International Journal of Trend in Scientific Research and Development (IJTSRD)
Special Issue on Interdisciplinary Horizons in Multidisciplinary Studies
Research and Analysis | January 2024
Available Online: www.ijtsrd.com e-ISSN: 2456 – 6470

Recent Advances in Solar Cell Technology and Future Aspects in India

Dr. Dipti Mathur

S.S. Jain Subodh PG Autonomous College, Jaipur, Rajasthan, India

ABSTRACT

A solar cell or photovoltaic cell (PV cell) is an electronic device that converts the energy of light directly into electricity by means of the photovoltaic effect.[1] It is a form of photoelectric cell, a device whose electrical characteristics (such as current, voltage, or resistance) vary when exposed to light. Individual solar cell devices are often the electrical building blocks of photovoltaic modules, known colloquially as "solar panels". The common single-junction silicon solar cell can produce a maximum open-circuit voltage of approximately 0.5 to 0.6 volts.[2]

Photovoltaic cells may operate under sunlight or artificial light. In addition to producing energy, they can be used as a photodetector (for example infrared detectors), detecting light or other electromagnetic radiation near the visible range, or measuring light intensity.

KEYWORDS: *solar cell, technology, aspects, advances, India*

INTRODUCTION:-

The operation of a PV cell requires three basic attributes:

- The absorption of light, generating excitons (bound electron-hole pairs), unbound electron-hole pairs (via excitons), or plasmons.
- The separation of charge carriers of opposite types.
- The separate extraction of those carriers to an external circuit.

In contrast, a solar thermal collector supplies heat by absorbing sunlight, for the purpose of either direct heating or indirect electrical power generation from heat. A "photoelectrolytic cell" (photoelectrochemical cell), on the other hand, refers either to a type of photovoltaic cell (like that developed by Edmond Becquerel and modern dye-sensitized solar cells), or to a device that splits water directly into hydrogen and oxygen using only solar illumination.

Photovoltaic cells and solar collectors are the two means of producing solar power.

Applications

Assemblies of solar cells are used to make solar modules that generate electrical power from sunlight, as distinguished from a "solar thermal module" or "solar hot water panel". A solar array generates solar power using solar energy.

Vehicular applications

Application of solar cells as an alternative energy source for vehicular applications is a growing industry. Electric vehicles that operate off of solar energy and/or sunlight are commonly referred to as solar cars. These vehicles use solar panels to convert absorbed light into electrical energy that is then stored in batteries. There are multiple input factors that affect the output power of solar cells such as temperature, material properties, weather conditions, solar irradiance and more.[3]

The first instance of photovoltaic cells within vehicular applications was around midway through the second half of the 1900's. In an effort to increase publicity and awareness in solar powered transportation Hans Tholstrup decided to set up the first edition of the World Solar Challenge in 1987. It was a 3000 km race across the Australian outback where competitors from industry research groups and top universities around the globe were invited to compete. General Motors ended up winning the event by a significant margin with their Sunraycer vehicle that achieved speeds of over 40 mph. Contrary to popular belief however solar powered cars are one of the oldest alternative energy vehicles.[4]

Current solar vehicles harness energy from the Sun via Solar panels which are a collected group of solar cells working in tandem towards a common goal.[5] These solid-state devices use quantum mechanical transitions in order to convert a given amount of solar power into electrical power.[5] The electricity produced as a result is then stored in the vehicle's battery in order to run the motor of the vehicle.[5] Batteries in solar-powered vehicles differ from those in standard ICE cars because they are fashioned in a way to impart more power towards the electrical components of the vehicle for a longer duration.[6]

Cells, modules, panels and systems

Multiple solar cells in an integrated group, all oriented in one plane, constitute a solar photovoltaic panel or module. Photovoltaic modules often have a sheet of glass on the sun-facing side, allowing light to pass while protecting the semiconductor wafers. Solar cells are usually connected in series creating additive voltage. Connecting cells in parallel yields a higher current.

However, problems in paralleled cells such as shadow effects can shut down the weaker (less illuminated) parallel string (a number of series connected cells) causing substantial power loss and possible damage because of the reverse bias applied to the shadowed cells by their illuminated partners.[citation needed]

Although modules can be interconnected to create an array with the desired peak DC voltage and loading current capacity, which can be done with or without using independent MPPTs (maximum power point trackers) or, specific to each module, with or without module level power electronic (MLPE) units such as microinverters or DC-DC optimizers. Shunt diodes can reduce shadowing power loss in arrays with series/parallel connected cells.

Typical PV system prices in 2013 in selected countries (US$/W)								
	Australia	China	France	Germany	Italy	Japan	United Kingdom	United States
Residential	1.8	1.5	4.1	2.4	2.8	4.2	2.8	4.9
Commercial	1.7	1.4	2.7	1.8	1.9	3.6	2.4	4.5
Utility-scale	2.0	1.4	2.2	1.4	1.5	2.9	1.9	3.3
Source: IEA – Technology Roadmap: Solar Photovoltaic Energy report, 2014 edition[7]:15 Note: DOE – Photovoltaic System Pricing Trends reports lower prices for the U.S.[8]								

By 2020, the United States cost per watt for a utility scale system had declined to $0.94.[9]

The photovoltaic effect was experimentally demonstrated first by French physicist Edmond Becquerel. In 1839, at age 19, he built the world's first photovoltaic cell in his father's laboratory. Willoughby Smith first described the "Effect of Light on Selenium during the passage of an Electric Current" in a 20 February 1873 issue of Nature. In 1883 Charles Fritts built the first solid state photovoltaic cell by coating the semiconductor selenium with a thin layer of gold to form the junctions; the device was only around 1% efficient. Other milestones include:

- 1888 – Russian physicist Aleksandr Stoletov built the first cell based on the outer photoelectric effect discovered by Heinrich Hertz in 1887.[10]
- 1904 – Julius Elster, together with Hans Friedrich Geitel, devised the first practical photoelectric cell.[11]
- 1905 – Albert Einstein proposed a new quantum theory of light and explained the photoelectric effect in a landmark paper, for which he received the Nobel Prize in Physics in 1921.[12]
- 1941 – Vadim Lashkaryov discovered p-n-junctions in Cu_2O and Ag_2S protocells.[13]
- 1946 – Russell Ohl patented the modern junction semiconductor solar cell,[14] while working on the series of advances that would lead to the transistor.
- 1948 - Introduction to the World of Semiconductors states Kurt Lehovec may have been the first to explain the photo-voltaic effect in the peer reviewed journal Physical Review.[15][16]
- 1954 – The first practical photovoltaic cell was publicly demonstrated at Bell Laboratories.[17] The inventors were Calvin Souther Fuller, Daryl Chapin and Gerald Pearson.[18]
- 1958 – Solar cells gained prominence with their incorporation onto the Vanguard I satellite.

Space applications

NASA used solar cells on its spacecraft from the very beginning. For Example, Explorer 6, launched in 1959, had four arrays that folded out once in orbit. They provided power for months in space.

Solar cells were first used in a prominent application when they were proposed and flown on the Vanguard satellite in 1958, as an alternative power source to the primary battery power source. By adding cells to the outside of the body, the mission time could be extended with no major changes to the spacecraft or its power systems. In 1959 the United States launched Explorer 6, featuring large wing-shaped solar arrays, which became a common feature in satellites. These arrays consisted of 9600 Hoffman solar cells.

By the 1960s, solar cells were (and still are) the main power source for most Earth orbiting satellites and a number of probes into the solar system, since they offered the best power-to-weight ratio. However, this success was possible because in the space application, power system costs could be high, because space users had few other power options, and were willing to pay for the best possible cells. The space power market drove the development of higher efficiencies in solar cells up until the National Science Foundation "Research Applied to National Needs" program began to push development of solar cells for terrestrial applications.

In the early 1990s the technology used for space solar cells diverged from the silicon technology used for terrestrial panels, with the spacecraft application shifting to gallium arsenide-based III-V semiconductor materials, which then evolved into the modern III-V multijunction photovoltaic cell used on spacecraft.

