact with the solar cell and produce more current. These devices only collect light at the tips, but future fiber cells could be made to absorb light along the entire length of the fiber, which would require a coating that is conductive as well as transparent. Max Shtein of the University of Michigan said a sun-tracking system would not be necessary for such cells, and would work on cloudy days when light is diffuse.

2010

Researchers at the École Polytechnique Fédérale de Lausanne and at the Université du Québec à Montréal claim to have overcome two of the DSC's major issues:

- "new molecules" have been created for the electrolyte, resulting in a liquid or gel that is transparent and non-corrosive, which can increase the photovoltage and improve the cell's output and stability.
- At the cathode, platinum was replaced by cobalt sulfide, which is far less expensive, more efficient, more stable and easier to produce in the laboratory.

Chapter 8

Solar Cell Research and Third Generation Photovoltaic Cell

Solar Cell Research

There are currently many **research groups active in the field of photovoltaics** in universities and research institutions around the world. This research can be divided into three areas: making current technology solar cells cheaper and/or more efficient to effectively compete with other energy sources; developing new technologies based on new solar cell architectural designs; and developing new materials to serve as light absorbers and charge carriers.

Silicon processing

One way of reducing the cost is to develop cheaper methods of obtaining silicon that is sufficiently pure. Silicon is a very common element, but is normally bound in silica, or silica sand. Processing silica (SiO_2) to produce silicon is a very high energy process - at current efficiencies, it takes one to two years for a conventional solar cell to generate as much energy as was used to make the silicon it contains. More energy efficient methods of synthesis are not only beneficial to the solar industry, but also to industries surrounding silicon technology as a whole.

The current industrial production of silicon is via the reaction between carbon (charcoal) and silica at a temperature around 1700 °C. In this process, known as carbothermic reduction, each tonne of silicon (metallurgical grade, about 98% pure) is produced with the emission of about 1.5 tonnes of carbon dioxide.

Solid silica can be directly converted (reduced) to pure silicon by electrolysis in a molten salt bath at a fairly mild temperature (800 to 900 °C).<reilif>Jin X, Gao P, Wang D, Hu X, Chen GZ (2004). "Electrochemical preparation of silicon and its alloys from solid oxides in molten calcium chloride". *Angew. Chem. Int. Ed. Engl.* **43** (6): 733–6. doi:10.1002/anie.200352786. PMID 14755706.</ref> While this new process is in principle the same as the FFC Cambridge Process which was first discovered in late 1996, the interesting laboratory finding is that such electrolytic silicon is in the form of porous silicon which turns readily into a fine powder, with a particle size of a few micrometres, and may therefore offer new opportunities for development of solar cell technologies.

Another approach is also to reduce the amount of silicon used and thus cost, is by micromachining wafers into very thin, virtually transparent layers that could be used as transparent architectural coverings. The technique involves taking a silicon wafer, typically 1 to 2 mm thick, and making a multitude of parallel, transverse slices across the wafer, creating a large number of slivers that have a thickness of 50 micrometres and a width equal to the thickness of the original wafer. These slices are rotated 90 degrees, so that the surfaces corresponding to the faces of the original wafer become the edges of the slivers. The result is to convert, for example, a 150 mm diameter, 2 mm-thick wafer having an exposed silicon surface area of about 175 cm^2 per side into about 1000 slivers having dimensions of 100 mm × 2 mm × 0.1 mm, yielding a total exposed silicon surface area of about 2000 cm^2 per side. As a result of this rotation, the electrical doping and contacts that were on the face of the wafer are located at the edges of the sliver, rather than at the front and rear as in the case of conventional wafer cells. This has the interesting effect of making the cell sensitive from both the front and rear of the cell (a property known as bifaciality). Using this technique, one silicon wafer is enough to build a 140 watt panel, compared to about 60 wafers needed for conventional modules of same power output.

Nanocrystalline solar cells

These structures make use of some of the same thin-film light absorbing materials but are overlain as an extremely thin absorber on a supporting matrix of conductive polymer or mesoporous metal oxide having a very high surface area to increase internal reflections (and hence increase the probability of light absorption). Using nanocrystals allows one to design architectures on the length scale of nanometers, the typical exciton diffusion length. In particular, single-nanocrystal ('channel') devices, an array of single p-n junctions between the electrodes and separated by a period of about a diffusion length, represent a new architecture for solar cells and potentially high efficiency.

Nanocrystal solar cells are solar cells based on a substrate with a coating of nanocrystals. The nanocrystals are typically based on silicon, CdTe or CIGS and the substrates are generally silicon or various organic conductors. Quantum dot solar cells are a variant of this approach, but take advantage of quantum mechanical effects to extract further performance. Dye-sensitized solar cells are another related approach, but in this case the nano-structuring is part of the substrate.

While previous methods of creation relied on expensive molecular beam epitaxy processes, fabrication using colloidal synthesis allows for a more cost-effective manufacture. A thin film of nanocrystals is obtained by a process known as “spin-coating”. This involves placing an amount of the quantum dot solution onto a flat substrate, which is then rotated very quickly. The solution spreads out uniformly, and the substrate is spun until the required thickness is achieved.

Quantum dot based photovoltaic cells based around dye-sensitized colloidal TiO_2 films were investigated in 1991 and were found to exhibit promising efficiency of converting incident light energy to electrical energy, and were found to be incredibly encouraging due to the low cost of materials in the search for more commercially viable/affordable renewable energy sources. A single-nanocrystal (channel) architecture in which an array of single particles between the electrodes, each separated by ~1 exciton diffusion length, was proposed to improve the device efficiency (figure below) and research on this type of solar cell is being conducted by groups at Stanford, Berkeley and the University of Tokyo.

Although research is still in its infancy and is ongoing, in the future nanocrystal photovoltaics may offer advantages such as mechanical flexibility (quantum dot-polymer composite photovoltaics) as well as low cost, clean power generation and an efficiency of 65%.

It is also argued that many measurements conducted for measuring the efficiency of the nanocrystal solar cell are incorrect. Also, the nanocrystal solar cells are not suitable for large scale manufacturing.

Recent research in experimenting with lead selenide (PbSe) semiconductor, as well as with cadmium telluride (CdTe), which has already been well established in the production of "classic" solar cells. Other materials are being researched as well.

Thin-film processing

Thin-film photovoltaic cells can use less than 1% of the expensive raw material (silicon or other light absorbers) compared to wafer-based solar cells, leading to a significant price drop per Watt peak capacity. There are many research groups around the world actively researching different thin-film approaches and/or materials.

One particularly promising technology is crystalline silicon thin films on glass substrates. This technology combines the advantages of crystalline silicon as a solar cell material (abundance, non-toxicity, high efficiency, long-term stability) with the cost savings of using a thin-film approach.

Another interesting aspect of thin-film solar cells is the possibility to deposit the cells on all kind of materials, including flexible substrates (PET for example), which opens a new dimension for new applications.

Metamorphic multijunction solar cell

The National Renewable Energy Laboratory won one of *R&D Magazine*'s R&D 100 Awards for its Metamorphic Multijunction Solar Cell, an ultra-light and flexible cell that converts solar energy with record efficiency.

The ultra-light, highly efficient solar cell was developed at NREL and is being commercialized by Emcore Corp. of Albuquerque, N.M., in partnership with the Air Force Research Laboratories Space Vehicles Directorate at Kirtland Air Force Base in Albuquerque.

It represents a new class of solar cells with clear advantages in performance, engineering design, operation and cost. For decades, conventional cells have featured wafers of semiconducting materials with similar crystalline structure. Their performance and cost effectiveness is constrained by growing the cells in an upright configuration. Meanwhile, the cells are rigid, heavy and thick with a bottom layer made of germanium.

In the new method, the cell is grown upside down. These layers use high-energy materials with extremely high quality crystals, especially in the upper layers of the cell where most of the power is produced. Not all of the layers follow the lattice pattern of even atomic spacing. Instead, the cell includes a full range of atomic spacing, which allows for greater absorption and use of sunlight. The thick, rigid germanium layer is removed, reducing the cell's cost and 94% of its weight. By turning the conventional approach to cells on its head, the result is an ultra-light and flexible cell that also converts solar energy with record efficiency (40.8% under 326 suns concentration).

Polymer processing

The invention of conductive polymers (for which Alan Heeger, Alan G. MacDiarmid and Hideki Shirakawa were awarded a Nobel prize) may lead to the development of much cheaper cells that are based on inexpensive plastics. However, organic solar cells generally suffer from degradation upon exposure to UV light, and hence have lifetimes which are far too short to be viable. The bonds in the polymers, are always susceptible to breaking up when radiated with shorter wavelengths. Additionally, the conjugated double bond systems in the polymers which carry the charge, react more readily with light and oxygen. So most conductive polymers, being highly unsaturated and reactive, are highly sensitive to atmospheric moisture and oxidation, making commercial applications difficult.

Nanoparticle processing

Experimental non-silicon solar panels can be made of quantum heterostructures, e.g. carbon nanotubes or quantum dots, embedded in conductive polymers or mesoporous metal oxides. In addition, thin films of many of these materials on conventional silicon solar cells can increase the optical coupling efficiency into the silicon cell, thus boosting the overall efficiency. By varying the size of the quantum dots, the cells can be tuned to absorb different wavelengths. Although the research is still in its infancy, quantum dot modified photovoltaics may be able to achieve up to 42% energy conversion efficiency due to multiple exciton generation (MEG).

Transparent conductors

Many new solar cells use transparent thin films that are also conductors of electrical charge. The dominant conductive thin films used in research now are transparent conductive oxides (abbreviated "TCO"), and include fluorine-doped tin oxide (SnO_2:F, or "FTO"), doped zinc oxide (e.g.: ZnO:Al), and indium tin oxide (abbreviated "ITO"). These conductive films are also used in the LCD industry for flat panel displays. The dual function of a TCO allows light to pass through a substrate window to the active light-absorbing material beneath, and also serves as an ohmic contact to transport photogenerated charge carriers away from that light-absorbing material. The present TCO materials are effective for research, but perhaps are not yet optimized for large-scale photovoltaic production. They require very special deposition conditions at high vacuum, they can sometimes suffer from poor mechanical strength, and most have poor transmittance in the infrared portion of the spectrum (e.g.: ITO thin films can also be used as infrared filters in airplane windows). These factors make large-scale manufacturing more costly.

A relatively new area has emerged using carbon nanotube networks as a transparent conductor for organic solar cells. Nanotube networks are flexible and can be deposited on surfaces a variety of ways. With some treatment, nanotube films can be highly transparent in the infrared, possibly enabling efficient low-bandgap solar cells. Nanotube networks are p-type conductors, whereas traditional transparent conductors are exclusively n-type. The availability of a p-type transparent conductor could lead to new cell designs that simplify manufacturing and improve efficiency.

Silicon wafer-based solar cells

Despite the numerous attempts at making better solar cells by using new and exotic materials, the reality is that the photovoltaics market is still dominated by silicon wafer-based solar cells (first-generation solar cells). This means that most solar cell manufacturers are currently equipped to produce this type of solar cells. Consequently, a large body of research is being done all over the world to manufacture silicon wafer-based solar cells at lower cost and to increase the conversion efficiencies without an exorbitant increase in production cost. The ultimate goal for both wafer-based and alternative photovoltaic concepts is to produce solar electricity at a cost comparable to currently market-dominant coal, natural gas, and nuclear power in order to make it the leading primary energy source. To achieve this it may be necessary to reduce the cost of installed solar systems from currently about US$ 1.80 (for bulk Si technologies) to about US$ 0.50 per Watt peak power. Since a major part of the final cost of a traditional bulk silicon module is related to the high cost of solar grade polysilicon feedstock (about US$ 0.4/Watt peak) there exists substantial drive to make Si solar cells thinner (material savings) or to make solar cells from cheaper upgraded metallurgical silicon (so called "dirty Si").

IBM has a semiconductor wafer reclamation process that uses a specialized pattern removal technique to repurpose scrap semiconductor wafers to a form used to manufacture silicon-based solar panels. The new process was recently awarded the “2007 Most Valuable Pollution Prevention Award” from The National Pollution Prevention Roundtable (NPPR).

Infrared solar cells

Researchers at Idaho National Laboratory, along with partners at Lightwave Power Inc. in Cambridge, MA and Patrick Pinhero of the University of Missouri, have devised an inexpensive way to produce plastic sheets containing billions of nanoantennas that collect heat energy generated by the sun and other sources, which garnered two 2007 Nano50 awards. The company ceased operations in 2010. While methods to convert the energy into usable electricity still need to be developed, the sheets could one day be manufactured as lightweight "skins" that power everything from hybrid cars to computers and iPods with higher efficiency than traditional solar cells. The nanoantennas target mid-infrared rays, which the Earth continuously radiates as heat after absorbing energy from the sun during the day; also double-sided nanoantenna sheets can harvest energy from different parts of the Sun's spectrum. In contrast, traditional solar cells can only use visible light, rendering them idle after dark.

UV solar cells

Japan's National Institute of Advanced Industrial Science and Technology (AIST) has succeeded in developing a transparent solar cell that uses ultraviolet (UV) light to generate electricity but allows visible light to pass through it. Most conventional solar cells use visible and infrared light to generate electricity. Used to replace conventional window glass, the installation surface area could be large, leading to potential uses that take advantage of the combined functions of power generation, lighting and temperature control. Also, easily fabricated PEDOT:PSS photovoltaic cells are ultraviolet light selective and sensitive.

3D solar cells

Three-dimensional solar cells that capture nearly all of the light that strikes them and could boost the efficiency of photovoltaic systems while reducing their size, weight and mechanical complexity. The new 3D solar cells, created at the Georgia Tech Research Institute, capture photons from sunlight using an array of miniature “tower” structures that resemble high-rise buildings in a city street grid.

Luminescent solar concentrator

Luminescent solar concentrators are plastics which concentrate sunlight into a small spot, where the concentrated solar energy can then be converted into electricity by a multi-junction PV solar cell. This not only increases efficiency, but also decreases cost, as luminescent solar concentrator panels can be made cheaply from plastics, while PV-cells need to be constructed from expensive materials such as silicon.

Research is being conducted at universities such as RU Nijmegen and TU Delft, as well as others. Massachusetts Institute of Technology researchers have found a way to convert windows into devices that concentrate sunlight for conversion into electricity. They have developed a mixture of dyes that can be painted onto a pane of glass or plastic. The dyes absorb sunlight and then re-emit it within the glass at a different wavelength, which then reflects off the interior surfaces of the glass. As the light reflects within the glass pane, it is channeled along the length of the glass to its edges, where it is emitted. The sunlight is concentrated by a factor of about 40, allowing solar cells that are optimized for such concentrated sunlight to be mounted along the edges of the window. The unique optics of the approach yield a cheap solar concentrator that does not need to be pointed toward the sun, as is needed for lens-based concentrators. Covalent Solar is attempting to commercialize the process within the next 3 years.

Metamaterials

Metamaterials are heterogeneous materials employing the juxtaposition of many microscopic elements, giving rise to properties not seen in ordinary solids. Using these, it *may* become possible to fashion solar cells that are excellent absorbers over a narrow range of wavelengths. High absorption in the microwave regime has been demonstrated, but not yet in the 300-1100-nm wavelength regime.

Photovoltaic thermal hybrid

Some systems combine photovoltaic with thermal solar, with the advantage that the thermal solar part carries heat away and cools the photovoltaic cells. Keeping temperature down lowers the resistance and improves the cell efficiency.

Third generation photovoltaic cell

Third generation solar cells are solar cells that are potentially able to overcome the Shockley–Queisser limit of 31-41% power efficiency for single bandgap solar cells. This includes a range of alternatives to the so-called "first generation solar cells" (which are solar cells made of semiconducting p-n junctions) and "second generation solar cells" (based on reducing the cost of first generation cells by employing thin film technologies). Common third-generation systems include multi-layer ("tandem") cells made of amorphous silicon or gallium arsenide, while more theoretical developments include frequency conversion, hot-carrier effects and other multiple-carrier ejection.

Background

Solar cells can be thought of as visible light counterparts to radio receivers. A receiver consists of three basic parts; an antenna that converts the radio waves (light) into wave-like motions of electrons in the antenna material, an electronic valve that traps the electrons as they pop off the end of the antenna, and a tuner that amplifies electrons of a selected frequency. It is possible to build a solar cell identical to a radio, a system known as an optical rectenna, but to date these have not been practical.

Instead, the vast majority of the solar electric market is made up of silicon-based devices. In silicon cells, the silicon acts as both the antenna (or electron donor, technically) as well as the electronic valve. Silicon is almost ideal as a solar cell material; is it widely available, relatively inexpensive, and has a bandgap that is ideal for solar collection. On the downside it is energetically expensive to produce silicon in bulk, and great efforts have been made to reduce or eliminate the silicon in a cell. Moreover it is mechanically fragile, which typically requires a sheet of strong glass to be used as mechanical support and protection from the elements. The glass alone is a significant portion of the cost of a typical solar module.

According to the Shockley–Queisser limit, the majority of a cell's theoretical efficiency is due to the difference in energy between the bandgap and solar photon. Any photon with more energy than the bandgap can cause photoexcitation, but in this case any energy above and beyond the bandgap energy is lost. Consider the solar spectrum; only a small portion of the light reaching the ground is blue, but those photons have three times the energy of red light. Silicon's bandgap is 1.1 eV, about that of red light, so in this case the extra energy contained in blue light is lost in a silicon cell. If the bandgap is tuned higher, say to blue, that energy is now captured, but only at the cost of rejecting all the lower energy photons.

It is possible to greatly improve on a single-junction cell by stacking extremely thin cells with different bandgaps on top of each other - the "tandem cell" or "multi-junction" approach. Traditional silicon preparation methods do not lend themselves to this approach. There has been some progress using thin-films of amorphous silicon, notably Uni-Solar's products, but other issues have prevented these from matching the performance of traditional cells. Most tandem-cell structures are based on higher performance semiconductors, notably gallium arsenide (GaAs). Three-layer GaAs cells hold the production record of 41.6% for experimental examples.

Numerical analysis shows that the "perfect" single-layer solar cell should have a bandgap of 1.13 eV, almost exactly that of silicon. Such a cell can have a maximum theoretical power conversion efficiency of 33.7% - the solar power below red (in the infrared) is lost, and the extra energy of the higher colors is also lost. For a two layer cell, one layer should be tuned to 1.64 eV and the other at 0.94 eV, with a theoretical performance of 44%. A three-layer cell should be tuned to 1.83, 1.16 and 0.71 eV, with an efficiency of 48%. A theoretical "infinity-layer" cell would have a theoretical efficiency of 64%.

Technologies

The third generation is somewhat ambiguous in the technologies that it encompasses, though generally it tends to include, among others, non-semiconductor technologies (including polymer cells and biomimetics), quantum dot, tandem/multi-junction cells, intermediate band solar cell, hot-carrier cells, upconversion and downconversion technologies, and solar thermal technologies, such as thermophotonics, which is one technology identified by Green as being third generation.

It also includes:

- Silicon nanostructures
- Modifying incident spectrum (concentration), to reach 300-500 suns and efficiencies of 32% (already attained in Sol3g cells) to +50%.
- Use of excess thermal generation (caused by UV light) to enhance voltages or carrier collection.
- Use of infrared spectrum to produce electricity at night.

Expected market shift

There has been a lot of hype circling around the possibilities of advanced solar technology in recent years. Major companies and investors such as Google, have invested hundreds of millions of dollars towards this new generation of solar power. They are counting on the likely possibility that the new technologies could compete with not only traditional solar cells, but more importantly with fossil fuels and nuclear energy (to reach and surpass grid parity). This would revolutionize our energy market; as said, in order for this to happen, third generation solar cells will need to be more efficient and cheaper.

Future possibilities

The new materials that solar energy can be harnessed with is one of the most exciting elements of the new technology. The flexible and lightweight physical characteristics of the different types of third generation solar cells makes many new applications possible.

There is the possibility that solar cells could be integrated into clothing which would allow us to have personal wireless power without batteries.

Another plausible application could be a type of automobile paint that is blended with polymer solar cells. This could help maintain the lightweight form of a solar car while still providing ample energy to power it.

One application of third generation solar cells that has the possibility of becoming commercially viable relatively soon is solar paint. Tata Steel is working with researchers at Swansea University to produce sheet steel treated with a sensitive coating of solar cells. According to Dr. Worsley, the project leader for the Swansea Solar Paint Project, if all the steel cladding produced by one manufacturer was energy generating, it would be the equivalent of 50 wind farms (or 4500 gigawatts/year) at an efficiency rate of 5%.

Types of third generation solar cells

While the new solar technologies that have been discovered center around nanotechnology, there are several different material methods currently used.

A-Si

- Anwell Technologies Limited
- Uni-Solar

CdTe (second generation)

- First Solar

CIGS (copper indium gallium selenide) (second generation)

- Honda Solar
- Nanosolar
- Solarion
- Solyndra

Chapter 9

Photovoltaics

Nellis Solar Power Plant at Nellis Air Force Base in the USA. These panels track the sun in one axis.

Photovoltaic system 'tree' in Styria, Austria

Photovoltaics (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels composed of a number of cells containing a photovoltaic material. Materials presently used for photovoltaics include monocrystalline silicon, polycrystalline silicon, amorphous silicon, cadmium telluride, and copper indium selenide/sulfide. Due to the growing demand for renewable energy sources, the manufacturing of solar cells and photovoltaic arrays has advanced considerably in recent years.

As of 2010, solar photovoltaics generates electricity in more than 100 countries and, while yet comprising a tiny fraction of the 4.8 TW total global power-generating capacity from all sources, is the fastest growing power-generation technology in the world. Between 2004 and 2009, grid-connected PV capacity increased at an annual average rate of 60 percent, to some 21 GW. Such installations may be ground-mounted (and sometimes integrated with farming and grazing) or built into the roof or walls of a building, known as Building Integrated Photovoltaics or BIPV for short. Off-grid PV accounts for an additional 3–4 GW.

Driven by advances in technology and increases in manufacturing scale and sophistication, the cost of photovoltaics has declined steadily since the first solar cells were manufactured. Net metering and financial incentives, such as preferential feed-in tariffs for solar-generated electricity, have supported solar PV installations in many countries.

Photovoltaic effect

The photovoltaic effect is the creation of a voltage (or a corresponding electric current) in a material upon exposure to light. Though the photovoltaic effect is directly related to the photoelectric effect, the two processes are different and should be distinguished. In the photoelectric effect, electrons are ejected from a material's surface upon exposure to radiation of sufficient energy. The photovoltaic effect is different in that the generated electrons are transferred between different bands (i.e., from the valence to conduction bands) within the material, resulting in the buildup of a voltage between two electrodes.

In most photovoltaic applications the radiation is sunlight and for this reason the devices are known as solar cells. In the case of a p-n junction solar cell, illumination of the material results in the creation of an electric current as excited electrons and the remaining holes are swept in different directions by the built-in electric field of the depletion region.

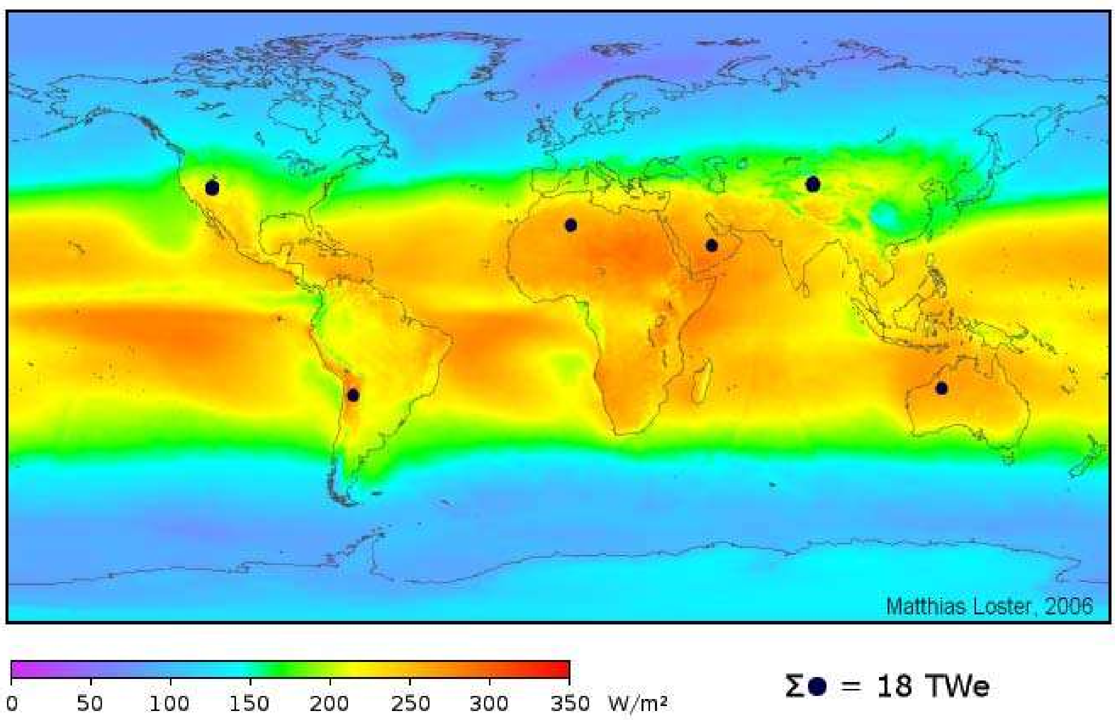
The photovoltaic effect was first observed by Alexandre-Edmond Becquerel in 1839.

Solar cells

Solar cells produce electricity directly from sunlight

Photovoltaics are best known as a method for generating electric power by using solar cells to convert energy from the sun into electricity. The photovoltaic effect refers to photons of light knocking electrons into a higher state of energy to create electricity. The term photovoltaic denotes the unbiased operating mode of a photodiode in which current through the device is entirely due to the transduced light energy. Virtually all photovoltaic devices are some type of photodiode.

Solar cells produce direct current electricity from sun light, which can be used to power equipment or to recharge a battery. The first practical application of photovoltaics was to power orbiting satellites and other spacecraft, but today the majority of photovoltaic modules are used for grid connected power generation. In this case an inverter is required to convert the DC to AC. There is a smaller market for off-grid power for remote dwellings, boats, recreational vehicles, electric cars, roadside emergency telephones, remote sensing, and cathodic protection of pipelines.



Average solar irradiance, watts per square metre. Note that this is for a horizontal surface, whereas solar panels are normally mounted at an angle and receive more energy per unit area. The small black dots show the area of solar panels needed to generate all of the world's energy using 8% efficient photovoltaics.

Cells require protection from the environment and are usually packaged tightly behind a glass sheet. When more power is required than a single cell can deliver, cells are electrically connected together to form photovoltaic modules, or solar panels. A single module is enough to power an emergency telephone, but for a house or a power plant the modules must be arranged in multiples as arrays. Although the selling price of modules is still too high to compete with grid electricity in most places, significant financial incentives in Japan and then Germany, Italy, Greece and France triggered a huge growth in demand, followed quickly by production. In 2008, Spain installed 45% of all photovoltaics, but a change in law limiting the feed-in tariff is expected to cause a precipitous drop in the rate of new installations there, from an extra 2.5 GW in 2008, to an expected additional 375 MW in 2009.

A significant market has emerged in off-grid locations for solar-power-charged storage-battery based solutions. These often provide the only electricity available. The first commercial installation of this kind was in 1966 on Ogami Island in Japan to transition Ogami Lighthouse from gas torch to fully self-sufficient electrical power.

Due to the growing demand for renewable energy sources, the manufacture of solar cells and photovoltaic arrays has advanced dramatically in recent years.

Photovoltaic production has been increasing by an average of more than 20 percent each year since 2002, making it the world's fastest-growing energy technology. At the end of 2009, the cumulative global PV installations surpassed 21 GW. Roughly 90% of this generating capacity consists of grid-tied electrical systems. Such installations may be ground-mounted (and sometimes integrated with farming and grazing) or built into the roof or walls of a building, known as Building Integrated Photovoltaics or BIPV for short. Solar PV power stations today have capacities ranging from 10–60 MW although proposed solar PV power stations will have a capacity of 150 MW or more.

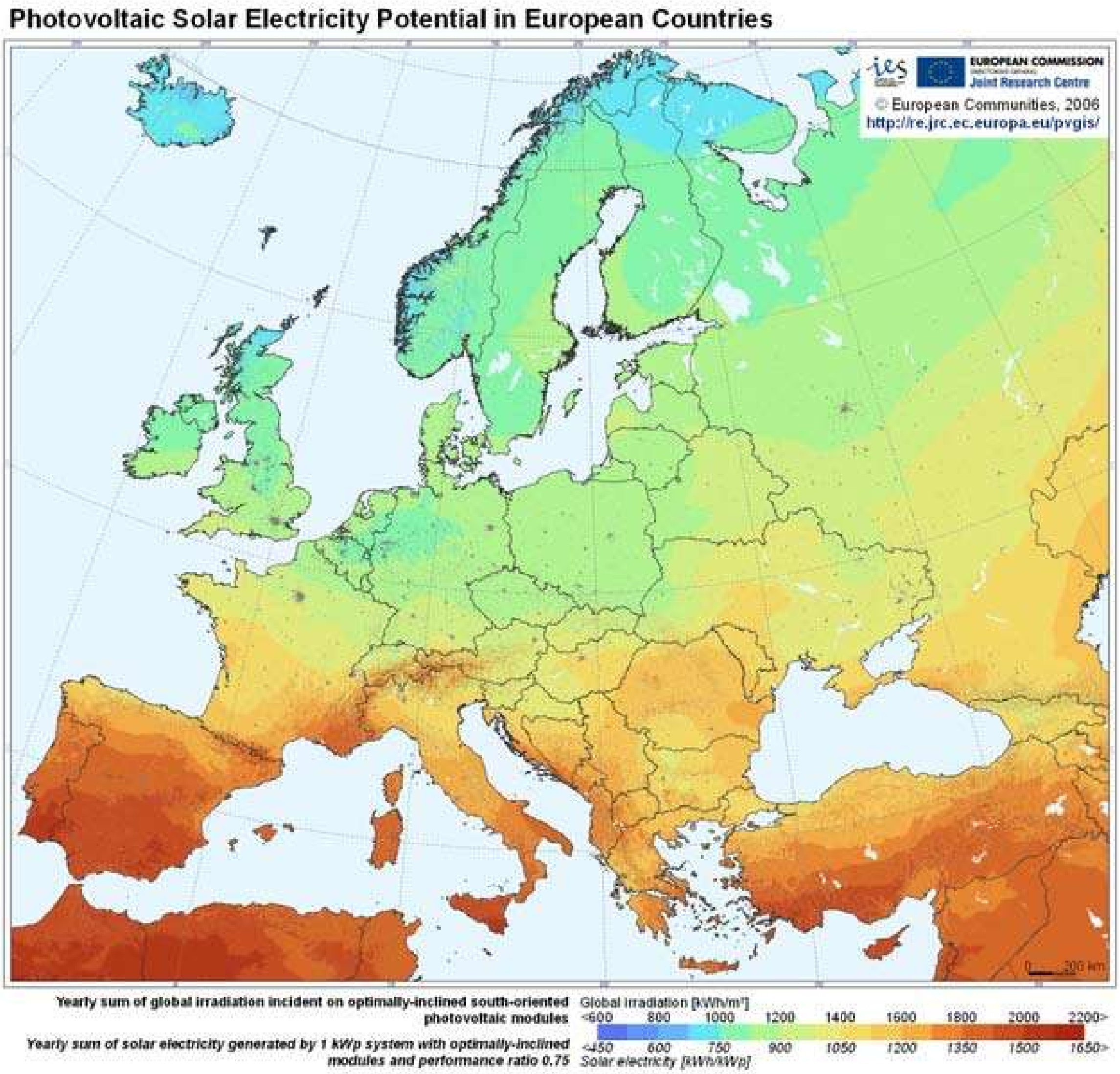
World solar photovoltaic (PV) installations were 2.826 GW peak (GWp) in 2007, and 5.95 GW in 2008, and 7.5 GW in 2009. The three leading countries (Germany, Japan and the US) represent nearly 89% of the total worldwide PV installed capacity. According to Navigant Consulting and Electronic Trend Publications, the estimated PV worldwide installations outlooks of 2012 are 18.8 GW and 12.3 GW respectively. Notably, the manufacture of solar cells and modules had expanded in recent years.

Germany installed a record 3.8 GW of solar PV in 2009; in contrast, the US installed about 500 MW in 2009. The previous record, 2.6 GW, was set by Spain in 2008. Germany was also the fastest growing major PV market in the world from 2006 to 2007 industry observers speculate that Germany could install more than 4.5 GW in 2010. The German PV industry generates over 10,000 jobs in production, distribution and installation. By the end of 2006, nearly 88% of all solar PV installations in the EU were in grid-tied applications in Germany.

Photovoltaic power capacity is measured as maximum power output under standardized test conditions (STC) in "Wp" (Watts peak). The actual power output at a particular point in time may be less than or greater than this standardized, or "rated," value, depending on geographical location, time of day, weather conditions, and other factors. Solar photovoltaic array capacity factors are typically under 25%, which is lower than many other industrial sources of electricity. Therefore the 2008 installed base peak output would have provided an average output of 3.04 GW (assuming 20% × 15.2 GWp). This represented 0.15 percent of global demand at the time.

The EPIA/Greenpeace Advanced Scenario shows that by the year 2030, PV systems could be generating approximately 1.8 TW of electricity around the world. This means that, assuming a serious commitment is made to energy efficiency, enough solar power would be produced globally in twenty-five years' time to satisfy the electricity needs of almost 14% of the world's population.

Current developments



Map of solar electricity potential in Europe. Germany is the current leader in solar production.

Photovoltaic panels based on crystalline silicon modules are being partially replaced in the market by panels that employ thin-film solar cells (CdTe CIGS, amorphous Si, microcrystalline Si), which are rapidly growing and are expected to account for 31 percent of the global installed power by 2013. Other developments include casting wafers instead of sawing, concentrator modules, 'Sliver' cells, and continuous printing processes. Due to economies of scale solar panels get less costly as people use and buy more — as manufacturers increase production to meet demand, the cost and price is expected to drop in the years to come. By early 2006, the average cost per installed watt for a residential sized system was about USD 7.50 to USD 9.50, including panels, inverters, mounts, and electrical items.

In 2006 investors began offering free solar panel installation in return for a 25 year contract, or Power Purchase Agreement, to purchase electricity at a fixed price, normally set at or below current electric rates. It is expected that by 2009 over 90% of commercial photovoltaics installed in the United States will be installed using a power purchase agreement. An innovative financing arrangement in Berkeley, California, funded by grants from the United States Environmental Protection Agency and the Bay Area Air Quality Management District, lends money to a homeowner for solar system, to be repaid via an additional tax assessment on the property which remains in place for 20 years. This allows installation of the solar system at "relatively little up-front cost to the property owner."

The current market leader in solar panel efficiency (measured by energy conversion ratio) is SunPower, a San Jose based company. Sunpower's cells have a conversion ratio of 24.2%, well above the market average of 12–18%. However, advances past this efficiency mark are being pursued in academia and research and development labs with efficiencies of 42% achieved at the University of Delaware in conjunction with DuPont by means of concentration of light The highest efficiencies achieved without concentration include Sharp Corporation at 35.8% using a proprietary triple-junction manufacturing technology in 2009, and Boeing Spectrolab (40.7% also using a triple layer design). A March 2010 experimental demonstration of a design by a Caltech group which has an absorption efficiency of 85% in sunlight and 95% at certain wavelengths (it is claimed to have near perfect quantum efficiency). However, absorption efficiency should not be confused with the sunlight-to-electricity conversion efficiency.

Applications

Power stations

President Barack Obama speaks at the DeSoto Next Generation Solar Energy Center

As of December 2010, the largest photovoltaic (PV) power plants in the world are the Sarnia Photovoltaic Power Plant (Canada, 97 MW), Montalto di Castro Photovoltaic Power Station (Italy, 84.2 MW), Finsterwalde Solar Park (Germany, 80.7 MW), Rovigo Photovoltaic Power Plant (Italy, 70 MW), Olmedilla Photovoltaic Park (Spain, 60 MW), the Strasskirchen Solar Park (Germany, 54 MW), and the Lieberose Photovoltaic Park (Germany, 53 MW). Larger power stations are under construction, some proposed will have a capacity of 150 MW or more.

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

PV power station	Country	DC peak power (MW_p)	Notes
Sarnia Photovoltaic Power Plant	Canada	97	Constructed 2009-2010
Montalto di Castro Photovoltaic Power Station	Italy	84.2	Constructed 2009-2010
Finsterwalde Solar Park	Germany	80.7	Phase I completed 2009, phase II and III 2010
Rovigo Photovoltaic Power Plant	Italy	70	Completed November 2010
Olmedilla Photovoltaic Park	Spain	60	Completed September 2008

Strasskirchen Solar Park	Germany	54	
Lieberose Photovoltaic Park	Germany	53	Completed in 2009
Puertollano Photovoltaic Park	Spain	50	231,653 crystalline silicon modules, Suntech and Solaria, opened 2008

Topaz Solar Farm is a proposed 550 MW solar photovoltaic power plant which is to be built northwest of California Valley in the US at a cost of over $1 billion. Built on 9.5 square miles (25 km^2) of ranchland, the project would utilize thin-film PV panels designed and manufactured by OptiSolar in Hayward and Sacramento. The project would deliver approximately 1,100 GW-hours (GWh) annually of renewable energy. The project is expected to begin construction in 2010, begin power delivery in 2011, and be fully operational by 2013.

High Plains Ranch is a proposed 250 MW solar photovoltaic power plant which is to be built by SunPower in the Carrizo Plain, northwest of California Valley.

In buildings

Photovoltaic arrays are often associated with buildings: either integrated into them, mounted on them or mounted nearby on the ground.

Arrays are most often retrofitted into existing buildings, usually mounted on top of the existing roof structure or on the existing walls. Alternatively, an array can be located separately from the building but connected by cable to supply power for the building. In 2010, more than four-fifths of the 9,000 MW of solar PV operating in Germany was installed on rooftops.