In recent years, research has moved towards designing and manufacturing lightweight, flexible, and highly efficient solar cells. Terrestrial solar cell technology generally uses photovoltaic cells that are laminated with a layer of glass for strength and protection. Space applications for solar cells require that the cells and arrays are both highly efficient and extremely lightweight. Some newer technology implemented on satellites are multi-junction photovoltaic cells, which are composed of different PN junctions with varying bandgaps in order to utilize a wider spectrum of the sun's energy. Additionally, large satellites require the use of large solar arrays to produce electricity. These solar arrays need to be broken down to fit in the geometric constraints of the launch vehicle the satellite travels on before being injected into orbit. Historically, solar cells on satellites consisted of several small terrestrial panels folded together. These small panels would be unfolded into a large panel after the satellite is deployed in its orbit. Newer satellites aim to use flexible rollable solar arrays that are very lightweight and can be packed into a very small volume. The smaller size and weight of these flexible arrays drastically decreases the overall cost of launching a satellite due to the direct relationship between payload weight and launch cost of a launch vehicle.[19]

In 2020, the US Naval Research Laboratory conducted its first test of solar power generation in a satellite, the Photovoltaic Radio-frequency Antenna Module (PRAM) experiment aboard the Boeing X-37.[20][21]

Improved manufacturing methods

Improvements were gradual over the 1960s. This was also the reason that costs remained high, because space users were willing to pay for the best possible cells, leaving no reason to invest in lower-cost, less-efficient solutions. The price 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. These effects lowered 1971 cell costs to some $100 per watt.[22]

In late 1969 Elliot Berman joined Exxon's task force which was looking for projects 30 years in the future and in April

1973 he founded Solar Power Corporation (SPC), a wholly owned subsidiary of Exxon at that time.[23][24][25] The group had concluded that electrical power would be much more expensive by 2000, and felt that this increase in price would make alternative energy sources more attractive. He conducted a market study and concluded that a price per watt of about $20/watt would create significant demand.[23] The team eliminated the steps of polishing the wafers and coating them with an anti-reflective layer, relying on the rough-sawn wafer surface. The team also replaced 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 glue between the two, "potting" the cells.[26] Solar cells could be made using cast-off material from the electronics market. By 1973 they announced a product, and SPC convinced Tideland Signal to use its panels to power navigational buoys, initially for the U.S. Coast Guard.[24]

Research and industrial production

Research into solar power for terrestrial applications became prominent with the U.S. National Science Foundation's Advanced Solar Energy Research and Development Division within the "Research Applied to National Needs" program, which ran from 1969 to 1977,[27] and funded research on developing solar power for ground electrical power systems. A 1973 conference, the "Cherry Hill Conference", set forth the technology goals required to achieve this goal and outlined an ambitious project for achieving them, kicking off an applied research program that would be ongoing for several decades.[28] The program was eventually taken over by the Energy Research and Development Administration (ERDA),[29] which was later merged into the U.S. Department of Energy.

Following the 1973 oil crisis, oil companies used their higher profits to start (or buy) solar firms, and were for decades the largest producers. Exxon, ARCO, Shell, Amoco (later purchased by BP) and Mobil all had major solar divisions during the 1970s and 1980s. Technology companies also participated, including General Electric, Motorola, IBM, Tyco and RCA.[30]

Declining costs and exponential growth

Adjusting for inflation, it cost $96 per watt for a solar module in the mid-1970s. Process improvements and a very large boost in production have brought that figure down more than 99%, to 30¢ per watt in 2018 [33] and as low as 20¢ per watt in 2020. [34] Swanson's law is an observation similar to Moore's Law that states that solar cell prices fall 20% for every doubling of industry capacity. It was featured in an article in the British weekly newspaper The Economist in late 2012.[35] Balance of system costs were then higher than those of the panels. Large commercial arrays could be built, as of 2018, at below $1.00 a watt, fully commissioned.[9]

As the semiconductor industry moved to ever-larger boules, older equipment became inexpensive. Cell sizes grew as equipment became available on the surplus market; ARCO Solar's original panels used cells 2 to 4 inches (50 to 100 mm) in diameter. Panels in the 1990s and early 2000s generally used 125 mm wafers; since 2008, almost all new panels use 156 mm cells. The widespread introduction of flat screen televisions in the late 1990s and early 2000s led to the wide availability of large, high-quality glass sheets to cover the panels.

During the 1990s, polysilicon ("poly") cells became increasingly popular. These cells offer less efficiency than their monosilicon ("mono") counterparts, but they are grown in large vats that reduce cost. By the mid-2000s, poly was dominant in the low-cost panel market, but more recently the mono returned to widespread use.

Manufacturers of wafer-based cells responded to high silicon prices in 2004–2008 with rapid reductions in silicon consumption. In 2008, according to Jef Poortmans, director of IMEC's organic and solar department, current cells use 8–9 grams (0.28–0.32 oz) of silicon per watt of power generation, with wafer thicknesses in the neighborhood of 200 microns. Crystalline silicon panels dominate worldwide markets and are mostly manufactured in China and Taiwan. By late 2011, a drop in European demand dropped prices for crystalline solar modules to about $1.09[36] per watt down sharply from 2010. Prices continued to fall in 2012, reaching $0.62/watt by 4Q2012.[37]

Solar PV is growing fastest in Asia, with China and Japan currently accounting for half of worldwide deployment.[38] Global installed PV capacity reached at least 301 gigawatts in 2016, and grew to supply 1.3% of global power by 2016.[39]

It was anticipated that electricity from PV will be competitive with wholesale electricity costs all across Europe and the energy payback time of crystalline silicon modules can be reduced to below 0.5 years by 2020.[40]

Falling costs are considered one of the biggest factors in the rapid growth of renewable energy, with the cost of solar photovoltaic electricity falling by ~85% between 2010 (when solar and wind made up 1.7% of global electricity generation) and 2021 (where they made up 8.7%).[41] In 2019 solar cells accounted for ~3 % of the world's electricity generation.[42]

Subsidies and grid parity

Solar-specific feed-in tariffs vary by country and within countries. Such tariffs encourage the development of solar power projects. Widespread grid parity, the point at which photovoltaic electricity is equal to or cheaper than grid power without subsidies, likely requires advances on all three fronts. Proponents of solar hope to achieve grid parity first in areas with abundant sun and high electricity costs such as in California and Japan.[43] In 2007 BP claimed grid parity for Hawaii and other islands that otherwise use diesel fuel to produce electricity. George W. Bush set 2015 as the date for grid parity in the US.[44][45] The Photovoltaic Association reported in 2012 that Australia had reached grid parity (ignoring feed in tariffs).[46]

The price of solar panels fell steadily for 40 years, interrupted in 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). The recession of 2008 and the onset of Chinese manufacturing caused prices to resume their decline. In the four years after January 2008 prices for solar modules in Germany dropped from €3 to €1 per peak watt. During that same time production capacity surged with an annual growth of more than 50%. China increased market share from 8% in 2008 to over 55% in the last quarter of 2010.[47] In December 2012 the price of Chinese solar panels had dropped to $0.60/Wp (crystalline modules).[48] (The abbreviation Wp stands for watt peak capacity, or the maximum capacity under optimal conditions.[49])

As of the end of 2016, it was reported that spot prices for assembled solar panels (not cells) had fallen to a record-low of US$0.36/Wp. The second largest supplier, Canadian Solar Inc., had reported costs of US$0.37/Wp in the third quarter of 2016, having dropped $0.02 from the previous quarter, and hence was probably still at least breaking even. Many producers expected costs would drop to the vicinity of $0.30 by the end of 2017.[50] It was also reported that new solar installations were cheaper than coal-based thermal power plants in some regions of the world, and this was expected to be the case in most of the world within a decade.[51]

Theory

A solar cell is made of semiconducting materials, such as silicon, that have been fabricated into a p–n junction. Such junctions are made by doping one side of the device p-type and the other n-type, for example in the case of silicon by introducing small concentrations of boron or phosphorus respectively.

In operation, photons in sunlight hit the solar cell and are absorbed by the semiconductor. When the photons are absorbed, electrons are excited from the valence band to the conduction band (or from occupied to unoccupied molecular orbitals in the case of an organic solar cell), producing electron-hole pairs. If the electron-hole pairs are created near the junction between p-type and n-type materials the local electric field sweeps them apart to opposite electrodes, producing an excess of electrons on one side and an excess of holes on the other. When the solar cell is unconnected (or the external electrical load is very high) the electrons and holes will ultimately restore equilibrium by diffusing back across the junction against the field and recombine with each other giving off heat, but if the load is small enough then it is easier for equilibrium to be restored by the excess electrons going around the external circuit, doing useful work along the way.

An array of solar cells converts solar energy into a usable amount of direct current (DC) electricity. An inverter can convert the power to alternating current (AC).

The most commonly known solar cell is configured as a large-area p–n junction made from silicon. Other possible solar cell types are organic solar cells, dye sensitized solar cells, perovskite solar cells, quantum dot solar cells etc. The illuminated side of a solar cell generally has a transparent conducting film for allowing light to enter into the active material and to collect the generated charge carriers. Typically, films with high transmittance and high electrical conductance such as indium tin oxide, conducting polymers or conducting nanowire networks are used for the purpose.[52]

Efficiency

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

The power conversion efficiency of a solar cell is a parameter which is defined by the fraction of incident power converted into electricity.[53]

A solar cell has a voltage dependent efficiency curve, temperature coefficients, and allowable shadow angles.

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

The fill factor is the ratio of the actual maximum obtainable power to the product of the open-circuit voltage and short-circuit current. This is a key parameter in evaluating performance. In 2009, typical commercial solar cells had a fill factor > 0.70. Grade B cells were usually between 0.4 and 0.7.[54] Cells with a high fill factor have a low equivalent series resistance and a high equivalent shunt resistance, so less of the current produced by the cell is dissipated in internal losses.