Photovoltaic solar panels on a house roof

Building-integrated photovoltaics (BIPV) are increasingly incorporated into new domestic and industrial buildings as a principal or ancillary source of electrical power. Typically, an array is incorporated into the roof or walls of a building. Roof tiles with integrated PV cells are also common.

The power output of photovoltaic systems for installation in buildings is usually described in kilowatt-peak units (kWp).

In transport

PV has traditionally been used for electric power in space. PV is rarely used to provide motive power in transport applications, but is being used increasingly to provide auxiliary power in boats and cars. A self-contained solar vehicle would have limited power and low utility, but a solar-charged vehicle would allow use of solar power for transportation. Solar-powered cars have been demonstrated.

Standalone devices

Solar parking meter

Until a decade or so ago, PV was used frequently to power calculators and novelty devices. Improvements in integrated circuits and low power LCD displays make it possible to power such devices for several years between battery changes, making PV use less common. In contrast, solar powered remote fixed devices have seen increasing use recently in locations where significant connection cost makes grid power prohibitively expensive. Such applications include water pumps, parking meters, emergency telephones, trash compactors, temporary traffic signs, and remote guard posts & signals.

Rural electrification

Developing countries where many villages are often more than five kilometers away from grid power have begun using photovoltaics. In remote locations in India a rural lighting program has been providing solar powered LED lighting to replace kerosene lamps. The solar powered lamps were sold at about the cost of a few month's supply of kerosene. Cuba is working to provide solar power for areas that are off grid. These are areas where the social costs and benefits offer an excellent case for going solar though the lack of profitability could relegate such endeavors to humanitarian goals.

Solar roadways

A 45 mi (72 km) section of roadway in Idaho is being used to test the possibility of installing solar panels into the road surface, as roads are generally unobstructed to the sun and represent about the percentage of land area needed to replace other energy sources with solar power.

Solar Power satellites

Design studies of large solar power collection satellites have been conducted for decades. The idea was first proposed by Peter Glaser, then of Arthur D. Little Inc; NASA conducted a long series of engineering and economic feasibility studies in the 1970s, and interest has revived in first years of the 21st century.

From a practical economic viewpoint, the key issue for such satellites appears to be the launch cost. Additional considerations will include developing space based assembly techniques, but they seem to be less a hurdle than the capital cost. These will be reduced as photovoltaic cell costs are reduced or alternatively efficiency increased.

Performance

Temperature

Generally, temperatures above room temperature reduce the performance of photovoltaics.

Optimum Orientation of Solar Panels

For best performance, terrestrial PV systems aim to maximize the time they face the sun. Solar trackers aim to achieve this by moving PV panels to follow the sun. The increase can be by as much as 20% in winter and by as much as 50% in summer. Static mounted systems can be optimized by analysis of the Sun path. Panels are often set to latitude tilt, an angle equal to the latitude, but performance can be improved by adjusting the angle for summer or winter.

Advantages

The 89,000 TW of sunlight reaching the Earth's surface is plentiful – almost 6,000 times more than the 15 TW equivalent of average power consumed by humans. Additionally, solar electric generation has the highest power density (global mean of 170 W/m²) among renewable energies.

Solar power is pollution-free during use. Production end-wastes and emissions are manageable using existing pollution controls. End-of-use recycling technologies are under development and policies are being produced that encourage recycling from producers.

PV installations can operate for many years with little maintenance or intervention after their initial set-up, so after the initial capital cost of building any solar power plant, operating costs are extremely low compared to existing power technologies.

Solar electric generation is economically superior where grid connection or fuel transport is difficult, costly or impossible. Long-standing examples include satellites, island communities, remote locations and ocean vessels.

When grid-connected, solar electric generation replaces some or all of the highest-cost electricity used during times of peak demand (in most climatic regions). This can reduce grid loading, and can eliminate the need for local battery power to provide for use in times of darkness. These features are enabled by net metering. Time-of-use net metering can be highly favorable, but requires newer electronic metering, which may still be impractical for some users.

Grid-connected solar electricity can be used locally thus reducing transmission/distribution losses (transmission losses in the US were approximately 7.2% in 1995).

Compared to fossil and nuclear energy sources, very little research money has been invested in the development of solar cells, so there is considerable room for improvement. Nevertheless, experimental high efficiency solar cells already have efficiencies of over 40% in case of concentrating photovoltaic cells and efficiencies are rapidly rising while mass-production costs are rapidly falling.

Disadvantages

Photovoltaics are costly to install. While the modules are often warranteed for upwards of 20 years, much of the investment in a home-mounted system may be lost if the home-owner moves and the buyer puts less value on the system than the seller.

Solar electricity is more expensive than most other forms of small-scale alternative energy production. Without governments mandating "feed-in tariffs" for green solar energy, solar PV is in less affordable to homeowners than solar hot water or solar space heating.

Solar electricity is not produced at night and is much reduced in cloudy conditions. Therefore, a storage or complementary power system is required.

Solar electricity production depends on the limited power density of the location's insolation. Average daily output of a flat plate collector at latitude tilt in the contiguous US is 3–7 kilowatt·h/m² and on average lower in Europe.

Solar cells produce DC which must be converted to AC (using a grid tie inverter) when used in existing distribution grids. This incurs an energy loss of 4–12%.

Chapter 10

Photovoltaic Array

A photovoltaic array is a linked assembly of PV modules

Timber framed house with a photovoltaic array

The solar panels on this small yacht at sea can charge the 12 volt batteries at up to 9 amperes in full, direct sunlight.

A **photovoltaic array** (also called a **solar array**) is a linked collection of photovoltaic modules, which are in turn made of multiple interconnected solar cells. By their modularity, they are able to be configured to supply most loads.

The cells convert solar energy into direct current electricity via the photovoltaic effect. The power that one module can produce is seldom enough to meet requirements of a home or a business, so the modules are linked together to form an *array*. Most PV arrays use an inverter to convert the DC power produced by the modules into alternating current that can plug into the existing infrastructure to power lights, motors, and other loads. The modules in a PV array are usually first connected in series to obtain the desired voltage; the individual strings are then connected in parallel to allow the system to produce more current. Solar arrays are typically measured under STC(Standard Test Conditions) or PTC(PVUSA Test Conditions), in watts, kilowatts, or even megawatts.

Costs of production have been reduced in recent years for more widespread use through production and technological advances. One source claims the cost in February 2006 ranged $3–10/watt while a similar size is said to have cost $8–10/watt in February 1996, depending on type. For example, crystal silicon solar cells have largely been replaced by less expensive multicrystalline silicon solar cells, and thin film silicon solar cells have also been developed recently at lower costs of production yet. Although they are reduced in energy conversion efficiency from single crystalline "siwafers", they are also much easier to produce at comparably lower costs.

Applications

Urban uses

In urban and suburban areas, photovoltaic arrays are commonly used on rooftops to supplement power use; often the building will have a connection to the power grid, in which case the energy produced by the PV array can be sold back to the utility in some sort of net metering agreement. Solar trees are arrays that, as the name implies, mimic the look of trees, provide shade, and at night can function as street lights. In agricultural settings, the array may be used to directly power DC pumps, without the need for an inverter. In remote settings such as mountainous areas, islands, or other places where a power grid is unavailable, solar arrays can be used as the sole source of electricity, usually by charging a storage battery.

There is financial support available for people wishing to install PV arrays. In the UK, households are paid a 'Feedback Fee' to buy excess electricity at a flat rate per kWh. This is up to 44.3p/kWh which can allow a home to earn double their usual annual domestic electricity bill. The current UK feed-in tariff system is due for review on 31 March 2012, after which the current scheme may no longer be available.

Performance

A solar panel on top of a parking meter

At high noon on a cloudless day at the equator, the solar irradiance can get up to 1.6 kW/m² or higher, on the Earth's surface, to a plane that is perpendicular to the sun's rays. As such, PV arrays can track the sun through each day to greatly enhance energy collection. However, tracking devices add cost, and require maintenance, so it is more common for PV arrays to have fixed mounts that tilt the array and face due South in the Northern Hemisphere (in the Southern Hemisphere, they should point due North). The tilt angle, from horizontal, can be varied for season, but if fixed, should be set to give optimal array output during the peak electrical demand portion of a typical year.

Trackers and sensors to optimise the performance are often seen as optional, but tracking systems can increase viable output by up to 100%. PV arrays that approach or exceed one megawatt often use solar trackers. Accounting for clouds, and the fact that most of the world is not on the equator, and that the sun sets in the evening, the correct measure of solar power is insolation – the average number of kilowatt-hours per square meter per day. For the weather and latitudes of the United States and Europe, typical insolation ranges from 4kWh/m²/day in northern climes to 6.5 kWh/m²/day in the sunniest regions.

In 2010, solar panels available for consumers can have a yield of up to 19%, while commercially available panels can go as far as 27%. Thus, a photovoltaic installation in the southern latitudes of Europe or the United States may expect to produce 1 kWh/m²/day. A typical "150 watt" solar panel is about a square meter in size. Such a panel may be expected to produce 1 kWh every day, on average, after taking into account the weather and the latitude.

In the Sahara desert, with less cloud cover and a better solar angle, one can obtain closer to 8.3 kWh/m²/day.

The unpopulated area of the Sahara desert is over 9 million km², which if covered with solar panels would provide 630 terawatts total power. The Earth's current energy consumption rate is around 13.5 TW at any given moment (including oil, gas, coal, nuclear, and hydroelectric).

Other factors affect PV performance. Many Photovoltaic cells' electrical output is extremely sensitive to shading. Majority of modules have bypass diodes between each cell or string of cells that minimize the effects of shading and only lose the power of the shaded portion of the array (The main job of the bypass diode is to eliminate hot spots that form on cells that can cause further damage to the array, and cause fires.). When even a small portion of a cell, module, or array is shaded, while the remainder is in sunlight, the output falls dramatically due to internal 'short-circuiting' (the electrons reversing course through the shaded portion of the p-n junction). Therefore it is extremely important that a PV installation is not shaded at all by trees, architectural features, flag poles, or other obstructions like continuously parked cars. Sunlight can be absorbed by dust, fallout, or other impurities at the surface of the module. This can cut down the amount of light that actually strikes the cells by as much as half. Maintaining a clean module surface will increase output performance over the life of the module. Module output and life are also degraded by increased temperature. Allowing ambient air to flow over, and if possible behind, PV modules reduces this problem.

Effective module lives are typically 25 years or more.

Chapter 11

Concentrated Photovoltaics

Concentrated photovoltaics (CPV) is one of the newest forms of solar energy technology on the market today. CPV systems focus a large amount of sunlight onto a small area of solar photovoltaic materials to generate electricity. Unlike traditional, more conventional flat panel systems, CPV systems are often much less expensive to produce, because the concentration allows for the production of a much smaller area of solar cells.

History

There are recordsof concentrating of the Sun to aid in the performance of tasks in ancient China. Research into concentrated photovoltaics has taken place from the 1970s until today. Sandia National Laboratories in Livermore, Calif., was the site for most of the early work, with the first modern photovoltaic concentrating system produced there late in the decade. Their first system was a linear-trough concentrator system that used a point focus acrylic Fresnel lens focusing on water-cooled silicon cells and two axis tracking. Ramón Areces' system, also developed in the late 1970s, used hybrid silicone-glass Fresnel lenses, while cooling of silicon cells was achieved with a passive heat sink.

Challenges

CPV systems operate most efficiently in concentrated sunlight, as long as the solar cell is kept cool through use of heat sinks. Diffuse light, which occurs in cloudy and overcast conditions, cannot be concentrated. To reach their maximum efficiency, CPV systems must be located in areas that receive plentiful direct sunlight.

Efficiency

Semiconductor properties allow solar cells to operate more efficiently in concentrated light, as long as the cell junction temperature is kept cool by suitable heat sinks. Expected future efficiencies are nearly 50%.

Currently, prices are nearing $1/watt. At this cost, it is conceivable that CPV will soon reach grid parity.

Grid parity

Compared to conventional flat panel solar cells, CPV is advantageous because the solar collector is less expensive than an equivalent area of solar cells. CPV hardware (solar collector and tracker) is targeted to be priced well under 3 USD/Watt, whereas silicon flat panels that are commonly sold are 3 to 5 USD/Watt (not including any associated power systems or installation charges). CPV could reach grid parity in 2011.

Types of CPV

CPV systems are categorized according to the amount of their solar concentration, measured in "suns" (the square of the magnification).

Low concentration CPV

Low concentration CPV are systems with a solar concentration of 2-100 suns. For economic reasons, conventional or modified silicon solar cells are typically used, and, at these concentrations, the heat flux is low enough that the cells do not need to be actively cooled. The laws of optics dictate that a solar collector with a low concentration ratio can have a high acceptance angle and thus in some instances does not require active solar tracking. Luminescent solar concentrators can be used to construct non-tracking CPV with concentrations in range of 2 suns.

Medium concentration CPV

From concentrations of 100 to 300 suns, the CPV systems require two-axes solar tracking and cooling (whether passive or active), which makes them more complex.

High concentration photovoltaics (HCPV)

High concentration photovoltaics (HCPV) systems employ concentrating optics consisting of dish reflectors or fresnel lenses that concentrate sunlight to intensities of 300 suns or more. The solar cells require high-capacity heat sinks to prevent thermal destruction and to manage temperature related performance losses. Multijunction solar cells are currently favored over silicon as they are more efficient and have a lower temperature coefficient (less loss in efficiency with an increase in temperature). The efficiency of both cell types rises with increased concentration; multijunction efficiency rises faster. Multijunction solar cells, originally designed for non-concentrating space-based satellites, have been re-designed due to the high-current density encountered with CPV (typically 8 A/cm^2 at 500 suns). Though the cost of multijunction solar cells is roughly 100 times that of silicon cells of the same area, the small cell area employed makes the relative costs of cells in each system comparable and the system economics favor the multijunction cells. Multijunction cell efficiency has now reached 41% in production cells.

The 41% value given above is for a specific set of conditions known as "standard test conditions". These include a specific spectrum, an incident optical power of 850 W/m², and a cell temperate of 25° C. In a concentrating system, the cell will typically operate under conditions of variable spectrum, lower optical power, and higher temperature. The optics needed to concentrate the light have limited efficiency themselves, in the range of 75-90%. Taking these factors into account, a solar module incorporating a 40% multijunction cell might deliver a DC efficiency around 30%. Under similar conditions, a silicon-cell module would deliver an efficiency of less than 18%.

Concentrated photovoltaics and thermal

Concentrated photovoltaics and thermal (**CPVT**), also sometimes called **combined heat and power solar** (**CHAPS**), is a cogeneration technology used in concentrated photovoltaics that produces both electricity and heat in the same module. The heat may be employed in district heating, water heating and air conditioning, desalination or process heat.

CPVT systems are currently in production in Europe, with the Israeli company Zenith Solar developing CPVT systems with a claimed efficiency of 72%.

Chapter 12

Solar Micro-Inverter

The canonical microinverter: the Enphase M190 in the process of being installed. The ground wire is attached to the lug and the panel's DC connections are attached to the cables on the lower right. The AC parallel truck cable runs at the top (just visible).

A **solar micro-inverter**, or simply **microinverter**, is a device that converts direct current (DC) from a single solar module (panel) to alternating current (AC) for grid consumption. Microinverters contrast with the conventional "string inverter" devices, which support a large number of solar panels connected to a single inverter.

Microinverters have several advantages over conventional devices; they eliminate high voltage DC runs, reduce line losses, individually control the panels output and act as maximum power point trackers, and introduce redundancy to the array. Their primary disadvantages are that they are generally more expensive than the equivalent string inverter, and are normally located on the panel, where they may be harder to maintain.

It is not uncommon to refer to any small inverter as a micro-inverter, although this is not a modern use of the term. The key feature of a "true" micro-inverter is not its small size or power rating, but its one-to-one control over a single panel, and its mounting on the panel or near it. Small string inverters, like larger ones, control multiple panels and are generally mounted remotely, often indoors. The term is also commonly used to refer to small wind power inverters.

Description

Inverters

Solar panels produce DC current at a voltage that depends on the module's design and the current lighting conditions. Modern panels using 6" cells normally contain 60 cells and produce a nominal 30 volts. For conversion into AC, this is too low a voltage to be efficient, so panels are daisy-chained in series to produce what is effectively a single larger panel with a nominal rating of around 300 to 600 VDC. The power is then run to an inverter, which converts it into local grid ratings, typically 240VAC/60Hz for the North American market, or 220VAC/50Hz in Europe.

The main problem with this "string inverter" approach is that the string of panels will act as if it was a single larger panel rated to the worst of the individual panels within it. For instance, if one panel in a string has 5% higher resistance due to a minor manufacturing defect, the string as a whole will perform 5% worse (or thereabouts). This situation is dynamic; if a panel is shaded its output drops dramatically, effecting the output of the string as a whole even if the other panels are not shaded. Even slight changes in orientation can cause mis-matches in output in this fashion. Additionally, the efficiency of a panel's output is strongly effected by the load the inverter places on it, which requires a technique known as maximum power point tracking to ensure optimal collection. This varies from panel to panel, so string inverters will necessarily be imperfect at this task.

A further problem, although minor, is that string inverters come in a limited selection of power ratings. This means that a given array will normally upsize the inverter to the next-largest model over the rating of the panel array. For instance, a 10-panel array of 2300 W might have to use a 2500 or even 3000 W inverter, paying for power they cannot possibly use. This same effect makes it difficult to change array sizes over time, adding power when funds are available.

Other challenges associated with centralized inverters include the space required to locate the device, as well as heat dissipation requirements. Large central inverters are typically actively cooled. These cooling fans can make a tremendous amount of noise, so location of the inverter relative to offices and occupied areas must be considered.

Microinverters

Microinverters are essentially small inverters tuned to the output of a single typical panel. Modern grid-tie panels are normally rated between 220 and 245 Watts, but rarely produce this in practice, so microinverters are typically rated between 190 and 220 W. Because it is operated at this lower power point, many design issues inherent to larger designs simply go away; the need for a large transformer is generally eliminated, large electrolytic capacitors can be replaced by smaller solid-state devices, and cooling loads are so reduced that no fans are needed. Mean time between failures (MTBF) are quoted in the hundreds of years.

More importantly, a microinverter attached to a single panel allows it to isolate and tune the output of that panel. For instance, in the same array used as an example above, the single panel that is underperforming will have no effect on the panels around it. In that case, the array as a whole will produce 5% more power than it would with a string inverter. When shadowing, if present, is factored in, these gains can become considerable, with manufacturers generally claiming 5% better output at a minimum, and up to 25% better in some cases.

Microinverters produce grid-matching power directly at the back of the panel. Arrays of panels are connected in parallel to each other, and then to the grid feed. This has the major advantage that a single failing panel or inverter will not take the entire string offline. Combined with the lower power and heat loads, and improved MTBF, it is suggested that overall array reliability of a microinverter-based system will be significantly greater than a string-inverter based one. Additionally, when faults occur, they are identifiable to a single point, as opposed to an entire string. This not only makes fault isolation easier, but unmasks minor problems that might never become visible otherwise - a single underperforming panel may not effect a short string's output enough to be noticed.

The main disadvantage of the microinverter concept is cost related. As each panel has to duplicate much of the complexity of a string inverter, the distributed and flat costs are much greater. This offsets any advantage in terms of simplification of the individual components. As of October 2010, a central inverter costs approximately $0.40 per watt, whereas a micro-inverter costs approximately $0.52 per watt. Like string inverters, economic considerations force manufacturers to limit the number of models they produce; most produce a single model that may be over- or under-designed when matched with a particular panel.

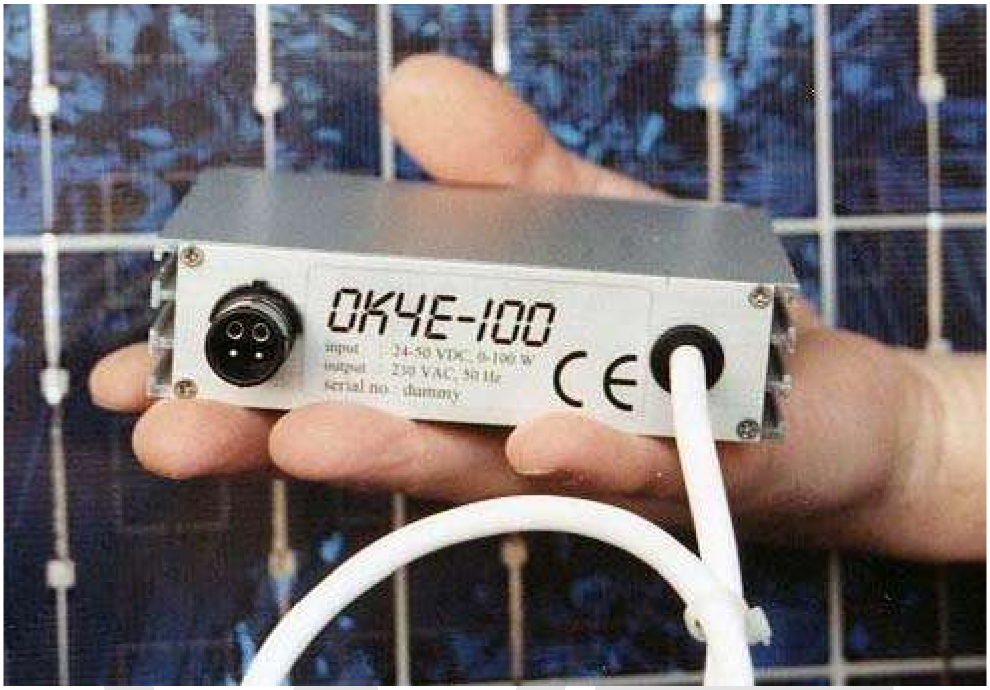
Generally speaking, microinverters have become common in applications where array sizes are small (thus reducing the cost differential) and maximizing performance from every panel is a concern. For this reason, microinverters have been most successful in the residential market.

History

The microinverter concept has been in the solar industry since it's inception. However, flat costs in manufacturing, like the cost of the transformer or enclosure, scaled favorably with size and meant that larger devices were inherently less expensive in terms of price per watt. Small inverters were available from companies like ExcelTech and others, but these were simply small versions of larger designs with poor price performance and were aimed at niche markets.

Early efforts

Released in 1993, Mastervolt's Sunmaster 130S was the first true micro-inverter



Another early micro-inverter, 1995's OK4E-100 - E for European, 100 for 100 watts

In 1991 the US company Ascension Technology started work on what was essentially a shrunken version of a traditional inverter, intended to be mounted on a panel to form an "AC panel". In 1994 they sent an example to Sandia Labs for testing. In 1997, Ascension partnered with US panel company ASE Americas to introduce the 300 W SunSine panel.

Design of what would today be recognized as a "true" microinverter traces its history to late 1980s work by Werner Kleinkauf at the Institut für Solare Energieversorgungstechnik (ISET). His work on "module integrated converters" was highly influential, especially in Europe.

In 1993 Mastervolt introduced their first grid-tie inverter, the Sunmaster 130S, based on a collaborative effort between Shell Solar, Ecofys and ECN. The 130 was designed to be mounted directly to the back of the panel, connecting both AC and DC lines using compression fittings. In 2000 the 130 was replaced by the Soladin 120, a micro-inverter in the form of a AC adapter that allows panels to be connected simply by plugging them into any wall socket.

In 1995, OKE-Services designed a high-frequency version with improved efficiency, which was introduced commercially as the OK4-100 in 1995 by NKF Kabel, and re-branded for US sales as the Trace Microsine. A new version, the OK4All, improved efficiency and had wider operating ranges.

In spite of this promising start, by 2003 most of these projects had ended. Ascension Technology was purchased by Applied Power Corporation, a large integrator. APC was in turn purchased by Schott in 2002, and SunSine production was canceled in favor of

Schott's existing designs. NKF ended production of the OK4 series in 2003 when a subsidy program ended. Mastervolt has moved on to a line of "mini-inverters" combining the ease-of-use of the 120 in a system designed to support up to 600 W of panels.

Enphase

In the aftermath of the 2001 Telecoms crash, Martin Fornage of Cerent Corporation was looking for new projects. When he saw the low performance of the string inverter for the solar array on his ranch, he found the project he was looking for. In 2006 he formed Enphase Energy with another Cerent engineer, Raghu Belur, and they spent the next year applying their telecommunications design expertise to the inverter problem.

Released in 2008, the Enphase M175 model was the first commercially successful microinverter; a successor, M190, was introduced in 2009. Encased in a lightweight aluminum enclosure, the M190 was designed to be mounted to the same "rails" used by the panels, typically located behind them where the DC cables emerged from the back of the panel. The M190 includes a CPU that uses power line communication to send status information when polled. A second device, the Envoy, periodically polls each inverter, then sends the information as a batch over the internet to Enphase. The data is collected and presented every 15 minutes on their Enlighten web site.

Backed by $100 million in private equity, Enphase quickly grew to 13% marketshare by mid-2010, aiming for 20% by year-end. They shipped their 500,000th inverter in early 2011. Manufacturing branched out, with Flextronics starting production runs in their factory in Ontario to supply the local market. In late 2010 they announced a re-designed version, tentatively called the M215, that reduces the cabling and ports on the inverters in order to further lower costs. A variant of the M215 can attach directly to the back of the panel, producing an "AC module". In early 2011, they announced that re-branded versions of the new design will be sold by Siemens directly to electrical contractors for widespread distribution.

Competition

Enphase's success did not go unnoticed, and since 2010 a host of competitors have appeared. Many of these are identical to the M190 in specs, and even in the casing and mounting details. Some differentiate by competing head-to-head with Enphase in terms of price or performance, while others are attacking niche markets. Larger firms have also stepped into the field. Many of the principles from Ascension Technology have re-formed as GreenRay Solar, and OKE-Services updated OK4-All product was recently bought by SMA, a major inverter manufacturer.

Another approach is the power optimizer, which is essentially a DC-to-DC version of the microinverter - everything except the actual "inverter". The power optimizer has all the benefits of the microinverter in terms of Maximum Power Point Tracking (MPPT) performance, module isolation, monitoring etc, but is even smaller and simpler than the microinverter. The arrays are then connected to a string inverter as normal. This approach minimizes the distributed costs, and theoretically produces a lower-cost system overall. However, the long runs of high-voltage DC wiring feeding the inverters remains, along with the need to group panels into acceptable groups to get those voltage levels. SolarEdge is leading the power optimizer approach; in 2010, the company shipped an estimated 250,000 power optimizers and 12,000 inverters – amounting to a total generation of 50 megawatts.

Chapter 13

Photovoltaics in Transport

There are many applications of **photovoltaics in transport** either for motive power or as auxiliary power units, particularly where fuel, maintenance, emissions or noise requirements preclude internal combustion engines or fuel cells. Due to the limited area available on each vehicle either speed or range or both are limited when used for motive power.

PV used for auxiliary power on a yacht

Space

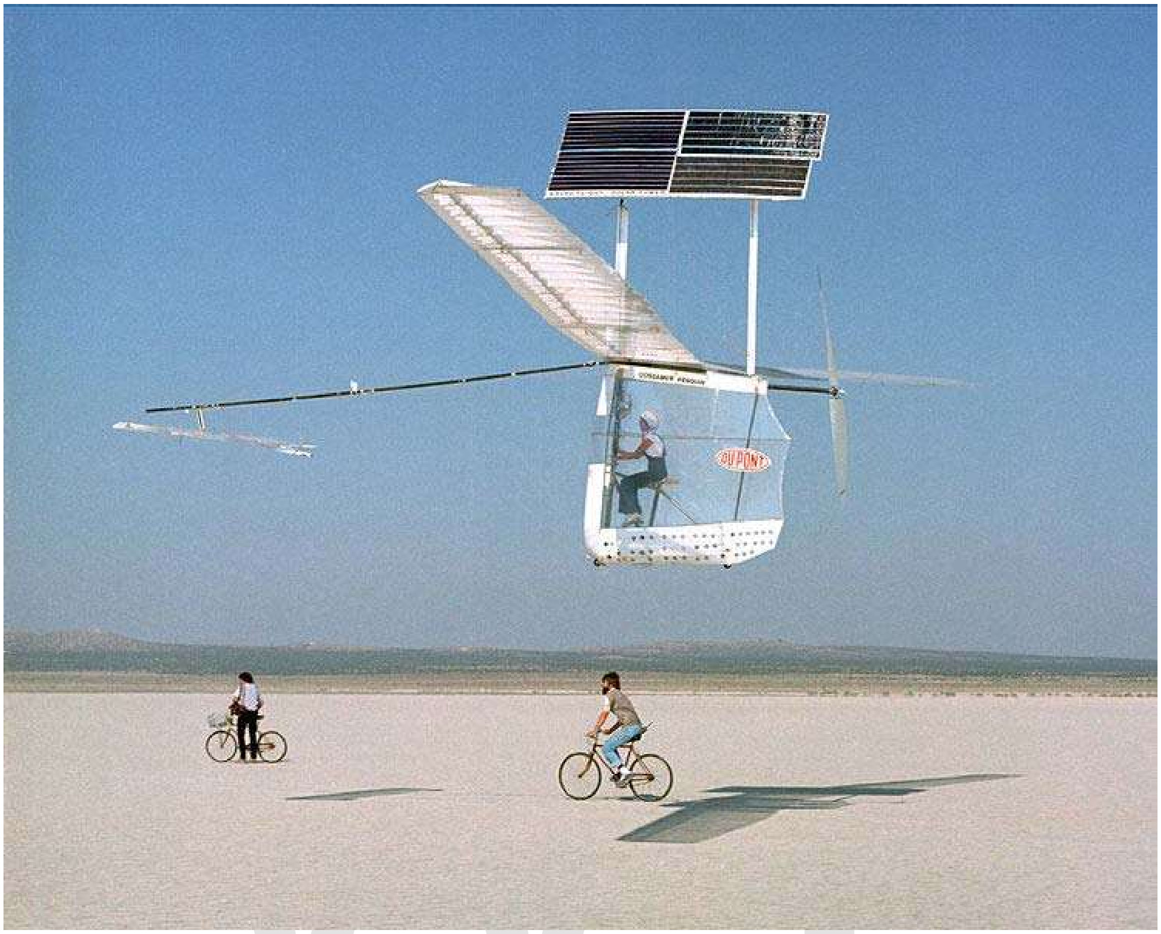
PV on the International Space Station

Solar energy is often used to supply power for satellites and spacecraft operating in the inner solar system due to its power/weight ratio. (In the outer solar system, where the sunlight is too weak, radioisotope thermal generators (RTGs) are used).

Air

There is considerable military interest in unmanned aerial vehicles (UAVs); solar power would enable these to stay aloft for months, becoming a much cheaper means of doing some tasks done today by satellites. In September 2007, the first successful flight for 48h under constant power of a UAV was reported. This is likely to be the first commercial use for photovoltaics in flight.

Many demonstration solar planes have been built, some of the best known by AeroVironment.



Gossamer Penguin

- Manned solar planes
    - Gossamer Penguin,
    - Solar Challenger - This plane flew 163 miles (262 km) from Paris France to England on solar power.
    - Sunseeker II - This plane is currently (May 9) on a tour of Europe
    - HB-SIA. Working prototype for Solar Impulse Project
- UAVs
    - Pathfinder and Pathfinder-Plus - This unmanned plane demonstrated that an airplane could stay aloft for an extended period of time fueled purely by solar power.
    - Helios - Derived from the Pathfinder-Plus, this solar cell & fuel cell powered UAV set a world record for flight at 96,863 feet (29,524 m).
    - Zephyr - built by Qinetiq, this UAV set the unofficial world record for longest duration unmanned flight at over 82 hours on 31 July 2008
- Future projects
    - Sky sailor (aimed at Martian flight)
    - Solar Impulse (aimed at manned circumnavigation of the globe)

- various solar airship projects e.g. Lockheed Martin's "High Altitude Airship"

Road

Nuna 3 PV powered car

"Solar Taxi"

Photovoltaic modules are used commercially as auxiliary power units on passenger cars in order to ventilate the car, reducing the temperature of the passenger compartment while it is parked in the sun. Vehicles such as the 2010 Prius, Aptera 2, Audi A8, and Mazda 929 have had solar sunroof options for ventilation purposes.

The area of photovoltaic modules required to power a car with conventional design is too large to be carried onboard. A prototype car and trailer has been built Solar Taxi. According to the website, it is capable of 100 km/day using $6m^2$ of standard crystalline silicon cells. Electricity is stored using a nickel/salt battery. A stationary system such as a rooftop solar panel, however, can be used to charge conventional electric vehicles.

It is also possible to use solar panels to extend the range of a hybrid or electric car, as incorporated in the Fisker Karma, available as an option on the Chevy Volt, on the hood and roof of "Destiny 2000" modifications of Pontiac Fieros, Italdesign Quaranta, Free Drive EV Solar Bug, and numerous other electric vehicles, both concept and production. In May 2007 a partnership of Canadian companies led by Hymotion added PV cells to a Toyota Prius to extend the range. SEV claims 20 miles per day from their combined 215W module mounted on the car roof and an additional 3kWh battery.

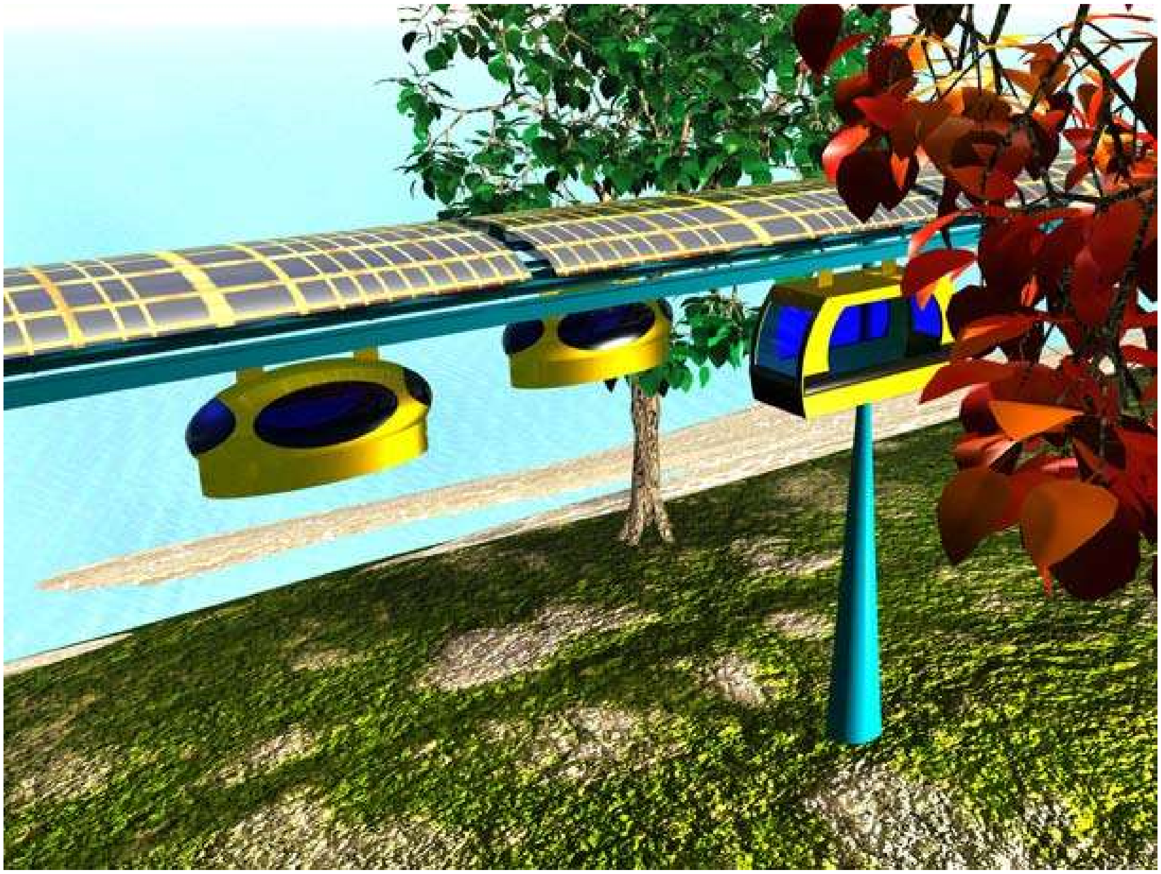
On 9 June 2008, the German and French Presidents announced a plan to offer a cedit of 6-8g/km of CO_2 emissions for cars fitted with technologies "not yet taken into consideration during the standard measuring cycle of the emissions of a car". This has given rise to speculation that photovoltaic panels might be widely adopted on autos in the near future

Anecdotal reports suggest that the 'Zap Xebra' PV module option could extend the car's 40-mile (64 km) by 5 miles (8 km).

It is much more feasible to run an ultralight vehicle on solar energy than a standard car. Many prototypes have been built for competitions such as the World Solar Challenge. The solar challenge cars can average 100 km/h for long distances. For 2007 a new Challenge class specified an upright seating position and smaller solar panels to create a class of vehicle which with little modification could be the basis for a practical proposition for sustainable transport. The winning car still achieved an average speed slightly in excess of 90 km/h (56 mph). The Venturi AstroLab in 2006 was hailed as the world's first commercial electro-solar hybrid car due to be released in January 2008, with a solar range of 18 km/day and a total range of 110 km it can be charged either from the sun or from AC mains.

It is also technically possible to use photovoltaic technology, (specifically thermophotovoltaic (TPV) technology) to provide motive power for a car. Fuel is used to heat an emitter. The infrared radiation generated is converted to electricity by a low band gap PV cell (e.g. GaSb). A protoype TPV hybrid car was even built. The "Viking 29" was the World’s first thermophotovoltaic (TPV) powered automobile, designed and built by the Vehicle Research Institute (VRI) at Western Washington University. Efficiency would need to be increased and cost decreased to make TPV competitive with fuel cells or internal combustion engines.