Single p–n junction crystalline silicon devices are now approaching the theoretical limiting power efficiency of 33.16%,[55] noted as the Shockley–Queisser limit in 1961. In the extreme, with an infinite number of layers, the corresponding limit is 86% using concentrated sunlight.[56]

In 2014, three companies broke the record of 25.6% for a silicon solar cell. Panasonic's was the most efficient. The company moved the front contacts to the rear of the panel, eliminating shaded areas. In addition they applied thin silicon films to the (high quality silicon) wafer's front and back to eliminate defects at or near the wafer surface.[57]

In 2015, a 4-junction GaInP/GaAs//GaInAsP/GaInAs solar cell achieved a new laboratory record efficiency of 46.1% (concentration ratio of sunlight = 312) in a French-German collaboration between the Fraunhofer Institute for Solar Energy Systems (Fraunhofer ISE), CEA-LETI and SOITEC.[58]

In September 2015, Fraunhofer ISE announced the achievement of an efficiency above 20% for epitaxial wafer cells. The work on optimizing the atmospheric-pressure chemical vapor deposition (APCVD) in-line production chain was done in collaboration with NexWafe GmbH, a company spun off from Fraunhofer ISE to commercialize production.[59][60]

For triple-junction thin-film solar cells, the world record is 13.6%, set in June 2015.[61]

In 2016, researchers at Fraunhofer ISE announced a GaInP/GaAs/Si triple-junction solar cell with two terminals reaching 30.2% efficiency without concentration.[62]

In 2017, a team of researchers at National Renewable Energy Laboratory (NREL), EPFL and CSEM (Switzerland) reported record one-sun efficiencies of 32.8% for dual-junction GaInP/GaAs solar cell devices. In addition, the dual-junction device was mechanically stacked with a Si solar cell, to achieve a record one-sun efficiency of 35.9% for triple-junction solar cells.[63]

Materials

Solar cells are typically named after the semiconducting material they are made of. These materials must have certain characteristics in order to absorb sunlight. Some cells are designed to handle sunlight that reaches the Earth's surface, while others are optimized for use in space. Solar cells can be made of a single layer of light-absorbing material (single-junction) or use multiple physical configurations (multi-junctions) to take advantage of various absorption and charge separation mechanisms.

Solar cells can be classified into first, second and third generation cells. The first generation cells—also called conventional, traditional or wafer-based cells—are made of crystalline silicon, the commercially predominant PV technology, that includes materials such as polysilicon and monocrystalline silicon. Second generation cells are thin film solar cells, that include amorphous silicon, CdTe and CIGS cells and are commercially significant in utility-scale photovoltaic power stations, building integrated photovoltaics or in small stand-alone power system. The third generation of solar cells includes a number of thin-film technologies often described as emerging photovoltaics—most of them have not yet been commercially applied and are still in the research or development phase. Many use organic materials, often organometallic compounds as well as inorganic substances. Despite the fact that their efficiencies had been low and the stability of the absorber material was often too short for commercial applications, there is research into these technologies as they promise to achieve the goal of producing low-cost, high-efficiency solar cells.[65] As of 2016, the most popular and efficient solar cells were those made from thin wafers of silicon which are also the oldest solar cell technology.[66]

Crystalline silicon

By far, the most prevalent bulk material for solar cells is crystalline silicon (c-Si), also known as "solar grade silicon".[67] Bulk silicon is separated into multiple categories according to crystallinity and crystal size in the resulting ingot, ribbon or wafer. These cells are entirely based around the concept of a p–n junction. Solar cells made of c-Si are made from wafers between 160 and 240 micrometers thick.

Monocrystalline silicon

Monocrystalline silicon (mono-Si) solar cells feature a single-crystal composition that enables electrons to move more freely than in a multi-crystal configuration. Consequently, monocrystalline solar panels deliver a higher efficiency than their multicrystalline counterparts.[68] The corners of the cells look clipped, like an octagon, because the wafer material is cut from cylindrical ingots, that are typically grown by the Czochralski process. Solar panels using mono-Si cells display a distinctive pattern of small white diamonds.

Epitaxial silicon development

Epitaxial wafers of crystalline silicon can be grown on a monocrystalline silicon "seed" wafer by chemical vapor deposition (CVD), and then detached as self-supporting wafers of some standard thickness (e.g., 250 µm) that can be manipulated by hand, and directly substituted for wafer cells cut from monocrystalline silicon ingots. Solar cells made with this "kerfless" technique can have efficiencies approaching those of wafer-cut cells, but at appreciably lower cost if the CVD can be done at atmospheric pressure in a high-throughput inline process.[59][60] The surface of epitaxial wafers may be textured to enhance light absorption.[69][70]

In June 2015, it was reported that heterojunction solar cells grown epitaxially on n-type monocrystalline silicon wafers had reached an efficiency of 22.5% over a total cell area of 243.4 cm

Polycrystalline silicon

Polycrystalline silicon, or multicrystalline silicon (multi-Si) cells are made from cast square ingots—large blocks of molten silicon carefully cooled and solidified. They consist of small crystals giving the material its typical metal flake effect. Polysilicon cells are the most common type used in photovoltaics and are less expensive, but also less efficient, than those made from monocrystalline silicon.

Ribbon silicon

Ribbon silicon is a type of polycrystalline silicon—it is formed by drawing flat thin films from molten silicon and results in a polycrystalline structure. These cells are cheaper to make than multi-Si, due to a great reduction in silicon waste, as this approach does not require sawing from ingots.[72] However, they are also less efficient.

Mono-like-multi silicon (MLM)

This form was developed in the 2000s and introduced commercially around 2009. Also called cast-mono, this design uses polycrystalline casting chambers with small "seeds" of mono material. The result is a bulk mono-like material that is polycrystalline around the outsides. When sliced for processing, the inner sections are high-efficiency mono-like cells (but square instead of "clipped"), while the outer edges are sold as conventional poly. This production method results in mono-like cells at poly-like prices.[73]

Thin film

Thin-film technologies reduce the amount of active material in a cell. Most designs sandwich active material between two panes of glass. Since silicon solar panels only use one pane of glass, thin film panels are approximately twice as heavy as crystalline silicon panels, although they have a smaller ecological impact (determined from life cycle analysis).[74] [75]

Cadmium telluride

Cadmium telluride is the only thin film material so far to rival crystalline silicon in cost/watt. However cadmium is highly toxic and tellurium (anion: "telluride") supplies are limited. 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.[76] 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.[76]

Copper indium gallium selenide

Copper indium gallium selenide (CIGS) is a direct band gap material. It has the highest efficiency (~20%) among all commercially significant thin film materials (see CIGS solar cell). Traditional methods of fabrication involve vacuum processes including co-evaporation and sputtering. Recent developments at IBM and Nanosolar attempt to lower the cost by using non-vacuum solution processes.[77]

Silicon thin film

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 amorphous silicon (a-Si or a-Si:H), protocrystalline silicon or nanocrystalline silicon (nc-Si or nc-Si:H), also called microcrystalline silicon.[78]

Amorphous silicon is the most well-developed thin film technology to-date. An amorphous silicon (a-Si) solar cell is made of non-crystalline or microcrystalline silicon. 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 higher power density infrared portion of the spectrum. 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).

Protocrystalline silicon with a low volume fraction of nanocrystalline silicon is optimal for high open-circuit voltage.[79] Nc-Si has about the same bandgap as c-Si and 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.

Gallium arsenide thin film

The semiconductor material gallium arsenide (GaAs) is also used for single-crystalline thin film solar cells. Although GaAs cells are very expensive they hold the world's record in efficiency for a single-junction solar cell at 28.8%.[80] Typically fabricated on crystalline silicon wafer[81] with a 41% fill factor, by moving to porous silicon fill factor can be increased to 56% with potentially reduced cost. Using less active GaAs material by fabricating nanowires is another potential pathway to cost reduction.[82] GaAs is more commonly used in multijunction photovoltaic cells for concentrated photovoltaics (CPV, HCPV) and for solar panels on spacecraft, as the industry favours efficiency over cost for space-based solar power. Based on the previous literature and some theoretical analysis, there are several reasons why GaAs has such high power conversion efficiency. First, GaAs bandgap is 1.43ev which is almost ideal for solar cells. Second, because Gallium is a by-product of the smelting of other metals, GaAs cells are relatively insensitive to heat and it can keep high efficiency when temperature is quite high. Third, GaAs has the wide range of design options. Using GaAs as active layer in solar cell, engineers can have multiple choices of other layers which can better generate electrons and holes in GaAs.

Multijunction cells

Multi-junction cells consist of multiple thin films, each essentially a solar cell grown on top of another, typically using metalorganic vapour phase epitaxy. Each layer has a different band gap energy to allow it to absorb electromagnetic radiation over a different portion of the spectrum. Multi-junction cells were originally developed for special applications such as satellites and space exploration, but are now used increasingly in terrestrial concentrator photovoltaics (CPV), an emerging technology that uses lenses and curved mirrors to concentrate sunlight onto small, highly efficient multi-junction solar cells. By concentrating sunlight up to a thousand times, High concentration photovoltaics (HCPV) has the potential to outcompete conventional solar PV in the future.

Tandem solar cells based on monolithic, series connected, gallium indium phosphide (GaInP), gallium arsenide (GaAs), and germanium (Ge) p–n junctions, are increasing sales, despite cost pressures.[84] Between December 2006 and December 2007, the cost of 4N gallium metal rose 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.