Personal Rapid Transit



JPods PRT concept with photovoltaic panels above guideways

Several Personal Rapid Transit (PRT) concepts incorporate photovoltaic panels.

Rail

PV panels were tested as APUs on Italian rolling stock under EU project. PVTRAIN

PVTrain concluded that the most interest for PV in rail transport was on freight cars where on board electrical power would allow new functionality:

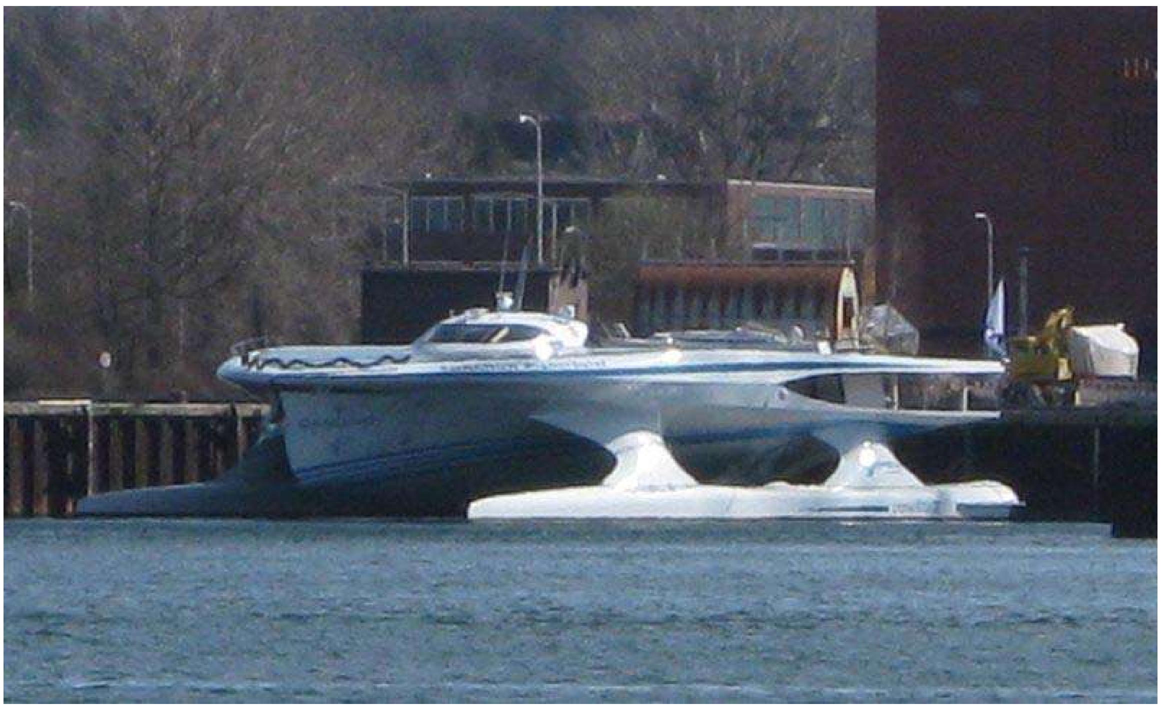
- GPS or other positioning devices, so as to improve its use in fleet management and efficiency.
- Electric locks, a video monitor and remote control system for cars with sliding doors, so as to reduce the risk of robbery for valuable goods.
- ABS brakes, which would raise the maximum velocity of freight cars to 160 km/h, improving productivity.

In addition to on-vehicle solar panels, there is the possibility to use stationary panels to generate electricity specifically for use in transport.

A few pilot plants have been built in the framework of the "Heliotram" project, such as the tram depots in Hannover Leinhausen and Geneva (Bachet de Pesay). The 150 kW_p Geneva site injected 600V DC directly into the tram/trolleybus electricity network provided about 1% of the electricity used by the Geneva transport network at its opening in 1999.

Direct feed to a DC grids avoids losses through DC to AC conversion. DC grids are only to be found in electric powered transport: railways, trams and trolleybuses.

Marine



Tûranor PlanetSolar, the world's largest solar-powered boat

Various demonstration systems have been made. Curiously, none yet takes advantage of the huge power gain that water cooling would bring.

Japan's biggest shipping line Nippon Yusen KK and Nippon Oil Corporation said solar panels capable of generating 40 kilowatts of electricity would be placed on top of a 60,000 tonne car carrier ship to be used by Toyota Motor Corporation.

n 2007, PV powered boat Transatlantic 21 successfully crossed the Atlantic Ocean power only by solar electricity.

In 2010, the Tûranor PlanetSolar, a 30 metre long, 15.2 metre wide catamaran yacht powered by 470 square metres of solar panels, was unveiled. It is set to circumnavigate the Earth and is so far the largest solar-powered boat ever built.

Sound barriers

For both road and rail transport in urban areas, there is an increasing requirement to protect people against the noise emitted by trains and road vehicles. Vertical or inclined walls are built by the side of the right of way to do this. The requirement to build the barrier can allocate the cost of the rigid packaging of a solar panel to the sound wall, making the marginal cost of installing a solar sound barrier instead of a passive one lower. In 2010, Belgian rail operator Infrabel was near to completing the world's largest solar installation on a railway, a 4MWp installation on a sound barrier roof near the Peerdsbos natural park, between Schoten et Brasschaat.

Chapter 14

Building-Integrated Photovoltaics

The CIS Tower in Manchester, England was clad in PV panels at a cost of £5.5 million. It started feeding electricity to the National Grid in November 2005

Building-integrated photovoltaics (**BIPV**) are photovoltaic materials that are used to replace conventional building materials in parts of the building envelope such as the roof, skylights, or facades. They are increasingly being incorporated into the construction of new buildings as a principal or ancillary source of electrical power, although existing buildings may be retrofitted with BIPV modules as well. The advantage of integrated photovoltaics over more common non-integrated systems is that the initial cost can be offset by reducing the amount spent on building materials and labor that would normally be used to construct the part of the building that the BIPV modules replace. These advantages make BIPV one of the fastest growing segments of the photovoltaic industry.

History

PV applications for buildings began appearing in the 1970s. Aluminum-framed photovoltaic modules were connected to, or mounted on, buildings that were usually in remote areas without access to an electric power grid. In the 1980s photovoltaic module add-ons to roofs began being demonstrated. These PV systems were usually installed on utility-grid-connected buildings in areas with centralized power stations. In the 1990s BIPV construction products specially designed to be integrated into a building envelope became commercially available.

Forms

Building-Integrated Photovoltaic modules are available in several forms.

- Flat roofs
  - The most widely installed to date is a thin film solar cell integrated to a flexible polymer roofing membrane.

- Pitched roofs

  -
  - Modules shaped like multiple roof tiles.
  - Solar shingles are modules designed to look and act like regular shingles, while incorporating a flexible thin film cell.
  - It extends normal roof life by protecting insulation and membranes from ultraviolet rays and water degradation. It does this by eliminating condensation because the dew point is kept above the roofing membrane.

- Facade
  - Facades can be installed on existing buildings, giving old buildings a whole new look. These modules are mounted on the facade of the building, over the existing structure, which can increase the appeal of the building and its resale value.

- Glazing
  - (Semi)transparent modules can be used to replace a number of architectural elements commonly made with glass or similar materials, such as windows and skylights.

Transparent and translucent photovoltaics

Transparent solar panels use a tin oxide coating on the inner surface of the glass panes to conduct current out of the cell. The cell contains titanium oxide that is coated with a photoelectric dye.

Most conventional solar cells use visible and infrared light to generate electricity. In contrast, the innovative new solar cell also uses ultraviolet radiation. Used to replace conventional window glass, or placed over the glass, the installation surface area could be large, leading to potential uses that take advantage of the combined functions of power generation, lighting and temperature control.

Another name for transparent photovoltaics is "translucent photovoltaics" (they transmit half the light that falls on them). Similar to inorganic photovoltaics, organic photovoltaics are also capable of being translucent.

Incentives

In some countries, additional incentives, or subsidies, are offered for building-integrated photovoltaics in addition to the existing feed-in tariffs for stand-alone solar systems. Since July 2006 France offered the highest incentive for BIPV, equal to an extra premium of EUR 0.25/kWh paid in addition to the 30 Euro cents for PV systems. These incentives are offered in the form of a rate paid for electricity fed to the grid.

European Union

- France + EUR 0.25/kWh
- Germany - former EUR 0,05/kWh facade bonus expired in 2009
- Italy + EUR 0.04-0.09 kWh
- Spain, compared with a non- building installation that receives 28,00 cent€/kWh (RD 1578/2008):
  - <= 20 KW, 34,00 cent€/kWh
  - >20 kW: 31,00cent€/kWh

USA

- USA - Varies by state. Check Database of State Incentives for Renewables & Efficiency.

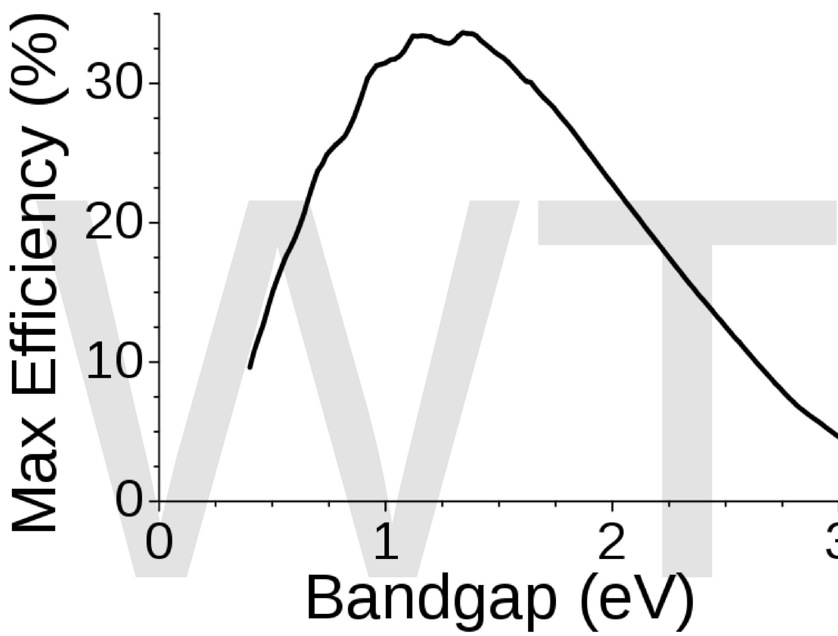
China

Further to the announcement of a subsidy program for BIPV projects in March 2009 offering RMB20/watt for BIPV systems and RMB15/watt for rooftop systems, the Chinese government recently unveiled a photovoltaic energy subsidy program "the Golden Sun Demonstration Project". The subsidy program aims at supporting the development of photovoltaic electricity generation ventures and the commercialization of

PV technology. The Ministry of Finance, the Ministry of Science and Technology and the National Energy Bureau have jointly announced the details of the program in July 2009. Qualified on-grid photovoltaic electricity generation projects including rooftop, BIPV, and ground mounted systems are entitled to receive a subsidy equal to 50% of the total investment of each project, including associated transmission infrastructure. Qualified off-grid independent projects in remote areas will be eligible for subsidies of up to 70% of the total investment. In mid November, China's finance ministry has selected 294 projects projects totaling 642 megawatts that come to roughly RMB 20 billion ($3 billion) in costs for its subsidy plan to dramatically boost the country's solar energy production.

Chapter 15

Shockley–Queisser Limit



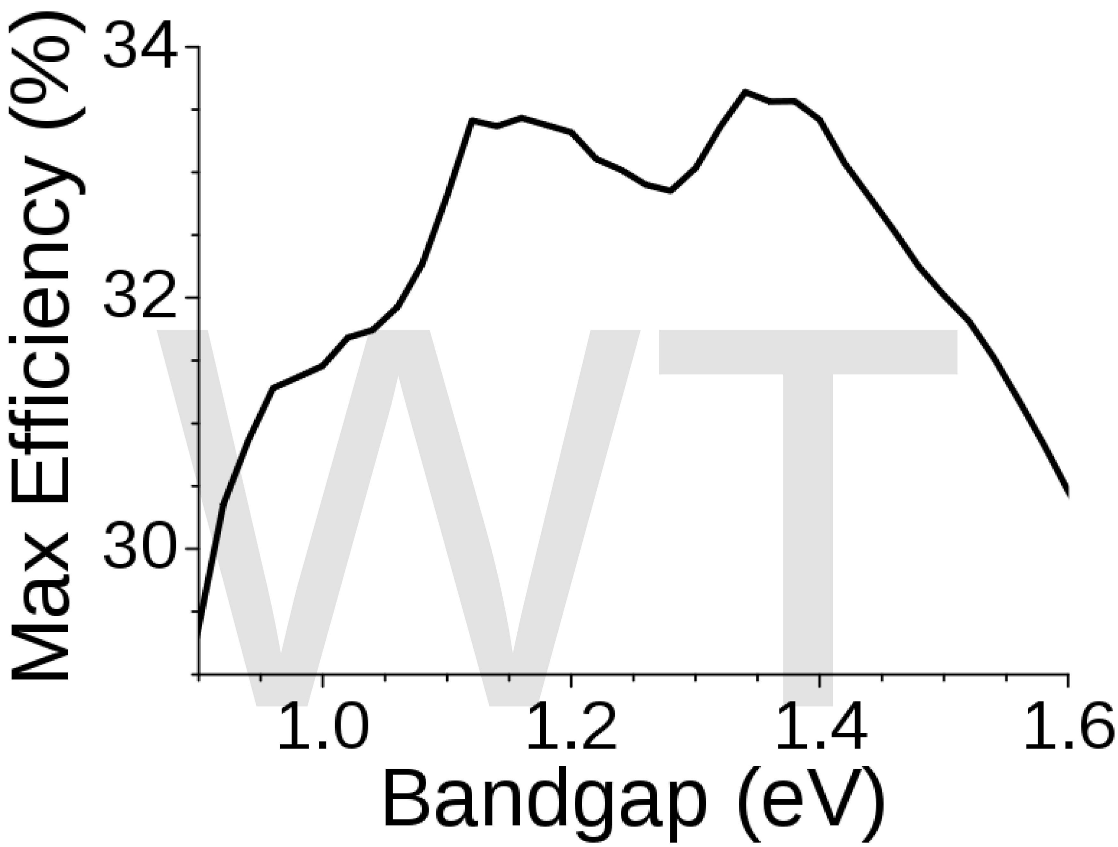
The Shockley-Queisser limit for the efficiency of a solar cell. The curve is wiggly because of IR absorption bands in the atmosphere. In the original paper, the solar spectrum was approximated by a smooth curve, the 6000K blackbody spectrum. As a result, the efficiency graph was smoother and the values were slightly different.

In physics, the **Shockley–Queisser limit** or **detailed balance limit** refers to the maximum theoretical efficiency of a solar cell using a p-n junction to collect power from the cell. It was first calculated by William Shockley and Hans Queisser at Shockley Semiconductor in 1961. The limit is one of the most fundamental to solar energy production, and is considered to be one of the most important contributions in the field.

The limit places maximum solar conversion efficiency around 33.7% assuming a p-n junction band gap of 1.1 eV (typical for silicon). That is, of all the power contained in sunlight falling on a silicon solar cell (about 1000 W/m²), only 33.7% of that could ever be turned into electricity (337 W/m²). Modern commercial single-crystalline solar cells produce about 22% conversion efficiency, the difference due largely to practical concerns like reflection off the front surface and light blockage from the thin wires on its surface.

The Shockley–Queisser limit only applies to cells with a single p-n junction; cells with multiple layers can outperform this limit. In the extreme, with an infinite number of layers, the corresponding limit is 86%.

Background



The Shockley-Queisser limit, zoomed in near the region of peak efficiency

In a traditional solid-state semiconductor, a solar cell is made from two doped crystals, one with a slight negative bias (n-type semiconductor), which has extra free electrons, and the other with a slight positive bias (p-type semiconductor), which is lacking free electrons. When placed in contact, some of the electrons in the n-type portion will flow into the p-type to "fill in" the missing electrons, also known as an electron hole. Eventually enough will flow across the boundary to equalize the Fermi levels of the two materials. The result is a region at the interface, the p-n junction, where charge carriers are depleted and/or accumulated on each side of the interface. In silicon, this transfer of electrons produces a potential barrier of about 0.6V to 0.7V.

When placed in the sun, photons in the sunlight can strike the bound electrons in the p-type side of the semiconductor, giving them more energy, a process known technically as photoexcitation. In silicon, sunlight can provide enough energy to push an electron out of the lower-energy valence band into the higher-energy conduction band. As the name implies, electrons in the conduction band are free to move about the silicon. When a load is placed across the cell as a whole, these electrons will flow out of the p-type side into the n-type side, lose energy while moving through the external circuit, and then back into the p-type material where they can once again re-combine with the valence-band hole they left behind, producing a lower-energy photon. In this way, sunlight creates an electrical current.

The Limit

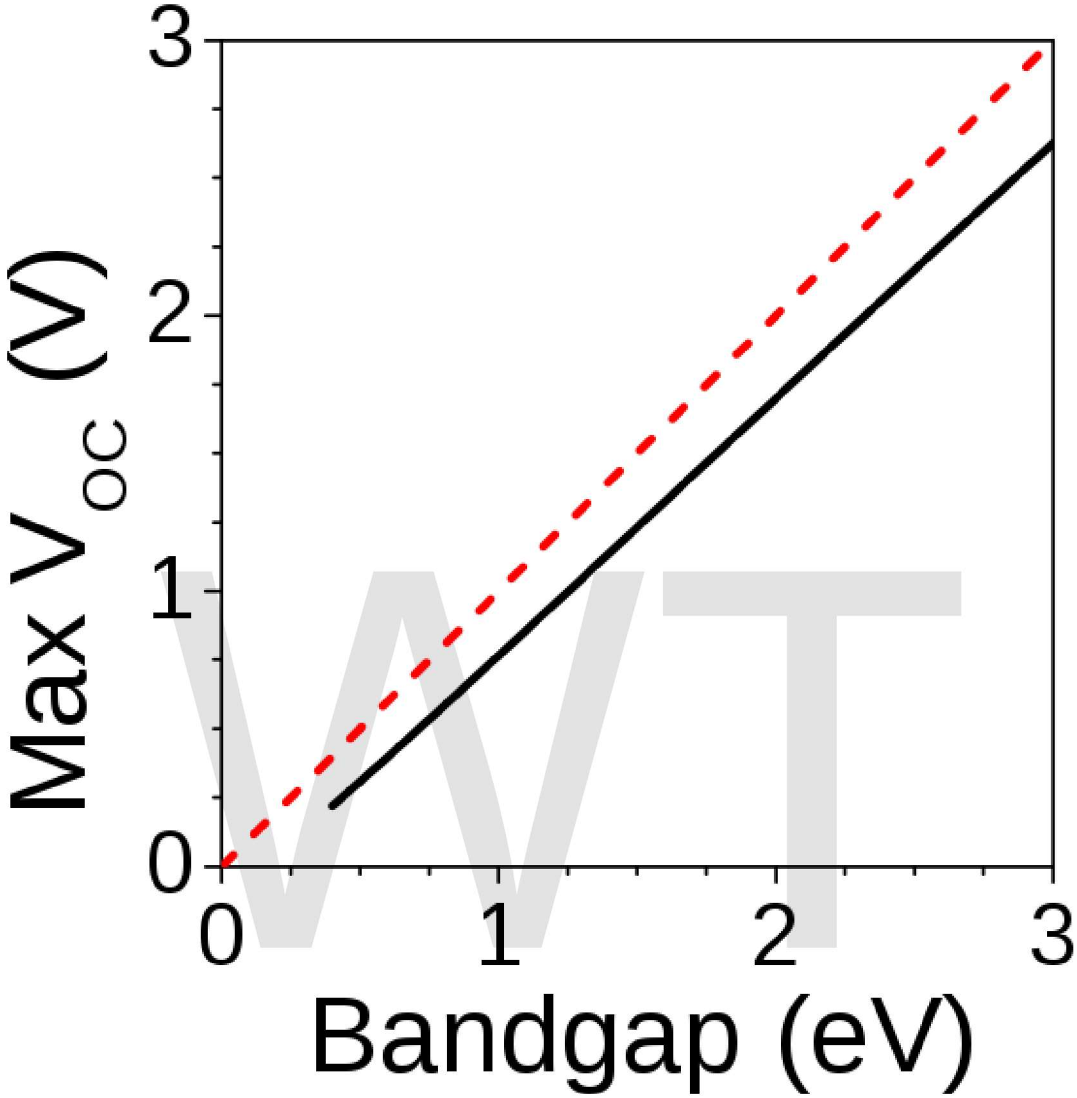
The Shockley–Queisser limit is calculated by examining the amount of electrical energy that is extracted per photon of incoming sunlight. There are three primary considerations:

Blackbody radiation

Any material above absolute zero temperature will emit radiation through blackbody radiation. In the case of a solar cell at ambient room temperature, at 300 Kelvin, a baseline energy is always being emitted. This energy cannot be captured by the cell, and represents about 7% of the available incoming energy.