A triple-junction cell, for example, may consist of the semiconductors: GaAs, Ge, and $GaInP_2$.[85] Triple-junction GaAs solar cells were used as the power source of the Dutch four-time World Solar Challenge winners Nuna in 2003, 2005 and 2007 and by the Dutch solar cars Solutra (2005), Twente One (2007) and 21Revolution (2009). GaAs based multi-junction devices are the most efficient solar cells to date. On 15 October 2012, triple junction metamorphic cells reached a record high of 44%.[86]

GaInP/Si dual-junction solar cells

In 2016, a new approach was described for producing hybrid photovoltaic wafers combining the high efficiency of III-V multi-junction solar cells with the economies and wealth of experience associated with silicon. The technical complications involved in growing the III-V material on silicon at the required high temperatures, a subject of study for some 30 years, are avoided by epitaxial growth of silicon on GaAs at low temperature by plasma-enhanced chemical vapor deposition (PECVD).[87]

Si single-junction solar cells have been widely studied for decades and are reaching their practical efficiency of ~26% under 1-sun conditions.[88] Increasing this efficiency may require adding more cells with bandgap energy larger than 1.1 eV to the Si cell, allowing to convert short-wavelength photons for generation of additional voltage. A dual-junction solar cell with a band gap of 1.6–1.8 eV as a top cell can reduce thermalization loss, produce a high external radiative efficiency and achieve theoretical efficiencies over 45%.[89] A tandem cell can be fabricated by growing the GaInP and Si cells. Growing them separately can overcome the 4% lattice constant mismatch between Si and the most common III–V layers that prevent direct integration into one cell. The two cells therefore are separated by a transparent glass slide so the lattice mismatch does not cause strain to the system. This creates a cell with four electrical contacts and two junctions that demonstrated an efficiency of 18.1%. With a fill factor (FF) of 76.2%, the Si bottom cell reaches an efficiency of 11.7% (± 0.4) in the tandem device, resulting in a cumulative tandem cell efficiency of 29.8%.[90] This efficiency exceeds the theoretical limit of 29.4%[91] and the record experimental efficiency value of a Si 1-sun solar cell, and is also higher than the record-efficiency 1-sun GaAs device. However, using a GaAs substrate is expensive and not practical. Hence researchers try to make a cell with two electrical contact points and one junction, which does not need a GaAs substrate. This means there will be direct integration of GaInP and Si.

Research in solar cells

Perovskite solar cells

Perovskite solar cells are solar cells that include a perovskite-structured material as the active layer. Most commonly, this is a solution-processed hybrid organic-inorganic tin or lead halide based material. Efficiencies have increased from below 5% at their first usage in 2009 to 25.5% in 2020, making them a very rapidly advancing technology and a hot topic in the solar cell field.[92] Researchers at University of Rochester reported in 2023 that significant further improvements in cell efficiency can be achieved by utilizing Purcell effect.[93]

Perovskite solar cells are also forecast to be extremely cheap to scale up, making them a very attractive option for commercialisation. So far most types of perovskite solar cells have not reached sufficient operational stability to be commercialised, although many research groups are investigating ways to solve this.[94] Energy and environmental sustainability of perovskite solar cells and tandem perovskite are shown to be dependent on the structures.[95][96][97] Photonic front contacts for light management can improve the perovskite cells' performance, via enhanced broadband absorption, while allowing better operational stability due to protection against the harmful high-energy (above Visible) radiation.[98] The inclusion of the toxic element lead in the most efficient perovskite solar cells is a potential problem for commercialisation.[99]

Bifacial solar cells

With a transparent rear side, bifacial solar cells can absorb light from both the front and rear sides. Hence, they can produce more electricity than conventional monofacial solar cells. The first patent of bifacial solar cells was filed by Japanese researcher Hiroshi Mori, in 1966.[100] Later, it is said that Russia was the first to deploy bifacial solar cells in their space program in the 1970s. In 1976, the Institute for Solar Energy of the Technical University of Madrid, began a research program for the development of bifacial solar cells led by Prof. Antonio Luque. Based on 1977 US and Spanish patents by Luque, a practical bifacial cell was proposed with a front face as anode and a rear face as cathode; in previously reported proposals and attempts both faces were anodic and interconnection between cells was complicated and expensive.[101][102][103] In 1980, Andrés Cuevas, a PhD student in Luque's team, demonstrated experimentally a 50% increase in output power of bifacial solar cells, relative to identically oriented and tilted monofacial ones, when a white background was provided.[104] In 1981 the company Isofoton was founded in Málaga to produce the developed bifacial cells, thus becoming the first industrialization of this PV cell technology. With an initial production capacity of 300 kW/yr of bifacial solar cells, early landmarks of Isofoton's production were the 20kWp power plant in San Agustín de Guadalix, built in 1986 for Iberdrola, and an off grid installation by 1988 also of 20kWp in the village of Noto Gouye Diama (Senegal) funded by the Spanish international aid and cooperation programs.

Due to the reduced manufacturing cost, companies have again started to produce commercial bifacial modules since 2010. By 2017, there were at least eight certified PV manufacturers providing bifacial modules in North America. The International Technology Roadmap for Photovoltaics (ITRPV) predicted that the global market share of bifacial technology will expand from less than 5% in 2016 to 30% in 2027.[105]

Due to the significant interest in the bifacial technology, a recent study has investigated the performance and optimization of bifacial solar modules worldwide.[106][107] The results indicate that, across the globe, ground-mounted bifacial modules can only offer ~10% gain in annual electricity yields compared to the monofacial counterparts for a ground albedo coefficient of 25% (typical for concrete and vegetation groundcovers). However, the gain can be increased to ~30% by elevating the module 1 m above the ground and enhancing the ground albedo coefficient to 50%. Sun et al. also derived a set of empirical equations that can optimize bifacial solar modules analytically.[106] In addition, there is evidence that bifacial panels work better than traditional panels in snowy environments as bifacials on dual-axis trackers made 14% more electricity in a year than their monofacial counterparts and 40% during the peak winter months.[108]

An online simulation tool is available to model the performance of bifacial modules in any arbitrary location across the entire world. It can also optimize bifacial modules as a function of tilt angle, azimuth angle, and elevation above the ground.[109]

Intermediate band

Intermediate band photovoltaics in solar cell research provides methods for exceeding the Shockley–Queisser limit on the efficiency of a cell. It introduces an intermediate band (IB) energy level in between the valence and conduction bands. Theoretically, introducing an IB allows two photons with energy less than the bandgap to excite an electron from the valence band to the conduction band. This increases the induced photocurrent and thereby efficiency.[110]

Luque and Marti first derived a theoretical limit for an IB device with one midgap energy level using detailed balance. They assumed no carriers were collected at the IB and that the device was under full concentration. They found the maximum efficiency to be 63.2%, for a bandgap of 1.95eV with the IB 0.71eV from either the valence or conduction band. Under one sun illumination the limiting efficiency is 47%.[111] Several means are under study to realize IB semiconductors with such optimum 3-bandgap configuration, namely via materials engineering (controlled inclusion of deep level impurities or highly-mismatched alloys) and nano-structuring (quantum-dots in host hetero-crystals).[112]

Liquid inks

Upconversion and downconversion

Photon upconversion is the process of using two low-energy (e.g., infrared) photons to produce one higher energy photon; downconversion is the process of using one high energy photon (e.g., ultraviolet) to produce two lower energy photons. Either of these techniques could be used to produce higher efficiency solar cells by allowing solar photons to be more efficiently used. The difficulty, however, is that the conversion efficiency of existing phosphors exhibiting up- or down-conversion is low, and is typically narrow band.

One upconversion technique is to incorporate lanthanide-doped materials (Er^{3+}, Yb^{3+}, Ho^{3+} or a combination), taking advantage of their luminescence to convert infrared radiation to visible light. Upconversion process occurs when two infrared photons are absorbed by rare-earth ions to generate a (high-energy) absorbable photon. As example, the energy transfer upconversion process (ETU), consists in successive transfer processes between excited ions in the near infrared. The upconverter material could be placed below the solar cell to absorb the infrared light that passes through the silicon. Useful ions are most commonly found in the trivalent state. Er^{+} ions have been the most used. Er^{3+} ions absorb solar radiation around 1.54 µm. Two Er^{3+} ions that have absorbed this radiation can interact with each other through an upconversion process. The excited ion emits light above the Si bandgap that is absorbed by the solar cell and creates an additional electron–hole pair that can generate current. However, the increased efficiency was small. In addition, fluoroindate glasses have low phonon energy and have been proposed as suitable matrix doped with Ho^{3+} ions.[114]

Light-absorbing dyes

Dye-sensitized solar cells (DSSCs) are made of low-cost materials and do not need elaborate manufacturing equipment, so they can be made in a DIY fashion. 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 may be high enough to allow them to compete with fossil fuel electrical generation.

Typically a ruthenium metalorganic dye (Ru-centered) is used as a monolayer of light-absorbing material, which is adsorbed onto a thin film of titanium dioxide. The dye-sensitized solar cell depends on this mesoporous layer of nanoparticulate titanium dioxide (TiO_2) 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) which allows for a greater number of dyes per solar cell area (which in term in increases the current). 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 more flexible use of materials and is typically manufactured by screen printing or 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. Due to this reason, researchers have developed solid-state dye-sensitized solar cells that use a solid electrolyte to avoid leakage.[115] The first commercial shipment of DSSC solar modules occurred in July 2009 from G24i Innovations.[116]

Quantum dots

Quantum dot solar cells (QDSCs) are based on the Gratzel cell, or dye-sensitized solar cell architecture, but employ low band gap semiconductor nanoparticles, fabricated with crystallite sizes small enough to form quantum dots (such as CdS, CdSe, Sb_2S_3, PbS, etc.), instead of organic or organometallic dyes as light absorbers. Due to the toxicity associated with Cd and Pb based compounds there are also a series of "green" QD sensitizing materials in development (such as $CuInS_2$, $CuInSe_2$ and CuInSeS).[117] QD's size quantization allows for the band gap to be tuned by simply changing particle size. They also have high extinction coefficients and have shown the possibility of multiple exciton generation.[118]

In a QDSC, a mesoporous layer of titanium dioxide nanoparticles forms the backbone of the cell, much like in a DSSC. This TiO_2 layer can then be made photoactive by coating with semiconductor quantum dots using chemical bath deposition, electrophoretic deposition or successive ionic layer adsorption and reaction. The electrical circuit is then completed through the use of a liquid or solid redox couple. The efficiency of QDSCs has increased[119] to over 5% shown for both liquid-junction[120] and solid state cells,[121] with a reported peak efficiency of 11.91%.[122] In an effort to decrease production costs, the Prashant Kamat research group[123] demonstrated a solar paint made with TiO_2 and CdSe that can be applied using a one-step method to any conductive surface with efficiencies over 1%.[124] However, the absorption of quantum dots (QDs) in QDSCs is weak at room temperature.[125] The plasmonic nanoparticles can be utilized to address the weak absorption of QDs (e.g., nanostars).[126] Adding an external infrared pumping source to excite intraband and interband transition of QDs is another solution.[125]

Organic/polymer solar cells

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.

They can be processed from liquid solution, offering the possibility of a simple roll-to-roll printing process, potentially leading to inexpensive, large-scale production. In addition, these cells could be beneficial for some applications where mechanical flexibility and disposability are important. Current cell efficiencies are, however, very low, and practical devices are essentially non-existent.

Energy conversion efficiencies achieved to date using conductive polymers are very low compared to inorganic materials. However, Konarka Power Plastic reached efficiency of 8.3%[127] and organic tandem cells in 2012 reached 11.1%.

The active region of an organic device consists of two materials, one electron donor and one electron 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, separating when the exciton diffuses to the donor-acceptor interface, unlike most other solar cell types. 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.[128]

In 2011, MIT and Michigan State researchers developed solar cells with a power efficiency close to 2% with a transparency to the human eye greater than 65%, achieved by selectively absorbing the ultraviolet and near-infrared parts of the spectrum with small-molecule compounds.[129][130] Researchers at UCLA more recently developed an analogous polymer solar cell, following the same approach, that is 70% transparent and has a 4% power conversion efficiency.[131][132][133] These lightweight, flexible cells can be produced in bulk at a low cost and could be used to create power generating windows.

In 2013, researchers announced polymer cells with some 3% efficiency. They used block copolymers, self-assembling organic materials that arrange themselves into distinct layers. The research focused on P3HT-b-PFTBT that separates into bands some 16 nanometers wide.[134][135]

Adaptive cells

Adaptive cells change their absorption/reflection characteristics depending on environmental conditions. An adaptive material responds to the intensity and angle of incident light. At the part of the cell where the light is most intense, the cell surface changes from reflective to adaptive, allowing the light to penetrate the cell. The other parts of the cell remain reflective increasing the retention of the absorbed light within the cell.[136]

In 2014, a system was developed that combined an adaptive surface with a glass substrate that redirect the absorbed to a light absorber on the edges of the sheet. The system also includes an array of fixed lenses/mirrors to concentrate light onto the adaptive surface. As the day continues, the concentrated light moves along the surface of the cell. That surface switches from reflective to adaptive when the light is most concentrated and back to reflective after the light moves along.[136]

Surface texturing

For the past years, researchers have been trying to reduce the price of solar cells while maximizing efficiency. Thin-film solar cell is a cost-effective second generation solar cell with much reduced thickness at the expense of light absorption efficiency. Efforts to maximize light absorption efficiency with reduced thickness have been made. Surface texturing is one of techniques used to reduce optical losses to maximize light absorbed. Currently, surface texturing techniques on silicon photovoltaics are drawing much attention. Surface texturing could be done in multiple ways. Etching single crystalline silicon substrate can produce randomly distributed square based pyramids on the surface using anisotropic etchants.[137] Recent studies show that c-Si wafers could be etched down to form nano-scale inverted pyramids. Multicrystalline silicon solar cells, due to poorer crystallographic quality, are less effective than single crystal solar cells, but mc-Si solar cells are still being used widely due to less manufacturing difficulties. It is reported that multicrystalline solar cells can be surface-textured to yield solar energy conversion efficiency comparable to that of monocrystalline silicon cells, through isotropic etching or photolithography techniques.[138][139] Incident light rays onto a textured surface do not reflect back out to the air as opposed to rays onto a flat surface. Rather some light rays are bounced back onto the other surface again due to the geometry of the surface. This process significantly improves light to electricity conversion efficiency, due to increased light absorption. This texture effect as well as the interaction with other interfaces in the PV module is a challenging optical simulation task. A particularly efficient method for modeling and optimization is the OPTOS formalism.[140] In 2012, researchers at MIT reported that c-Si films textured with nanoscale inverted pyramids could achieve light absorption comparable to 30 times thicker planar c-Si.[141] In combination with anti-reflective coating, surface texturing technique can effectively trap light rays within a thin film silicon solar cell. Consequently, required thickness for solar cells decreases with the increased absorption of light rays.

Encapsulation

Solar cells are commonly encapsulated in a transparent polymeric resin to protect the delicate solar cell regions for coming into contact with moisture, dirt, ice, and other conditions expected either during operation or when used outdoors. The encapsulants are commonly made from polyvinyl acetate or glass. Most encapsulants are uniform in structure and composition, which increases light collection owing to light trapping from total internal reflection of light within the resin. Research has been conducted into structuring the encapsulant to provide further collection of light. Such encapsulants have included roughened glass surfaces,[142] diffractive elements,[143] prism arrays,[144] air prisms,[145] v-grooves,[146] diffuse elements, as well as multi-directional waveguide arrays.[147] Prism arrays show an overall 5% increase in the total solar energy conversion.[145] Arrays of vertically aligned broadband waveguides provide a 10% increase at normal incidence, as well as wide-angle collection enhancement of up to 4%,[148] with optimized structures yielding up to a 20% increase in short circuit current.[149] Active coatings that convert infrared light into visible light have shown a 30% increase.[150] Nanoparticle coatings inducing plasmonic light scattering increase wide-angle conversion efficiency up to 3%. Optical structures have also been created in encapsulation materials to effectively "cloak" the metallic front contacts.[151][152]

Autonomous maintenance

Novel self-cleaning mechanisms for solar panels are being developed. For instance, in 2019 via wet-chemically etched nanowires and a hydrophobic coating on the surface water droplets could remove 98% of dust particles, which may be especially relevant for applications in the desert.[153][154]

Manufacture

Solar cells share some of the same processing and manufacturing techniques as other semiconductor devices. However, the strict requirements for cleanliness and quality control of semiconductor fabrication are more relaxed for solar cells, lowering costs.

Polycrystalline silicon wafers are made by wire-sawing block-cast silicon ingots into 180 to 350 micrometer wafers. The wafers are usually lightly p-type-doped. 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.

Anti-reflection coatings are then typically applied to increase the amount of light coupled into the solar cell. Silicon nitride has gradually replaced titanium dioxide as the preferred material, because of its excellent surface passivation qualities. It prevents carrier recombination at the cell surface. A layer several hundred nanometers thick is applied using plasma-enhanced chemical vapor deposition. Some solar cells have textured front surfaces that, like anti-reflection coatings, increase the amount of light reaching the wafer. Such surfaces were first applied to single-crystal silicon, followed by multicrystalline silicon somewhat later.

A full area metal contact is made on the back surface, and a grid-like metal contact made up of fine "fingers" and larger "bus bars" are screen-printed onto the front surface using a silver paste. This is an evolution of the so-called "wet" process for applying electrodes, first described in a US patent filed in 1981 by Bayer AG.[155] The rear contact is formed by screen-printing a metal paste, typically aluminium. Usually this contact covers the entire rear, though some designs employ 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 electroplating step to increase efficiency. After the metal contacts are made, the solar cells are interconnected 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.

Different types of manufacturing and recycling partly determine how effective it is in decreasing emissions and having a positive environmental effect.[42] Such differences and effectiveness could be quantified[42] for production of the most optimal types of products for different purposes in different regions across time.

Manufacturers and certification

National Renewable Energy Laboratory tests and validates solar technologies. Three reliable groups certify solar equipment: UL and IEEE (both U.S. standards) and IEC.

Solar cells are manufactured in volume in Japan, Germany, China, Taiwan, Malaysia and the United States, whereas Europe, China, the U.S., and Japan have dominated (94% or more as of 2013) in installed systems.[157] Other nations are acquiring significant solar cell production capacity.