This radiation effect is dependent on cell temperature. Any energy lost in a cell is generally turned into heat, so any inefficiency in the cell increases the cell temperature when it is placed in sunlight. The blackbody radiation effect will always be present, so cells will naturally heat up in practice. As their temperature increases, the blackbody radiation also increases, until an equilibrium is reached. In practice this equilibrium is normally reached at temperatures as high as 360 Kelvin, and cells normally operate at lower efficiencies than their room temperature rating. Module datasheets normally list this temperature dependancy as T_{NOTC}.

Recombination



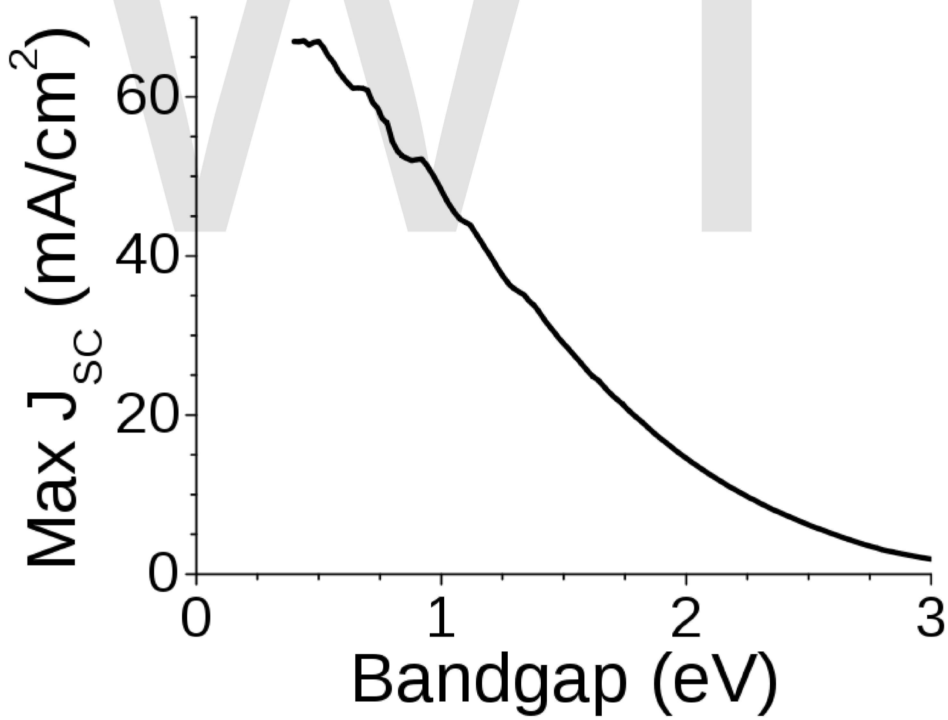
Black curve: The limit for open-circuit voltage in the Shockley-Queisser model (i.e., voltage at zero current). The red dotted line shows that this voltage is always below the bandgap. This voltage is limited by recombination.

When an electron is ejected through photoexcitation, the atom it was formerly bound to is left with a net positive charge. Under normal conditions, the atom will attempt to remove an electron from a surrounding atom in order to neutralize itself, a process known as recombination. That atom will then attempt to remove an electron from another atom, and so forth, producing a ionization that moves through the cell. Since these can be viewed as the motion of a positive charge, it is useful to refer to them as "holes", a sort of virtual positive electron.

Like electrons, holes move around the material, and will be attracted towards a source of electrons. Normally these are provided through an electrode on the back surface of the cell. Meanwhile the photoelectrons are moving forward towards the electrodes on the front surface. For a variety of reasons, holes move much more slowly than electrons. This means that during the finite time while the electron is moving forward towards the p-n junction, it may meet a slowly moving hole left behind by a previous photoexcitation. When this occurs, the electron recombines at that atom, and the energy is lost (normally through the emission of a photon of that energy, but there are a variety of possible processes).

Recombination places an upper limit on the *rate* of production; past a certain rate there are so many holes in motion that new electrons will never make it to the p-n junction. In silicon this reduces the theoretical performance under normal operating conditions by another 10% over and above the thermal losses noted above. Materials with higher electron (or hole) mobility can improve on silicon's performance; gallium arsenide (GaAs) cells gain about 5% in real-world examples due to this effect alone. In brighter light, when it is concentrated by mirrors or lenses for example, this effect is magnified. Normal silicon cells quickly saturate, while GaAs continue to improve at concentrations as high as 1500 times.

Spectrum losses



The limit for short-circuit current density (i.e., current density at zero voltage). This assumes that each solar photon gets converted into an electron that flows through the circuit. At higher bandgaps, there are fewer photons above the bandgap, and therefore the current density decreases.

Since the act of moving an electron from the valence band to the conduction band requires energy, only photons with more than that amount of energy will produce a photoelectron. In silicon the conduction band is about 1.1 eV away from the valence band, which corresponds to red light. In other words, photons of red, yellow and blue light will all contribute to power production, whereas infrared, microwaves and radio waves will not. This places an immediate limit on the amount of energy that can be extracted from the sun. Of the 1,000 W/m² in AM1.5 sunlight, about half of that has less than 1.1 eV of energy, and will not produce power in a silicon cell. That means there is a theoretical conversion efficiency of about 50% or less, ignoring all other factors.

Another important contributor to losses is that any energy above and beyond the bandgap energy is lost; while blue light has roughly twice the energy of red light, that energy is not captured by devices with a single p-n junction. The electron is ejected with higher energy when struck by a blue photon, but it loses this extra energy as it travels toward the p-n junction, this energy being turned into heat in the crystal.

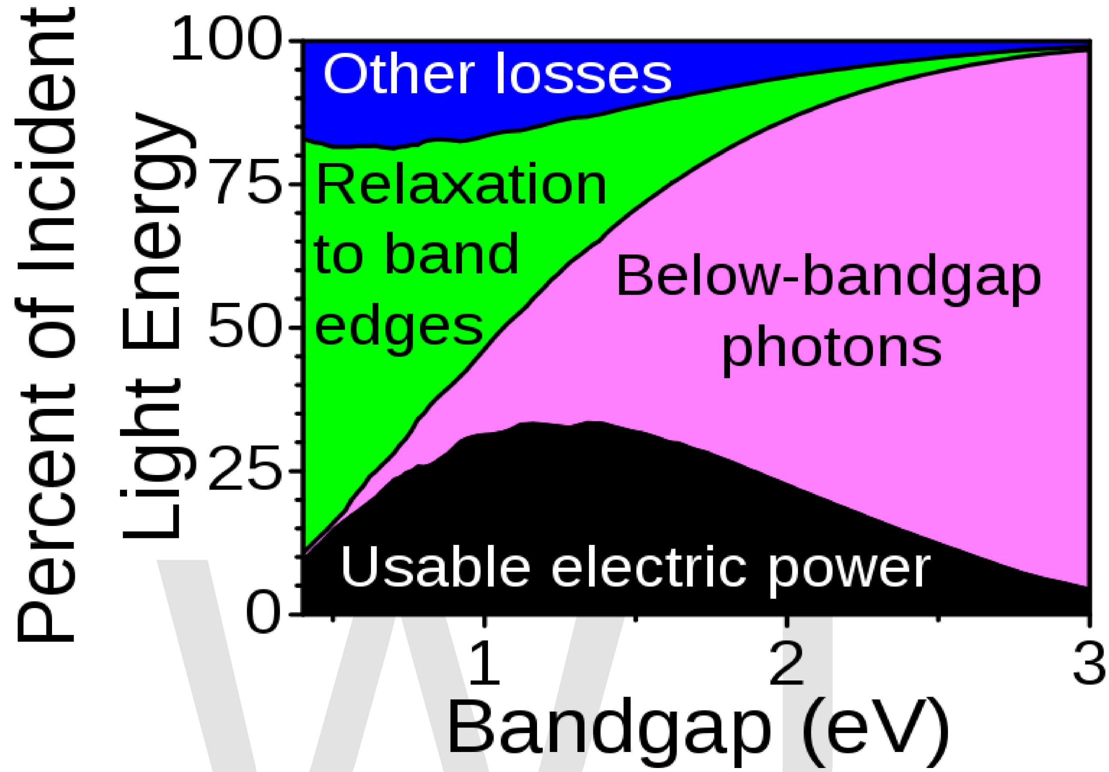
All together

Considering the blackbody and recombination effects alone, a solar cell has a peak theoretical efficiency of 68%. Thus the spectrum losses represent the vast majority of lost power. Considering all three effects, a single-junction cell made of silicon will have a theoretical peak performance of about 33.7%, or about 337 W/m² in AM1.5.

Other considerations

Shockley and Queisser's work considered the most basic physics only, there are a number of other factors that further reduce the theoretical power. Many of these have been explored since the 1980s. Landsberg and Baruch added various practical considerations like re-emission, while a number of researchers have attempted to characterize other losses in the cell, like interstitial defects. This latter effect explains why polysilicon cells are always outperformed by their single-crystal cousins.

Exceeding the Limit



Breakdown of the causes for the Shockley-Queisser limit. The black height is energy that can be extracted as useful electrical power (the Shockley-Queisser efficiency limit); the pink height is energy of below-bandgap photons; the green height is energy lost when hot photogenerated electrons and holes relax to the band edges; the blue height is energy lost in the tradeoff between low radiative recombination versus high operating voltage. Designs that exceed the Shockley-Queisser limit work by overcoming one or more of these three loss processes.

It is important to note that the limit makes several fundamental assumptions; that the cell contains a single p-n junction, that the junction is tuned to visible light, and that any extra energy in the photons is lost. None of these assumptions is necessarily true, and a number of different approaches have been used to significantly surpass the basic limit.

Tandem cells

The most widely explored path to higher efficiency solar cells has been to use multiple p-n junctions, each one tuned to a particular frequency of the spectrum. Since light will only react strongly with structures that contain roughly the same bandgap as their wavelength, as long as these layers are extremely thin they are almost transparent to lower frequencies. This allows the layers to be stacked, with the layers capturing higher frequencies (shortest wavelengths, bluish) on top, and the lower frequency light (longer wavelengths, reddish) traveling through them to the lower layers.

The calculation of the fundamental efficiency limits of these "tandem cells" (or "multi-junction cells") works in a fashion similar to those for single-junction cells, with the caveat that some of the light will be converted to other frequencies and re-emitted within the structure. Using methods similar to the original Shockley-Queisser analysis with these considerations in mind produces similar results; a two-layer cell can reach 42% efficiency, three-layer cells 49%, and a theoretical infinity-layer cell 68%.

The majority of tandem cells that have been produced to date use three layers, tuned to blue (on top), yellow (middle) and red (bottom). These cells require the use of semiconductors that can be tuned to specific frequencies, which has led to most of them being made of gallium arsenide (GaAs) compounds, often germanium for red, GaAs for yellow, and $GaInP_2$ for blue. They are very expensive to produce, using techniques similar to microprocessor construction but with "chip" sizes on the scale of several centimeters. In cases where outright performance is the only consideration, these cells have become common; they are widely used in satellite applications for instance, where the power-to-weight ratio overwhelms practically every other consideration.

Gallium arsenide has higher electron mobility than silicon, which means the photoelectrons reach their p-n junctions more quickly. It also has many more charge carriers available, which means the ratio of electrons/holes to neutral atoms is lower. These effects reduce the chance that electrons and holes will meet during the journey to the junction, which allows more light to fall on the cell before they reach equilibrium. These cells have increasing efficiency under concentrated light; under the best possible conditions and perfect lighting, a two-layer cell can reach 55% efficiency, 63% for three-layer cells, and 86% for infinite layers.

Using concentrations on the order of 500 to 1000, meaning that a 1 cm² square cell can use the light collected from a 1000 cm² area, produces the highest efficiencies seen to date. Three-layer cells are fundamentally limited to 63%, but existing commercial prototypes have already demonstrated over 40%. These cells capture about 2/3rds of their theoretical maximum performance, so assuming the same is true for a non-concentrated version of the same design, one might expect a three-layer cell of 30% efficiency under normal sunlight. This is not enough of an advantage over traditional silicon designs to make up for their extra production costs. For this reason, almost all tandem cell research for terrestrial use is dedicated to concentrator systems, normally using mirrors or fresnel lenses.

Using a concentrator also has the added benefit that the number of cells needed to cover a given amount of ground area is greatly reduced. A conventional system covering 1 m² would require 50 cells of 250 cm² (typical for modern cells), but for a concentrator system only a single cell is needed, along with a concentrator. The argument for concentrated tandem cells has been that the high cost of the cells themselves would be more than offset by the reduction in total number of cells and the much lower cost of the concentrators. The downside of the concentrator approach is that at high concentrations even small movements of the sun will cause the focussed sunlight to fall off the cell, so they need to be mounted in a machine that tracks the sun as it moves. Sun-tracking system are expensive, rising with the precision required, offsetting other advantages.

To date, no large-scale high-efficiency tandem cell commercial systems have been deployed, although one has been planned for Spain. PV generator deployments using conventional cells are currently reaching about $5 per peak Watt for deployment and installation costs, a number the concentrator systems cannot yet match. However, Boeing's Spectrolab division claims to be aiming for $3 a Watt in the short term. On the other hand, amorphous silicon solar cells for residential and commercial installations are often made as triple-junction tandem cells, and these are commercially available from Uni-Solar and other companies. Because amorphous silicon solar cells tend to have low efficiency, a triple-junction amorphous silicon solar cell can have a similar or even lower efficiency than a single-junction crystalline silicon solar cell. The advantages of tandem amorphous-silicon solar cells (compared to conventional non-tandem solar cells) is not higher efficiency, but lower cost and the possibility of using flexible substrates.

Impurity photovoltaics

There has been some work on the use of deliberate impurities to produce mid-energy states within single crystal structures. These cells would combine some of the advantages of the multi-junction cell with the simplicity of existing silicon designs. A detailed limit calculation for these cells with a wide variety of impurities suggests a maximum efficiency of 77.2% To date, no commercial cell using this technique has been produced.

Infrared capture

Approximately half of the solar energy reaching the Earth's surface is in the near and far infrared (IR). In silicon the energy of the bandgap is higher than the energy of these photons, and they do not contribute to energy production. Losing this energy limits cell efficiency to about 50% even if one ignores the other factors included in the Shockley–Queisser limit.

Various solutions to this problem have been proposed. The most obvious solution is to use a semiconductor with a lower bandgap that is suitable for capturing IR energy. This solution actually *lowers* efficiency, however, because it means more of the energy in the higher-frequency photons is lost. For this reason almost all IR-capture efforts are based on using two-layer cells with a conventional cell on top and an IR-sensitive one on the bottom. These cells have a fundamental limit the same as any other two-layer cell, at about 42%. Unlike the existing tandem cells, however, a conventional silicon cell can be used as the upper layer, which should be much less expensive to produce.

Although there have been a number of potential solutions to producing IR cells, none has reached commercial use.

Recently the two-photon photovoltaic effect has been demonstrated in silicon. This phenomenon which occurs at very high optical intensities allows infrared photons to be captured in conventional silicon and can improve the efficiency of standard silicon solar cells if sun light can be sufficiently concentrated.

Hot electron capture

Since much of the Shockley–Queisser limit is due to energy losses between the photon energy and the energy captured from the electrons they produce, it should be no surprise that there has been a considerable amount of research into ways to capture the energy of the electrons before they can lose it in the crystal structure. A related concept is to use photoproducers that release more than one electron, instead of a single electron of greater energy. There has been a considerable amount of effort investigating quantum dots for both of these roles.

Fluorescent downconversion

Another possibility for increased efficiency is to convert the frequency of light down towards the bandgap energy with a fluorescent material. Some fluorescent materials will convert a single high-energy photon into several lower-energy ones, although this conversion process tends to be relatively inefficient. On the upside, such a material could be painted on the front surface of an otherwise standard cell, boosting its efficiency for little cost. Overall operation of such a cell is similar to the quantum-dot case, releasing more electrons of lower energy and producing more energy overall.

Recent studies have discovered a new class of materials that can be tuned to produce electrons of any energy from light across the entire solar spectrum. In theory, these materials could capture all of the energy, and would be limited by optical issues (reflection off the front face, etc.), not the Shockley–Queisser limit.

Even without these sorts of materials, another use of fluorescence is to produce a low-cost concentrator system. In this concept, sheets of clear plastic are dyed with fluorescent paint. When the dye re-radiates the light falling on the front of the plate, it is trapped within the plastic and travels fiber optic-like to the edges of the sheet. Cells on the edges will see about 40 times concentration, far from the area of peak efficiency of GaAs cells, but without any need for tracking - light falling on the plate from any angle will still be sent to the edges.

Thermophotovoltaic downconversion

Thermophotovoltaic cells are similar to phosphorescent systems, but use a plate to act as the downconvertor. Solar energy falling on the plate, typically black-painted metal, is re-emitted as lower-energy IR, which can then be captured in an IR cell. This relies on a practical IR cell being available, but the theoretical conversion efficiency can be calculated. For a converter with a bandgap of 0.92 eV, efficiency is limited to 54% with a single-junction cell, and 85% for concentrated light shining on ideal components with no optical losses and only radiative recombination.

Chapter 16

Solar Inverter & Solar Simulator

Solar Inverter

A **Solar inverter** or **PV inverter** is a type of electrical inverter that is made to change the direct current (DC) electricity from a photovoltaic array into alternating current (AC) for use with home appliances and possibly a utility grid.

A PV inverter installed in an attic

Solar inverters may be classified into three broad types:

- Stand-alone inverters, used in isolated systems where the inverter draws its DC energy from batteries charged by photovoltaic arrays and/or other sources, such as wind turbines, hydro turbines, or engine generators. Many stand-alone inverters also incorporate integral battery chargers to replenish the battery from an AC source, when available. Normally these do not interface in any way with the utility grid, and as such, are not required to have anti-islanding protection.

- Grid tie inverters, which match phase with a utility-supplied sine wave. Grid-tie inverters are designed to shut down automatically upon loss of utility supply, for safety reasons. They do not provide backup power during utility outages.

- Battery backup inverters. These are special inverters which are designed to draw energy from a battery, manage the battery charge via an onboard charger, and export excess energy to the utility grid. These inverters are capable of supplying AC energy to selected loads during a utility outage, and are required to have anti-islanding protection.

Solar inverters use special procedures to deal with the PV array, including *maximum power point tracking* and *anti-islanding protection*.

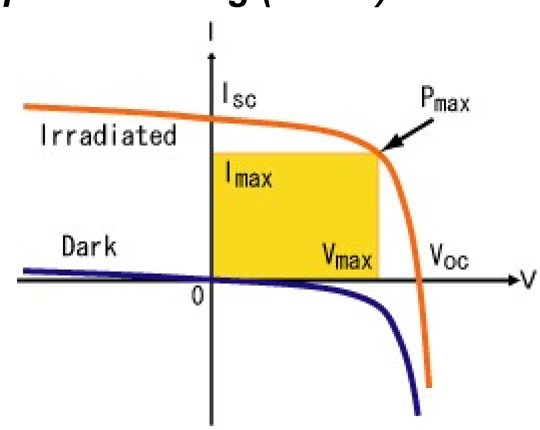
Anti-islanding protection

Normally, grid-tied inverters will shut off if they do not detect the presence of the utility grid. If, however, there are load circuits in the electrical system that happen to resonate at the frequency of the utility grid, the inverter may be fooled into thinking that the grid is still active even after it had been shut down. This is called islanding.

An inverter designed for grid-tie operation will have anti-islanding protection built in; it will inject small pulses that are slightly out of phase with the AC electrical system in order to cancel any stray resonances that may be present when the grid shuts down.

Since 1999, the standard for anti-islanding protection in the United States has been UL 1741, harmonized with IEEE 1547. Any inverter which is listed to the UL 1741 standard may be connected to a utility grid without the need for additional anti-islanding equipment, anywhere in the United States or other countries where UL standards are accepted.

Maximum power point tracking (MPPT)



I-V curve for a solar cell, showing the maximum power point *Pmax*

Maximum power point tracking is a technique that solar inverters use to get the most possible power from the PV array. Any given PV module or string of modules will have a *maximum power point*: essentially, this defines current that the inverter should draw from the PV in order to get the most possible power (power is equal to voltage times current).

Grid tie inverters

Many solar inverters are designed to be connected to a utility grid, and will not operate when they do not detect the presence of the grid. They contain special circuitry to precisely match the voltage and frequency of the grid.

Solar pumping inverters

Advanced solar pumping inverters convert DC voltage from the solar array into AC voltage to drive submersible pumps directly without the need for batteries or other energy storage devices. By utilizing MPPT (maximum power point tracking), solar pumping inverters regulate output frequency to control speed of the pumps in order to save pump motor from damage.

Charge controllers

Stand-alone inverters – that is, inverters that are designed to be used without the presence of the electrical utility grid – can be run from PV panels and batteries using a charge controller. The charge controller regulates the input from the PV and the batteries, regulates the battery output, and handles charging the batteries.

Solar Simulator

A **solar simulator** (also **artificial sun**) is a device that provides illumination approximating natural sunlight. The purpose of the solar simulator is to provide a controllable indoor test facility under laboratory conditions, used for the testing of solar cells, sun screen, plastics, and other materials and devices.

Classification

The ASTM E927-05 standard is a common specification for solar simulators used for photovoltaic testing. The light from a solar simulator is controlled in three dimensions:

1. spectral content
2. spatial uniformity
3. temporal stability

Each dimension is classified in one of three classes: A, B, or C. The specifications required for each class are defined in Table 1 below. A solar simulator meeting class A specifications in all three dimensions is referred to as a Class A solar simulator, or sometimes a Class AAA (referring to each of the dimensions in the order listed above) .

Table 1: ASTM class specifications

Classification	Spectral Match (each interval)	Irradiance Spatial Non-Uniformity	Irradiance Temporal Instability
Class A	0.75 - 1.25	2%	2%
Class B	0.6 - 1.4	5%	5%
Class C	0.4 - 2.0	10%	10%

The solar simulation spectrum is further specified via the integrated irradiance across several wavelength intervals. The percentage of total irradiance is shown below in Table 2 for the standard terrestrial spectra of AM1.5G and AM1.5D, and the extraterrestrial spectrum, AM0.

Table 2: ASTM spectral irradiance for three standard spectra

Wavelength Interval [nm]	AM1.5D	AM1.5G	AM0
300-400	no spec	no spec	8.0%
400-500	16.9%	18.4%	16.4%
500-600	19.7%	19.9%	16.3%
600-700	18.5%	18.4%	13.9%
700-800	15.2%	14.9%	11.2%
800-900	12.9%	12.5%	9.0%
900-1100	16.8%	15.9%	13.1%
1100-1400	no spec	no spec	12.2%

These specifications were primarily intended for silicon photovoltaics, and hence the spectral range over which the intervals were defined was limited mainly to the absorption region of silicon. While this definition is also adequate for several other photovoltaic technologies, including thin film solar cells constructed from CdTe or CIGS, it is not sufficient for the emerging sub-field of concentrated photovoltaics using high-efficiency III-V semiconductor multi-junction solar cells due to their wider absorption bandwidth of 300-1800 nm.

Types of Solar Simulators

Solar simulators can be divided into three broad categories: continuous, flashed, and pulsed. The first type is a familiar form of light source in which illumination is continuous in time. The specifications discussed in the previous section most directly relate to this type of solar simulator. This category is most often used for low intensity testing, from less than 1 sun up to several suns. In this context, 1 sun is typically defined as the nominal full sunlight intensity on a bright clear day on Earth, which measures 1000 W/m^2. Examples of low-intensity and high-intensity continuous sources are the Newport Oriel and Spectrolab XT-30 solar simulators.

The second type of solar simulator is the flashed simulator, which is qualitatively similar to flash photography and use flash tubes. With typical durations of several milliseconds, very high intensities of up to several thousand suns are possible. This type of equipment is often used to prevent unnecessary heat build-up in the device under test. However, due to the rapid heating and cooling of the lamp, the intensity and light spectrum are inherently transient, making repeated reliable testing more technically challenging. The temporal stability dimension of the standard does not directly apply to this category of solar simulators, although it can be replaced by an analogous shot-to-shot repeatability specification.

The third type of solar simulator is the pulsed simulator, which uses a shutter to quickly block or unblock the light from a continuous source. This category is a compromise between the continuous and flash, having the disadvantage of the high power usage and relatively low intensities of the continuous simulators, but advantage of stable output intensity and spectrum and low thermal loads of flashed simulators. Pulses are typically on the order of 100 milliseconds.

Types of Lamps

Several types of lamps have been used as the light sources within solar simulators.

Xenon arc lamp: this is the most common type of lamp both for continuous and flashed solar simulators. These lamps offer high intensities and an unfiltered spectrum which matches reasonably well to sunlight. However, the Xe spectrum is also characterized by many undesirable sharp atomic transitional peaks, making the spectrum less desirable for some spectrally-sensitive applications. Xe arc lamps can be designed for low powers or up to several kilowatts, providing the means for small- or large- area illumination, and low to high intensities.

QTH: quartz tungsten halogen lamps offer spectra which very closely match black body radiation, although typically with a lower color temperature than the sun.

LED: light-emitting diodes have recently been used in research laboratories to construct solar simulators, and may offer promise in the future for energy-efficient production of spectrally-tailored artificial sunlight.

Chapter 17

Space Solar Power

Space solar power (**SSP**) is a system for the collection of solar power in space, for use on Earth. SBSP differs from the usual method of solar power collection in that the solar panels used to collect energy would reside on a satellite in orbit, often referred to as a **solar power satellite** (SPS), rather than on Earth's surface. In space, collection of the Sun's energy is unaffected by the various obstructions which reduce efficiency or capacities of Earth surface solar power collection.

Solar energy reaching Earth's orbit is 144% of the maximum found on the surface of Earth, and includes wavelengths that don't even reach the surface due to the atmosphere. The length of time the solar collection panels can be exposed to a consistently high amount of solar radiation is also much longer in orbit: For most of the year, a satellite-based solar panel can collect power 24 hours per day, whereas a terrestrial station can collect for, at most, 12 hours per day. Collection at Earth's poles can take place for 24 hours per day, but not consistently, and only for 6 months of the year. Weather is also normally a concern for surface collectors, but would not affect an orbiting satellite.

A collecting satellite might also be able to direct power to different surface locations based on which areas need it most.

Collection of solar energy in space for use on Earth introduces several problems as well, primarily the transmission of energy from the collecting satellite to Earth's surface for use. Since wires extending from Earth's surface to an orbiting satellite are neither practical nor currently possible, many SBSP designs have proposed the use of wireless power transmission. The collecting satellite would convert solar energy into electrical energy, powering an emitter of some kind, such as microwave or laser, oriented toward a collector on the Earth's surface.

Some panel degradation problems normally associated with terrestrial solar power collection would be entirely avoided by such a design, for example contamination or corrosion and damage by wildlife or plant encroachment. Other problems could be encountered, though, such as more rapid radiation damage or micrometeoroid impacts.

Timeline

- **1968**: Dr. Peter Glaser introduced the idea of a large solar power satellite system with square miles of solar collectors in high geosynchronous orbit (GEO is an orbit 36,000 km above the equator), for collection and conversion of sun's energy into an electromagnetic microwave beam to transmit usable energy to large receiving antennas (rectennas) on Earth for distribution.

- **1973**: Dr. Peter Glaser was granted U.S. patent number 3,781,647 for his method of transmitting power over long distances (e.g., from an SPS to the Earth's surface) using microwaves from a large (on the close order of one square kilometer) antenna on the satellite to a much larger one on the ground, now known as a rectenna.

- **1970s**: United States Department of Energy and NASA examined the Solar Power Satellite (SPS) concept extensively, publishing the design and feasibility studies.

- **1994**: The United States Air Force conducted the Advanced Photovoltaic Experiment using a satellite launched into low Earth orbit by a Pegasus rocket.

- **1995–1997**: NASA conducted a "Fresh Look" study of space solar power (SSP) concepts and technologies.

- **1998**: Space Solar Power Concept Definition Study (CDS) identified credible commercially viable SSP concepts, identifying technical and programmatic risks.

- **1998**: Japan's space agency starts a program for developing a Space Solar Power System (SSPS), which continues to the present day.

- **1999**: NASA's Space Solar Power Exploratory Research and Technology program program begun.

- **2000**: John Mankins of NASA testified in the U.S. House of Representatives, saying "Large-scale SSP is a very complex integrated system of systems that requires numerous significant advances in current technology and capabilities. A technology roadmap has been developed that lays out potential paths for achieving all needed advances — albeit over several decades.

- **2001**: PowerSat Corporation founded by William Maness.

- **2001**: Dr. Neville Marzwell of NASA stated, "We now have the technology to convert the sun's energy at the rate of 42 to 56 percent... We have made tremendous progress. ...If you can concentrate the sun's rays through the use of large mirrors or lenses you get more for your money because most of the cost is in the PV arrays... There is a risk element but you can reduce it... You can put these small receivers in the desert or in the mountains away from populated areas. ...We believe that in 15 to 25 years we can lower that cost to 7 to 10 cents per kilowatt hour. ...We offer an advantage. You don't need cables, pipes, gas or copper wires. We can send it to you like a cell phone call—where you want it and when you want it, in real time."

- **2001**: NASDA (Japan's national space agency) announced plans to perform additional research and prototyping by launching an experimental satellite with 10 kilowatts and 1 megawatt of power.

- **2007**: The US Pentagon's National Security Space Office (NSSO) issued a report on October 10, 2007 stating they intend to collect solar energy from space for use on Earth to help the United States' ongoing relationship with the Middle East and the battle for oil. The International Space Station may be the first test ground for this new idea, even though it is in a low-earth orbit.

- **2007**: In May 2007 a workshop was held in the USA at the Massachusetts Institute of Technology (MIT) to review the current state of the market and technology.

- **2009**: A new company from the US, Space Energy, Inc., announced plans to provide commercial space-based solar power. They say they have developed a "rock-solid business platform" and should be able to provide space-based solar power within a decade.

- **2009**: American company Pacific Gas and Electric (PG&E) announced it is seeking regulatory approval for an agreement with Solaren to buy 200 MW of solar power, starting in 2016, which Solaren has plans to provide via SBSP. PG&E spokesman Jonathan Marshall stated that "We've been very careful not to bear risk in this."

- **2009**: PowerSat Corporation filed a patent application concerning ganging multiple power satellites to form a single coherent microwave beam, and a mechanism to use the solar array to power ion thrusters to lift a power satellite from low Earth orbit to geostationary orbit.

- **2009**: Jaxa, the Japan Aerospace Exploration Agency announced plans to orbit solar power satellites that will transmit energy back to earth via microwaves. They hope to have the first prototype orbiting by 2030.

- **2010**: Europe's largest space company EADS Astrium plans to put a solar-collecting demo satellite in space.

- **2010**: Prof. Andrea Massa and Prof. Giorgio Franceschetti will organize a Special Session on the "Analysis of Electromagnetic Wireless Systems for Solar Power Transmission" at the 2010 Institute of Electrical and Electronics Engineers International Symposium on Antennas and Propagation.

History

The SBSP concept, originally known as *Satellite Solar Power System* ("SSPS") was first described in November 1968. In 1973 Peter Glaser was granted U.S. patent number 3,781,647 for his method of transmitting power over long distances (e.g., from an SPS to the Earth's surface) using microwaves from a very large (up to one square kilometer) antenna on the satellite to a much larger one on the ground, now known as a rectenna.

Glaser then worked at Arthur D. Little, Inc., as a vice-president. NASA signed a contract with ADL to lead four other companies in a broader study in 1974. They found that, while the concept had several major problems—chiefly the expense of putting the required materials in orbit and the lack of experience on projects of this scale in space, it showed enough promise to merit further investigation and research.

Between 1978 and 1981, the Congress authorized the Department of Energy and NASA to jointly investigate the concept. They organized the Satellite Power System Concept Development and Evaluation Program. The study remains the most extensive performed to date. Several reports were published investigating the engineering feasibility of such an engineering project. They include:

- Resource Requirements (Critical Materials, Energy, and Land)
- Financial/Management Scenarios
- Public Acceptance
- State and Local Regulations as Applied to Satellite Power System Microwave Receiving Antenna Facilities
- Student Participation
- Potential of Laser for SBSP Power Transmission
- International Agreements
- Centralization/Decentralization
- Mapping of Exclusion Areas For Rectenna Sites
- Economic and Demographic Issues Related to Deployment
- Some Questions and Answers
- Meteorological Effects on Laser Beam Propagation and Direct Solar Pumped Lasers
- Public Outreach Experiment
- Power Transmission and Reception Technical Summary and Assessment
- Space Transportation

The project was not continued with the change in Administrations after the 1980 US Federal elections.

The Office of Technology Assessment concluded

Too little is currently known about the technical, economic, and environmental aspects of SPS to make a sound decision whether to proceed with its development and deployment.

In addition, without further research an SPS demonstration or systems-engineering verification program would be a high-risk venture.

More recently, the SBSP concept has again become interesting, due to increased energy demand, increased energy costs, and emission implications, starting in 1997 with the NASA "Fresh Look". In assessing "What has changed" since the DOE study, this study asserts that

Another important change has occurred at the US national policy level. US National Space Policy now calls for NASA to make significant investments in technology (not a particular vehicle) to drive the costs of ETO *[Earth to Orbit]* transportation down dramatically. This is, of course, an absolute requirement of space solar power.

One might take the NASA "Fresh Look" study as encouraging because the main difficulty identified is driving down Earth to Orbit costs. However, Dr. Pete Worden claimed that space-based solar is about five orders of magnitude more expensive than solar power from the Arizona desert. A major factor in this five orders of magnitude is the cost of transporting materials to orbit. Dr. Worden referred to possible solutions as speculative solutions that would not be available for decades at the best, leaving space-based solar power with no business case for the foreseeable future.

SERT

In 1999 NASA's Space Solar Power Exploratory Research and Technology program (SERT) was initiated for the following purpose:

- Perform design studies of selected flight demonstration concepts;
- Evaluate studies of the general feasibility, design, and requirements.
- Create conceptual designs of subsystems that make use of advanced SSP technologies to benefit future space or terrestrial applications.
- Formulate a preliminary plan of action for the U.S. (working with international partners) to undertake an aggressive technology initiative.
- Construct technology development and demonstration roadmaps for critical Space Solar Power (SSP) elements.

It was to develop a solar power satellite (SPS) concept for a future gigawatt space power systems to provide electrical power by converting the Sun’s energy and beaming it to the Earth's surface. It was also to provide a developmental path to solutions for current space power architectures. Subject to further study, it proposed an inflatable photovoltaic gossamer structure with concentrator lenses or solar heat engines to convert sunlight into electricity. The program looked at both systems in sun-synchronous orbit and geosynchronous orbit.

Some of SERT's conclusions include the following:

- The increasing global energy demand is likely to continue for many decades resulting in new power plants of all sizes being built.
- The environmental impact of those plants and their impact on world energy supplies and geopolitical relationships can be problematic.
- Renewable energy is a compelling approach, both philosophically and in engineering terms.
- Many renewable energy sources are limited in their ability to affordably provide the base load power required for global industrial development and prosperity, because of inherent land and water requirements.
- Based on their Concept Definition Study, space solar power concepts may be ready to reenter the discussion.
- Solar power satellites should no longer be envisioned as requiring unimaginably large initial investments in fixed infrastructure before the emplacement of productive power plants can begin.
- Space solar power systems appear to possess many significant environmental advantages when compared to alternative approaches.
- The economic viability of space solar power systems depends on many factors and the successful development of various new technologies (not least of which is the availability of much lower cost access to space than has been available), however, the same can be said of many other advanced power technologies options.
- Space solar power may well emerge as a serious candidate among the options for meeting the energy demands of the 21st century.