Global PV cell/module production increased by 10% in 2012 despite a 9% decline in solar energy investments according to the annual "PV Status Report" released by the European Commission's Joint Research Centre. Between 2009 and 2013 cell production has quadrupled.[157][158][159]

China

Since 2013 China has been the world's leading installer of solar photovoltaics (PV).[157] As of September 2018, sixty percent of the world's solar photovoltaic modules were made in China.[160] As of May 2018, the largest photovoltaic plant in the world is located in the Tengger desert in China.[161] In 2018, China added more photovoltaic installed capacity (in GW) than the next 9 countries combined.[162] As of 2022, China's share in the manufacturing of solar panels exceeded 80% across all manufacturing stages.[163]

Malaysia

In 2014, Malaysia was the world's third largest manufacturer of photovoltaics equipment, behind China and the European Union.[164]

United States

Solar energy production in the U.S. has doubled from 2013 to 2019.[165] This was driven first by the falling price of quality silicon,[166][167][168] and later simply by the globally plunging cost of photovoltaic modules.[161][169] In 2018, the U.S. added 10.8GW of installed solar photovoltaic energy, an increase of 21%.[162]

Latin America : Latin America has emerged as a promising region for solar energy development in recent years, with over 10 GW of installations in 2020. The solar market in Latin America has been driven by abundant solar resources, falling costs, competitive auctions and growing electricity demand. Some of the leading countries for solar energy in Latin America are Brazil, Mexico, Chile and Argentina. However, the solar market in Latin America also faces some challenges, such as political instability, financing gaps and power transmission bottlenecks.

Middle East and Africa : The Middle East and Africa has also experienced significant growth in solar energy deployment in recent years, with over 8 GW installations in 2020. The solar market in the Middle East and Africa has been driven by the low-cost generation of solar energy, the diversification of energy sources, the fight against climate change and rural electrification are motivated. Some of the notable countries for solar energy in the Middle East and Africa are Saudi Arabia, United Arab Emirates, Egypt, Morocco and South Africa. However, the solar market in the Middle East and Africa also faces several obstacles, including social unrest, regulatory uncertainty and technical barriers.[170]

Materials sourcing Like many other energy generation technologies, the manufacture of solar cells, especially its rapid expansion, has many environmental and supply-chain implications. Global mining may adapt and potentially expand for sourcing the needed minerals which vary per type of solar cell.[171][172] Recycling solar panels could be a source for materials that would otherwise need to be mined.[42]

Disposal

Solar cells degrade over time and lose their efficiency. Solar cells in extreme climates, such as desert or polar, are more prone to degradation due to exposure to harsh UV light and snow loads respectively.[173] Usually, solar panels are given a lifespan of 25–30 years before they get decommissioned.[174]

The International Renewable Energy Agency estimated that the amount of solar panel electronic waste generated in 2016 was 43,500–250,000 metric tons. This number is estimated to increase substantially by 2030, reaching an estimated waste volume of 60–78 million metric tons in 2050.[175]

Recycling

The most widely used solar cells in the market are crystalline solar cells. A product is truly recyclable if it can harvested again. In the 2016 Paris Agreement, 195 countries agreed to reduce their carbon emissions by shifting their focus away from fossil fuels and towards renewable energy sources. Owing to this, Solar will be a major contributor to electricity generation all over the world. So, there will be a plethora of solar panels to be recycled after the end of their life cycle. In fact, many researchers around the globe have voiced their concern about finding ways to use silicon cells after recycling.[176][177][178][179]

Additionally, these cells have hazardous elements/compounds, including lead (Pb), cadmium (Cd) or cadmium sulfide (CdS), selenium (Se), and barium (Ba) as dopants aside from the valuables silicon (Si), aluminum (Al), silver (Ag), and copper (Cu). The harmful elements/compounds if not disposed of with the proper technique can have severe harmful effects on human life and wildlife alike.[180]

RECYCLING

There are various ways c-Si can be recycled. Mainly thermal and chemical separation methods are used. This happens in two stages[181]

- PV solar cell separation: in thermal delamination, the ethylene vinyl acetate (EVA) is removed and materials such as glass, Tedlar®, aluminium frame, steel, copper and plastics are separated;
- cleansing the surface of PV solar cells: unwanted layers (antireflection layer, metal coating and p–n semiconductor) are removed from the silicon solar cells separated from the PV modules; as a result, the silicon substrate, suitable for re-use, can be recovered.

CONVERSION

A research study was conducted by scientists to see how efficiently the solar panels were made from nanosilicon and nanosilicon/graphite hybrids.[180] The experiment techniques consist of

1. Recovery of PV Cells from End-of-Life PV Module – This is a patented technique where the solar panels are deconstructed and each material is cleaned separately.
2. Purification of Broken PV Cells – 40 g of broken PV cells were placed in a glass bottle of 500ml which contained 20% KOH (potassium oxide). Heat treatment of this aqueous solution was done at 80 °C for 0.5 h. All Al metal and other impurities were dissolved in a 20% KOH solution, and the solid PV silicon was deposited as sediment. The solid PV was dried in a vacuum and 32 g of impurity-free PV recycled silicon was obtained.
3. Conversion of Purified PV Recycled Silicon into Nanosilicon and Nanosilicon/Graphite Hybrid Production - A large-scale planetary ball mill (PULVERISETTE P5 5/4 classic line) was used. Impurity-free PV recycled cells/silicon were loaded inside a stainless-steel milling container together with five hardened steel balls (diameter of 25.4 mm). The sample

was milled at a rotation speed of 160 rpm for 15 h at room temperature under an argon atmosphere of 300 kPa. During high-energy ball milling, particle size was reduced to nanometer level (<100 nm). The same process was used to produce a PV nano-Si/graphite hybrid except for commercial graphite powder (Product-282863, Sigma-Aldrich, powder <20 μm, synthetic) which was added with eight hardened steel balls. The mixture was milled at a rotation speed of 160 rpm for 20 h at room temperature under an argon atmosphere of 300 kPa. A hybrid of PV nano-Si/graphite with a weight ratio of 5 wt% PV nano-Si and 95 wt% graphite was obtained.

The obtained PV nano-Si/graphite electrode showed excellent cyclic stability with high-capacity retention even after long-term 600 cycles. These results proved that silicon can be easily converted into nano-Si/graphite hybrids and harvested into PV modules and can work with the same efficiency as a c-Si module.

CHALLENGES

There are a lot of different PV modules in the market which have different compositions. So, it is difficult to have a common PV cell breakdown process. Also, recyclers have to do quality control which is not possible if different PV modules have to be recycled. There are also various applications of pure Si outside of the Solar industry and the recyclers might be tempted to sell there if they get a higher value for the product.[182]

Other questions that need to be answered are[183]

- To whom do the recyclers sell the recovered modules, components, and/or materials?
- What are the costs for different recycling scenarios?
- Location of recycling facilities?
- Would mobile recycling facilities make more sense over centralized ones?
- What infrastructure should be established for waste module collection?
- On the policy side, the main questions are the following:
- Who should pay for waste module recycling?

The First Solar panel recycling plant opened in Rousset, France in 2018. It was set to recycle 1300 tonnes of solar panel waste a year, and can increase its capacity to 4000 tonnes.[184][185][186] If recycling is driven only by market-based prices, rather than also environmental regulations, the economic incentives for recycling remain uncertain and as of 2021 the environmental impact of different types of developed recycling techniques still need to be quantified.[42]

DISCUSSION

Solar-cell efficiency refers to the portion of energy in the form of sunlight that can be converted via photovoltaics into electricity by the solar cell.

The efficiency of the solar cells used in a photovoltaic system, in combination with latitude and climate, determines the annual energy output of the system. For example, a solar panel with 20% efficiency and an area of 1 m^2 will produce 200 kWh/yr at Standard Test Conditions if exposed to the Standard Test Condition solar irradiance value of 1000 W/m^2 for 2.74 hours a day. Usually solar panels are exposed to sunlight for longer than this in a given day, but the solar irradiance is less than 1000 W/m^2 for most of the day. A solar panel can produce more when the sun is high in the sky and will produce less in cloudy conditions or when the sun is low in the sky, usually the sun is lower in the sky in the winter.

Two location dependant factors that affect solar PV yield are the dispersion and intensity of solar radiation. These two variables can vary greatly between each country.[1] The global regions that have high radiation levels throughout the year are the middle east, Northern Chile, Australia, China, and Southwestern USA.[1][2] In a high-yield solar area like central Colorado, which receives annual insolation of 2000 kWh/m^2/year,[3] a panel can be expected to produce 400 kWh of energy per year. However, in Michigan, which receives only 1400 kWh/m^2/year,[3] annual energy yield will drop to 280 kWh for the same panel. At more northerly European latitudes, yields are significantly lower: 175 kWh annual energy yield in southern England under the same conditions.[4]

Several factors affect a cell's conversion efficiency, including its reflectance, thermodynamic efficiency, charge carrier separation efficiency, charge carrier collection efficiency and conduction efficiency values.[6][5] Because these parameters can be difficult to measure directly, other parameters are measured instead, including quantum efficiency, open-circuit voltage (V_{OC}) ratio, and § Fill factor. Reflectance losses are accounted for by the quantum efficiency value, as they affect "external quantum efficiency". Recombination losses are accounted for by the quantum efficiency, V_{OC} ratio, and fill factor values. Resistive losses are predominantly accounted for by the fill factor value, but also contribute to the quantum efficiency and V_{OC} ratio values.

As of 2022, the world record for solar cell efficiency is 47.1%, set in 2019 by multi-junction concentrator solar cells developed at National Renewable Energy Laboratory (NREL), Golden, Colorado, USA.[7] This record was set in lab conditions, under extremely concentrated light. The record in real-world conditions is also held by NREL, who developed triple junction cells with a tested efficiency of 39.5%.[8][9]

Factors affecting energy conversion efficiency

The factors affecting energy conversion efficiency were expounded in a landmark paper by William Shockley and Hans Queisser in 1961.[10] See Shockley–Queisser limit for more detail.