Advantages

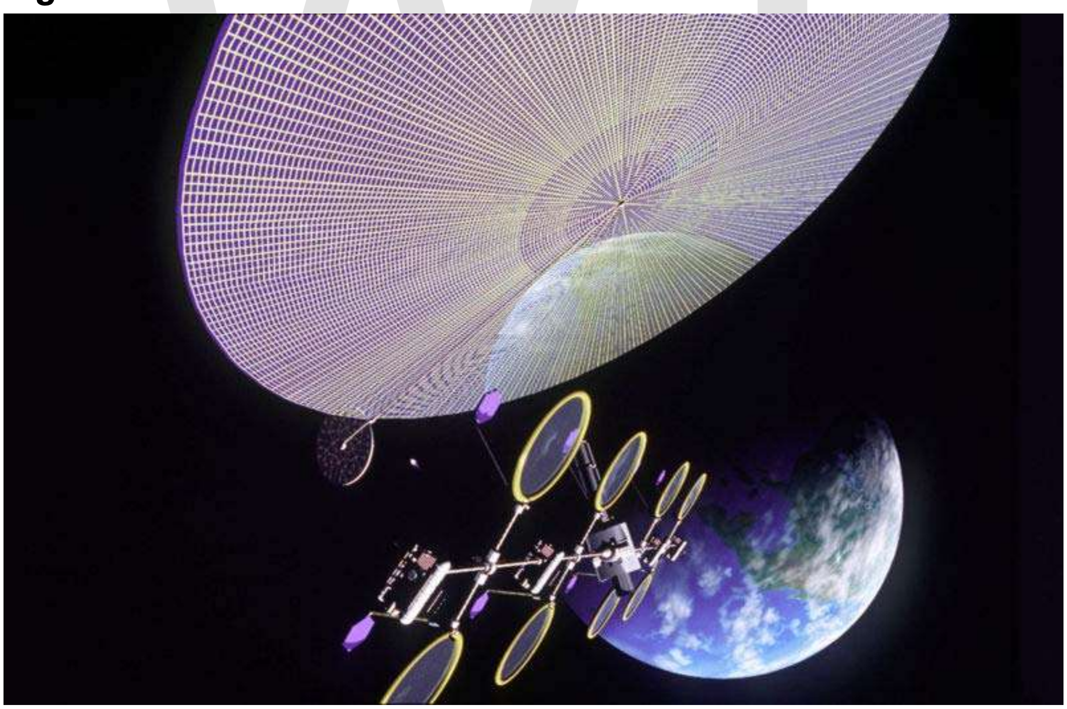
The SBSP concept is attractive because space has several major advantages over the Earth's surface for the collection of solar power. There is no air in space, so the collecting surfaces would receive much more intense sunlight, unaffected by weather. In geostationary orbit, an SPS would be illuminated over 99% of the time; such an SPS would be in Earth's shadow on only a few days at the spring and fall equinoxes; and even then for a maximum of 75 minutes late at night when power demands are at their lowest. This characteristic of SBSP avoids the expense of storage facilities (dams, oil storage tanks, coal dumps) necessary in many Earth-based power generation systems. Additionally, SBSP would have fewer or none of the ecological (or political) consequences of fossil fuel systems.

SBSP would also be applicable on a global scale. Nuclear power raises questions of proliferation and waste disposal, which pose problems everywhere, but especially in undeveloped areas which are less capable of coping with them. SBSP poses no such known potential threat.

This technology can be of value to relief efforts in disaster areas. SBSP could step in at short notice to provide as much power as is necessary both for the relief effort and to provide continuity of energy until ground based transfer methods are restored.

There is a significant military advantage to SBSP in that it would provide the option to have almost instantaneous sustained power nearly anywhere on the globe. It has been estimated that the average price of fuel for the US Army exceeds $5 per gallon. During Operation Iraqi Freedom, there is an estimate that fuel costs in some areas approached $20 per gallon. This is undoubtedly due to the cost of physically moving large quantities of fuel, and the massive security costs in protecting these convoys in a war zone. The estimated costs given above do not include the high cost in the lives of American servicemen and women who are killed or injured during attacks on supply convoys. With a mobile SBSP receiving station, the Army could quickly be provided with megawatts of clean, sustained energy. If a conflict forced a rapid change in the geographic location of Army personnel, the power from SBSP could simply be redirected by altering the position of the SBSP satellites. If SBSP became an established source of power, it could also provide a military benefit in that the supply would inherently be much more secure than traditional energy delivery methods, chances of an energy scarcity based conflict could be much reduced.

Design



Space-based solar power essentially consists of three parts:

1. a means of collecting solar power in space, for example via solar cells or a heat engine
2. a means of transmitting power to earth, for example via microwave or laser

3. a means of receiving power on earth, for example via a microwave antenna (rectenna)

The space-based portion will be in a freefall, vacuum environment and will not need to support itself against gravity other than relatively weak tidal stresses. It needs no protection from terrestrial wind or weather, but will have to cope with space-based hazards such as micrometeors and solar storms.

Solar energy conversion (solar photons to DC current)

Two basic methods of converting sunlight to electricity have been studied: photovoltaic (PV) conversion, and solar dynamic (SD) conversion.

Most analyses of solar power satellites have focused on photovoltaic conversion (commonly known as “solar cells”). Photovoltaic conversion uses semiconductor cells (*e.g.*, silicon or gallium arsenide) to directly convert photons into electrical power via a quantum mechanical mechanism. Photovoltaic cells are not perfect in practice, as material purity and processing issues during production affect performance; each has been progressively improved for some decades. Some new, thin-film approaches are less efficient (about 20% vs 41% for best in class in each case as of late 2009), but are much less expensive and generally lighter.

In an SPS implementation, photovoltaic cells will likely be rather different from the glass-pane protected solar cell panels familiar to many in current terrestrial use, since they will be optimized for weight, and will be designed to be tolerant of the space radiation environment (some thin film silicon solar panels are highly insensitive to ionising radiation), but will not need to be encapsulated against corrosion from environmental exposure or biological deterioration. They do not require the structural support required for terrestrial use, where the considerable gravity and wind loading imposes structural requirements on terrestrial implementations.

Wireless power transmission to the Earth

Wireless power transmission was proposed early on as a means to transfer energy from collection to the Earth's surface. The power could be transmitted as either microwave or laser radiation at a variety of frequencies depending on system design. Whichever choice is made, the transmitting radiation would have to be non-ionizing to avoid potential disturbances either ecologically or biologically. This established an upper limit for the frequency used, as energy per photon (and consequently the ability to cause ionization) increases with frequency. Ionization of biological materials doesn't begin until ultraviolet or higher frequencies, so most radio frequencies would be feasible.

Microwave power transmission

William C. Brown demonstrated in 1964, during Walter Cronkite's CBS News program, a microwave-powered model helicopter that received all the power it needed for flight from a microwave beam. Between 1969 and 1975, Bill Brown was technical director of a JPL Raytheon program that beamed 30 kW of power over a distance of 1 mile at 84% efficiency.

Microwave power transmission of tens of kilowatts has been well proven by existing tests at Goldstone in California (1975) and Grand Bassin on Reunion Island (1997).

More recently, microwave power transmission has been demonstrated, in conjunction with solar energy capture, between a mountain top in Maui and the main island of Hawaii (92 miles away), by a team under John C. Mankins. Technological challenges in terms of array layout, single radiation element design, and overall efficiency, as well as the associated theoretical limits are presently a subject of research, as it is demonstrated by the upcoming Special Session on "Analysis of Electromagnetic Wireless Systems for Solar Power Transmission" to be held in the 2010 IEEE Symposium on Antennas and Propagation.

Laser power beaming experiments

A large-scale demonstration of power beaming is a necessary step to the development of solar power satellites. Laser power beaming was envisioned by some at NASA as a stepping stone to further industrialization of space.

In the 1980s researchers at NASA worked on the potential use of lasers for space-to-space power beaming, focusing primarily on the development of a solar-powered laser. In 1989 it was suggested that power could also be usefully beamed by laser from Earth to space. In 1991 the SELENE project (SpacE Laser ENErgy) was begun, which included the study of laser power beaming for supplying power to a lunar base.

In 1988 the use of an Earth-based laser to power an electric thruster for space propulsion was proposed by Grant Logan, with technical details worked out in 1989. He proposed using diamond solar cells operating at six hundred degrees to convert ultraviolet laser light, a technology that has yet to be demonstrated even in the laboratory. His ideas were adapted to be more practical.

The SELENE program was a two-year research effort, but the cost of taking the concept to operational status was too high, and the official project was ended in 1993, before reaching a space-based demonstration.

Spacecraft sizing

The size of a solar power satellite would be dominated by two factors: the size of the collecting apparatus (e.g. panels and mirrors), and the size of the transmitting antenna. The distance from Earth to geostationary orbit (22,300 miles, 35,700 km), the chosen wavelength of the microwaves, and certain laws of physics (specifically the Rayleigh Criterion or diffraction limit) will all be factors.

It has been suggested that, for best efficiency, the satellite antenna should be circular and about 1 kilometer in diameter or larger; the ground antenna (rectenna) should be elliptical, 10 km wide, and a length that makes the rectenna appear circular from GEO (Geostationary Orbit). (Typically, 14 km at some North American latitudes.) Smaller antennas would result in increased losses to diffraction/sidelobes. For the desired (23 mW/cm²) microwave intensity these antennas could transfer between 5 and 10 gigawatts of power.

According to some research, to collect and convert the target volume of power, the satellite would require between 50 and 100 square kilometers of collector area (if readily available ~14% efficient monocrystalline silicon solar cells were deployed). State of the art multi-junction solar cells with a maximum efficiency of 43% could reduce the necessary collector area by two thirds. In any case, an SPS's structure will necessarily be large (perhaps kilometers across), making it larger than most man-made structures on Earth, and building structures of such size in orbit has never been attempted.

Location

GEO

The main advantage of locating a space power station in geostationary orbit is that the antenna geometry stays constant, and so keeping the antennas lined up is simpler. Another advantage is that nearly continuous power transmission is immediately available as soon as the first space power station is placed in orbit; other space-based power stations have much longer start-up times before they are producing nearly continuous power.

LEO/MEO instead of GEO

A collection of LEO (Low Earth Orbit) space power stations has been proposed as a precursor to GEO (Geostationary Orbit) space-based solar power. There would be both advantages (shorter energy transmission path, lower cost) and disadvantages (frequent changes in antenna geometries, increased debris collisions, more power stations needed to receive power continuously). It might be possible to deploy LEO systems sooner than GEO because the antenna development would take less time, but it may take longer to prepare and launch the number of required satellites.

Moon

People such as David Criswell suggest that the moon is the optimum location for solar power stations, and promote **lunar solar power**.

The main advantages of locating the solar power collector on the moon is that most of its mass could be constructed out of locally available lunar materials, using in-situ resource utilization, significantly reducing the amount of mass and therefore the launch costs required compared to other space-based solar power stations.

Earth-based infrastructure

The Earth-based receiver antenna (or rectenna) is a critical part of the original SPS concept. It would probably consist of many short dipole antennas, connected via diodes. Microwaves broadcast from the SPS will be received in the dipoles with about 85% efficiency. With a conventional microwave antenna, the reception efficiency is still better, but the cost and complexity is also considerably greater, almost certainly prohibitively so. Rectennas would be multiple kilometers across. Crops and farm animals may be raised underneath a rectenna, as the thin wires used for support and for the dipoles will only slightly reduce sunlight, or non arable land could be used, so such a rectenna would not be as expensive in terms of land use as might be supposed.

Dealing with launch costs

One problem for the SBSP concept is the cost of space launches and the amount of material that would need to be launched.

Reusable launch systems are predicted to provide lower launch costs to low Earth orbit (LEO).

Much of the material launched need not be delivered to its eventual orbit immediately, which raises the possibility that high efficiency (but slower) engines could move SPS material from LEO to GEO at an acceptable cost. Examples include ion thrusters or nuclear propulsion.

Power beaming from geostationary orbit by microwaves carries the difficulty that the required 'optical aperture' sizes are very large. For example, the 1978 NASA SPS study 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 they have increased atmospheric absorption and even potential 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. The large size of the transmitting and receiving antennas means that the minimum practical power level for an SPS will necessarily be high; small SPS systems will be possible, but uneconomic.

To give an idea of the scale of the problem, assuming a solar panel mass of 20 kg per kilowatt (without considering the mass of the supporting structure, antenna, or any significant mass reduction of any focusing mirrors) a 4 GW power station would weigh about 80,000 metric tons, all of which would, in current circumstances, be launched from the Earth. Very lightweight designs could likely achieve 1 kg/kW, meaning 4,000 metric tons for the solar panels for the same 4 GW capacity station. This would be the equivalent of between 40 and 150 heavy-lift launch vehicle (HLLV) launches to send the material to low earth orbit, where it would likely be converted into subassembly solar arrays, which then could use high-efficiency ion-engine style rockets to (slowly) reach GEO (Geostationary orbit). With an estimated serial launch cost for shuttle-based HLLVs of $500 million to $800 million, and launch costs for alternative HLLVs at $78 million, total launch costs would range between $11 billion (low cost HLLV, low weight panels) and $320 billion ('expensive' HLLV, heavier panels). For comparison, the direct cost of a new coal or nuclear power plant ranges from $1 billion to $1.5 billion dollars per GW (not including the full cost to the environment from CO2 emissions or storage of spent nuclear fuel, respectively); another example is the Apollo missions to the Moon cost a grand total of $24 billion (1970's dollars), taking inflation into account, would cost $140 billion today, more expensive than the construction of the International Space Station.

Building from space

Gerard O'Neill, noting the problem of high launch costs in the early 1970s, proposed building the SPS's in orbit with materials from the Moon. Launch costs from the Moon are potentially much lower than from Earth, due to the lower gravity. This 1970s proposal assumed the then-advertised future launch costing of NASA's space shuttle. This approach would require substantial up front capital investment to establish mass drivers on the Moon.

Nevertheless, on 30 April 1979, the Final Report ("Lunar Resources Utilization for Space Construction") by General Dynamics' Convair Division, under NASA contract NAS9-15560, concluded that use of lunar resources would be cheaper than Earth-based materials for a system of as few as thirty Solar Power Satellites of 10GW capacity each.

In 1980, when it became obvious NASA's launch cost estimates for the space shuttle were grossly optimistic, O'Neill et al. published another route to manufacturing using lunar materials with much lower startup costs. This 1980s SPS concept relied less on human presence in space and more on partially self-replicating systems on the lunar surface under remote control of workers stationed on Earth. This proposal suffers from the current lack of such automated systems. The design and construction of these automated systems and their use to produce a mass driver launching system on the moon from lunar materials is expected to take more than twenty years. The partially self replicating systems would include locally produced power generation, perhaps solar cells or heat engine produced electrical power.

Asteroid mining has also been seriously considered. A NASA design study evaluated a 10,000 ton mining vehicle (to be assembled in orbit) that would return a 500,000 ton asteroid fragment to geostationary orbit. Only about 3,000 tons of the mining ship would be traditional aerospace-grade payload. The rest would be reaction mass for the mass-driver engine, which could be arranged to be the spent rocket stages used to launch the payload. Assuming that 100% of the returned asteroid was useful, and that the asteroid miner itself couldn't be reused, that represents nearly a 95% reduction in launch costs. However, the true merits of such a method would depend on a thorough mineral survey of the candidate asteroids; thus far, we have only estimates of their composition.

Having a relatively cheap per pound source of raw materials from space would lessen the concern for low mass designs and result in a different sort of SPS being built. The low cost per pound of lunar materials in O'neill's vision would be supported by using lunar material to manufacture more facilities in orbit than just solar power satellites.

Non-conventional launch methods

SBSP costs might be reduced if a means of putting the materials into orbit were developed that did not rely on rockets. Some possible technologies include ground launch systems such as mass drivers or Lofstrom loops, which would launch using electrical power, or the geosynchronous orbit space elevator. However, these require technology that is yet to be developed. John Hunter of Quicklaunch is working on commercialising the 'Hydrogen Gun', a new form of mass driver which proposes to deliver unmanned payloads to orbit for around 5% of regular launch costs (or $500 per pound; US$1,000 *per* kilogram) and perform 5 launches per day.

Advanced techniques for launching from the moon may reduce the cost of building a solar power satellite from lunar materials. Some proposed techniques include the lunar mass driver and the lunar space elevator, first described by Jerome Pearson. It would require establishing silicon mining and solar cell manufacturing facilities on the Moon.

Counter arguments

Safety

The use of microwave transmission of power has been the most controversial issue in considering any SPS design.

At the Earth's surface, a suggested microwave beam would have a maximum intensity at its center, of 23 mW/cm^2 (less than 1/4 the solar irradiation constant), and an intensity of less than 1 mW/cm^2 outside of the rectenna fenceline (the receiver's perimeter). These compare with current United States Occupational Safety and Health Act (OSHA) workplace exposure limits for microwaves, which are 10 mW/cm^2, - the limit itself being expressed in voluntary terms and ruled unenforceable for Federal OSHA enforcement purposes. A beam of this intensity is therefore at its center, of a similar magnitude to current safe workplace levels, even for long term or indefinite exposure. Outside the receiver, it is far less than the OSHA long-term levels Over 95% of the beam energy will fall on the rectenna. The remaining microwave energy will be absorbed and dispersed well within standards currently imposed upon microwave emissions around the world. It is important for system efficiency that as much of the microwave radiation as possible be focused on the rectenna. Outside of the rectenna, microwave intensities rapidly decrease, so nearby towns or other human activity should be completely unaffected.

Exposure to the beam is able to be minimized in other ways. On the ground, physical access is controllable (e.g., via fencing), and typical aircraft flying through the beam provide passengers with a protective metal shell (i.e., a Faraday Cage), which will intercept the microwaves. Other aircraft (balloons, ultralight, etc.) can avoid exposure by observing airflight control spaces, as is currently done for military and other controlled airspace.

The microwave beam intensity at ground level in the center of the beam would be designed and physically built into the system; simply, the transmitter would be too far away and too small to be able to increase the intensity to unsafe levels, even in principle.

In addition, a design constraint is that the microwave beam must not be so intense as to injure wildlife, particularly birds. Experiments with deliberate microwave irradiation at reasonable levels have failed to show negative effects even over multiple generations.

Some have suggested locating rectennas offshore, but this presents serious problems, including corrosion, mechanical stresses, and biological contamination.

A commonly proposed approach to ensuring fail-safe beam targeting is to use a retrodirective phased array antenna/rectenna. A "pilot" microwave beam emitted from the center of the rectenna on the ground establishes a phase front at the transmitting antenna. There, circuits in each of the antenna's subarrays compare the pilot beam's phase front with an internal clock phase to control the phase of the outgoing signal. This forces the transmitted beam to be centered precisely on the rectenna and to have a high degree of phase uniformity; if the pilot beam is lost for any reason (if the transmitting antenna is turned away from the rectenna, for example) the phase control value fails and the microwave power beam is automatically defocused. Such a system would be physically incapable of focusing its power beam anywhere that did not have a pilot beam transmitter.

The long-term effects of beaming power through the ionosphere in the form of microwaves has yet to be studied, but nothing has been suggested which might lead to any significant effect.

Atmospheric damage due to launches

When hot rocket exhaust reacts with atmospheric nitrogen, it can form nitrogen compounds. In particular these nitrogen compounds are problematic when they form in the stratosphere, as they can damage the ozone layer. However, the environmental effect of rocket launches is negligible compared to higher volume polluters, such as airplanes and automobiles.