Thermodynamic-efficiency limit and infinite-stack limit

If one has a source of heat at temperature T_s and cooler heat sink at temperature T_c, the maximum theoretically possible value for the ratio of work (or electric power) obtained to heat supplied is $1-T_c/T_s$, given by a Carnot heat engine. If we take 6000 K for the temperature of the sun and 300 K for ambient conditions on earth, this comes to 95%. In 1981, Alexis de Vos and Herman Pauwels showed that this is achievable with a stack of an infinite number of cells with band gaps ranging from infinity (the first cells encountered by the incoming photons) to zero, with a voltage in each cell very close to the open-circuit voltage, equal to 95% of the band gap of that cell, and with 6000 K blackbody radiation coming from all directions. However, the 95% efficiency thereby achieved means that the electric power is 95% of the net amount of light absorbed – the stack emits radiation as it has non-zero temperature, and this radiation has to be subtracted from the incoming radiation when calculating the amount of heat being transferred and the efficiency. They also considered the more relevant problem of maximizing the power output for a stack being illuminated from all directions by 6000 K blackbody radiation. In this case, the voltages must be lowered to less than 95% of the band gap (the percentage is not constant over all the cells). The maximum theoretical efficiency calculated is 86.8% for a stack of an infinite number of cells, using the incoming concentrated sunlight radiation.[11] When the incoming radiation comes only from an area of the sky the size of the sun, the efficiency limit drops to 68.7%.[12]

Ultimate efficiency
Normal photovoltaic systems however have only one p–n junction and are therefore subject to a lower efficiency limit, called the "ultimate efficiency" by Shockley and Queisser. Photons with an energy below the band gap of the absorber material cannot generate an electron-hole pair, 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. Traditional single-junction cells with an optimal band gap for the solar spectrum have a maximum theoretical efficiency of 33.16%, the Shockley–Queisser limit.[13]

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.[14]

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. There are two types of quantum that are usually referred to when talking about solar cells. The external quantum efficiency, that relates to the external measurable properties of the solar cell. The "external" quantum efficiency of a silicon solar cell includes the effect of optical losses such as transmission and reflection. In particular, some measures can be taken to reduce these losses. The reflection losses, which can account for up to 10% of the total incident energy, can be dramatically decreased using a technique called texturization, a light trapping method that modifies the average light path.[15]

The second type is the internal quantum efficiency, this measurement of the internal quantum efficiency gives a deeper insight of the internal material parameters like the absorption coefficient or internal luminescence quantum efficiency.[16] The internal quantum efficiency is mainly used when it comes to the understanding of the potential of a certain material rather than a device.[16]

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. However, the 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.

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).

The maximum power point of a solar cell is affected by its temperature. Knowing the technical data of certain solar cell, its power output at a certain temperature can be obtained by, where is the power generated at the standard testing condition; is the actual temperature of the solar cell.

A high quality, monocrystalline silicon solar cell, at 25 °C cell temperature, may produce 0.60 V 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 V 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 V 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 an 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 example, accumulation of dust on photovoltaic panels reduces the maximum power point.[17] Recently, new research to remove dust from solar panels has been developed by utilizing electrostatic cleaning systems. In such systems, an applied electrostatic field at the surface of the solar panels causes the dust particles to move in a "flip-flop" manner.[18] Then, due to gravity and the fact that the solar panels are slightly slanted, the dust particles get pulled downward by gravity.[18] These systems only require a small power consumption and enhance the performance of the solar cells, especially when installed in the desert, where dust accumulation contributes to decreasing the solar panel's performance. Also, 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 behaviour of a solar cell is the fill factor (FF). This factor is a measure of quality of a solar cell. This is 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}):

The fill factor can be represented graphically by the IV sweep, where it is the ratio of the different rectangular areas.[19]

The fill factor is directly affected by the values of the cell's series, shunt resistances and diodes losses. 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.[20]

Typical fill factors range from 50% to 82%. The fill factor for a normal silicon PV cell is 80%.

Comparison

Energy conversion efficiency is measured by dividing the electrical output by the incident light power. Factors influencing output include spectral distribution, spatial distribution of power, temperature, and resistive load. IEC standard 61215 is used to compare the performance of cells and is designed around standard (terrestrial, temperate) 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 affects output. In space, where there is no atmosphere, the spectrum of the sun is relatively unfiltered. However, on earth, air filters the incoming light, changing the solar spectrum. 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 yields the efficiency. Terrestrial efficiencies typically are greater than space efficiencies. For example, a silicon solar cell in space might have an efficiency of 14% at AM0, but 16% on earth at AM 1.5. Note, however, that the number of incident photons in space is considerably larger, so the solar cell might produce considerably more power in space, despite the lower efficiency as indicated by reduced percentage of the total incident energy captured.

Solar cell efficiencies vary from 6% for amorphous silicon-based solar cells to 44.0% with multiple-junction production cells and 44.4% with multiple dies assembled into a hybrid package.[21][22] Solar cell energy conversion efficiencies for commercially available multicrystalline Si solar cells are around 14–19%.[23] 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 produced at low volume might well cost one hundred times as much as an 8% efficient amorphous silicon cell in mass production, while delivering only about four times the output.

However, there is a way to "boost" solar power. By increasing the light intensity, typically photogenerated carriers are increased, increasing 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 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. Commercially available solar cells (as of 2006) reached system efficiencies between 5 and 19%.

Undoped crystalline silicon devices are approaching the theoretical limiting efficiency of 29.43%.[24] In 2017, efficiency of 26.63% was achieved in an amorphous silicon/crystalline silicon heterojunction cell that place both positive and negative contacts on the back of the cell.[25][26]

Energy payback

The energy payback time is defined as the recovery time required for generating the energy spent for manufacturing a modern photovoltaic module. In 2008, it was estimated to be from 1 to 4 years[27][28] depending on the module type and location. With a typical lifetime of 20 to 30 years, this means that modern solar cells would be net energy producers, i.e., they would generate more energy over their lifetime than the energy expended in producing them.[27][29][30] Generally, thin-film technologies—despite having comparatively low conversion efficiencies—achieve significantly shorter energy payback times than conventional systems (often < 1 year).[31]

A study published in 2013 which the existing literature found that energy payback time was between 0.75 and 3.5 years with thin film cells being at the lower end and multi-si-cells having a payback time of 1.5–2.6 years.[32] A 2015 review assessed the energy payback time and EROI of solar photovoltaics. In this meta study, which uses an insolation of 1,700 kWh/m^2/year and a system lifetime of 30 years, mean harmonized EROIs between 8.7 and 34.2 were found. Mean harmonized energy payback time varied from 1.0 to 4.1 years.[33] Crystalline silicon devices achieve on average an energy payback period of 2 years.[27][34]

Like any other technology, solar cell manufacture is dependent on the existence of a complex global industrial manufacturing system. This includes the fabrication systems typically accounted for in estimates of manufacturing energy; the contingent mining, refining and global transportation systems; and other energy intensive support systems including finance, information, and security systems. The difficulty in measuring such energy overhead confers some uncertainty on any estimate of payback times.[35]

Technical methods of improving efficiency

Choosing optimum transparent conductor

The illuminated side of some types of solar cells, thin films, have a transparent conducting film to allow light to enter into the active material and to collect the generated charge carriers. Typically, films with high transmittance and high electrical conductance such as indium tin oxide, conducting polymers or conducting nanowire networks are used for the purpose. There is a trade-off between high transmittance and electrical conductance, thus optimum density of conducting nanowires or conducting network structure should be chosen for high efficiency.[5]

Promoting light scattering

The inclusion of light-scattering effects in solar cells is a photonic strategy to increase the absorption for the lower-energy sunlight photons (chiefly in near-infrared range) for which the photovoltaic material presents reduced absorption coefficient. Such light-trapping scheme is accomplished by the deviation of the light rays from the incident direction, thereby increasing their path length in the cells' absorber.[37] Conventional approaches used to implement light diffusion are based on textured rear/front surfaces, but many alternative optical designs have been demonstrated with promising results based in diffraction gratings, arrays of metal or dielectric nano/micro particles, wave-optical micro-structuring, among others.[38] When applied in the devices' front these structures can act as geometric anti-reflective coatings, simultaneously reducing the reflection of out-going light.

For instance, lining the light-receiving surface of the cell with nano-sized metallic studs can substantially increase the cell efficiency. Light reflects off these studs at an oblique angle to the cell, increasing the length of the light path through the cell. This increases the number of photons absorbed by the cell and the amount of current generated.[39] The main materials used for the nano-studs are silver, gold, and aluminium. Gold and silver are not very efficient, as they absorb much of the light in the visible spectrum, which contains most of the energy present in sunlight, reducing the amount of light reaching the cell.[39] Aluminium absorbs only ultraviolet radiation, and reflects both visible and infra-red light, so energy loss is minimized. Aluminium can increase cell efficiency up to 22% (in lab conditions).[40]

Anti-reflective coatings and textures

Anti-reflective coatings are engineered to reduce the sunlight reflected from the solar cells, therefore enhancing the light transmitted into the photovoltaic absorber.[41] This can be accomplished by causing the destructive interference of the reflected light waves, such as with coatings based on the front (multi-)layer composition, and/or by geometric refractive-index matching caused by the surface topography, with many architectures inspired by nature.[42] For example, the nipple-array, a hexagonal array of subwavelength conical nanostructures, can be seen at the surface of the moth's eyes.[42] It was reported that utilizing this sort of surface architecture minimizes the reflection losses by 25%, converting the additional captured photon to a 12% increase in a solar cell's energy.[42]

The use of front micro-structures, such as those achieved with texturizing or other photonic features, can also be used as a method to achieve anti-reflectiveness, in which the surface of a solar cell is altered so that the impinging light experiences a gradually increasing effective refractive-index when travelling from air towards the photovoltaic material. These surfaces can be created by etching or using lithography. Concomitantly, they promote light scattering effects which further enhance the absorption, particularly of the longer wavelength sunlight photons.[43] Adding a flat back surface in addition to texturizing the front surface further helps to trap the light within the cell, thus providing a longer optical path.

Radiative cooling

An increase in solar cell temperature of approximately 1 °C causes an efficiency decrease of about 0.45%. To prevent this, a transparent silica crystal layer can be applied to solar panels. The silica layer acts as a thermal black body which emits heat as infrared radiation into space, cooling the cell up to 13 °C.[44] Radiative cooling can thus extend the life of solar cells.[45] Full-system integration of solar energy and radiative cooling is referred to as a combined SE–RC system, which have demonstrated higher energy gain per unit area when compared to non-integrated systems.[46]

Rear surface passivation

Surface passivation is critical to solar cell efficiency.[47] Many improvements have been made to the front side of mass-produced solar cells, but the aluminium back-surface is impeding efficiency improvements.[48] The efficiency of many solar cells has benefitted by creating so-called passivated emitter and rear cells (PERCs). The chemical deposition of a rear-surface dielectric passivation layer stack that is also made of a thin silica or aluminium oxide film topped with a silicon nitride film helps to improve efficiency in silicon solar cells. This helped increase cell efficiency for commercial Cz-Si wafer material from just over 17% to over 21% by the mid-2010s,[49] and the cell efficiency for quasi-mono-Si to a record 19.9%.

Concepts of the rear surface passivation for silicon solar cells has also been implemented for CIGS solar cells.[50] The rear surface passivation shows the potential to improve the efficiency. Al_2O_3 and SiO_2 have been used as the passivation materials. Nano-sized point contacts on Al_2O_3 layer[51] and line contacts on SiO2 layer[52] provide the electrical connection of CIGS absorber to the rear electrode Molybdenum. The point contacts on the Al_2O_3 layer are created by e-beam lithography and the line contacts on the SiO_2 layer are created using photolithography. Also, the implementation of the passivation layers does not change the morphology of the CIGS layers.

Thin film materials

Although not constituting a direct strategy to improve efficiency, thin film materials show a lot of promise for solar cells in terms of low costs and adaptability to existing structures and frameworks in technology.[53] Since the materials are so thin, they lack the optical absorption of bulk material solar cells. Attempts to correct this have been demonstrated, such as light-trapping schemes promoting light scattering.[54] Also important is thin film surface recombination. Since this is the dominant recombination process of nanoscale thin-film solar cells, it is crucial to their efficiency. Adding a passivating thin layer of silicon dioxide could reduce recombination.

Tandem cells

Tandem solar cells combine two materials to increase efficiency. In 2022 a device was announced that combined multiple perovskite with multiple layers of silicon. Perovskites harvest blue light, while silicon picks up red and infrared wavelengths. The cell achieved 32.5% efficiency.[55]

RESULTS

A solar panel is a device that converts sunlight into electricity by using photovoltaic (PV) cells. PV cells are made of materials that produce excited electrons when exposed to light. The electrons flow through a circuit and produce direct current (DC) electricity, which can be used to power various devices or be stored in batteries. Solar panels are also known as solar cell panels, solar electric panels, or PV modules.

Solar panels are usually arranged in groups called arrays or systems. A photovoltaic system consists of one or more solar panels, an inverter that converts DC electricity to alternating current (AC) electricity, and sometimes other components such as controllers, meters, and trackers. A photovoltaic system can be used to provide electricity for off-grid applications, such as remote homes or cabins, or to feed electricity into the grid and earn credits or payments from the utility company. This is called a grid-connected photovoltaic system.

Some advantages of solar panels are that they use a renewable and clean source of energy, reduce greenhouse gas emissions, and lower electricity bills. Some disadvantages are that they depend on the availability and intensity of sunlight, require cleaning, and have high initial costs. Solar panels are widely used for residential, commercial, and industrial purposes, as well as for space and transportation applications.

In 1839, the ability of some materials to create an electrical charge from light exposure was first observed by the French physicist Edmond Becquerel.[1] Though these initial solar panels were too inefficient for even simple electric devices, they were used as an instrument to measure light.[2]

The observation by Becquerel was not replicated again until 1873, when the English electrical engineer Willoughby Smith discovered that the charge could be caused by light hitting selenium. After this discovery, William Grylls Adams and Richard Evans Day published "The action of light on selenium" in 1876, describing the experiment they used to replicate Smith's results.[1][3]

In 1881, the American inventor Charles Fritts created the first commercial solar panel, which was reported by Fritts as "continuous, constant and of considerable force not only by exposure to sunlight but also to dim, diffused daylight".[4] However, these solar panels were very inefficient, especially compared to coal-fired power plants.

In 1939, Russell Ohl created the solar cell design that is used in many modern solar panels. He patented his design in 1941.[5] In 1954, this design was first used by Bell Labs to create the first commercially viable silicon solar cell.[1]

Solar panel installers saw significant growth between 2008 and 2013.[6] Due to that growth many installers had projects that were not "ideal" solar roof tops to work with and had to find solutions to shaded roofs and orientation difficulties.[7] This challenge was initially addressed by the re-popularization of micro-inverters and later the invention of power optimizers.

Solar panel manufacturers partnered with micro-inverter companies to create AC modules and power optimizer companies partnered with module manufacturers to create smart modules.[8] In 2013 many solar panel manufacturers announced and began shipping their smart module solutions.[9]

Theory and construction

Photovoltaic modules consist of a large number of solar cells and use light energy (photons) from the Sun to generate electricity through the photovoltaic effect. Most modules use wafer-based crystalline silicon cells or thin-film cells. The structural (load carrying) member of a module can be either the top layer or the back layer. Cells must be protected from mechanical damage and moisture. Most modules are rigid, but semi-flexible ones based on thin-film cells are also available. The cells are usually connected electrically in series, one to another to the desired voltage, and then in parallel to increase current. The power (in watts) of the module is the voltage (in volts) multiplied by the current (in amperes), and depends both on the amount of light and on the electrical load connected to the module. The manufacturing specifications on solar panels are obtained under standard conditions, which are usually not the true operating conditions the solar panels are exposed to on the installation site.[10]

A PV junction box is attached to the back of the solar panel and functions as its output interface. External connections for most photovoltaic modules use MC4 connectors to facilitate easy weatherproof connections to the rest of the system. A USB power interface can also be used.[11] Solar panels also use metal frames consisting of racking components, brackets, reflector shapes, and troughs to better support the panel structure.

Cell connection techniques

In solar modules, the cells themselves need to be connected together to form the module, with front electrodes blocking the solar cell front optical surface area slightly. To maximize frontal surface area available for sunlight and improve solar cell efficiency, manufacturers use varying rear electrode solar cell connection techniques:
- Passivated emitter rear contact (PERC) adds a polymer film to capture light
- Tunnel oxide passivated contact (TOPCon) adds an oxidation layer to the PERC film to capture more light[12]
- Interdigitated back contact (IBC)[13]

Arrays of PV modules

A single solar module can produce only a limited amount of power; most installations contain multiple modules adding their voltages or currents. A photovoltaic system typically includes an array of photovoltaic modules, an inverter, a battery pack for energy storage, a charge controller, interconnection wiring, circuit breakers, fuses, disconnect switches, voltage meters, and optionally a solar tracking mechanism. Equipment is carefully selected to optimize output, energy storage, and reduce power loss during power transmission, and convert from direct current to alternating current.

Smart solar modules

Smart modules are different from traditional solar panels because the power electronics embedded in the module offers enhanced functionality such as panel-level maximum power point tracking, monitoring, and enhanced safety. Power electronics attached to the frame of a solar module, or connected to the photovoltaic circuit through a connector, are not properly considered smart modules.[14]

Several companies have begun incorporating into each PV module various embedded power electronics such as:
- Maximum power point tracking (MPPT) power optimizers, a DC-to-DC converter technology developed to maximize the power harvest from solar photovoltaic systems by compensating for shading effects, wherein a shadow falling on a section of a module causes the electrical output of one or more strings of cells in the module to fall to near zero, but not having the output of the entire module fall to zero.[15]
- Solar performance monitors for data and fault detection

Technology

Most solar modules are currently produced from crystalline silicon (c-Si) solar cells made of polycrystalline or monocrystalline silicon. In 2021, crystalline silicon accounted for 95% of worldwide PV production,[16] while the rest of the overall market is made up of thin-film technologies using cadmium telluride (CdTe), copper indium gallium selenide (CIGS) and amorphous silicon (a-Si).[17]

Emerging, third-generation solar technologies use advanced thin-film cells. They produce a relatively high-efficiency conversion for a lower cost compared with other solar technologies. Also, high-cost, high-efficiency, and close-packed rectangular multi-junction (MJ) cells are usually used in solar panels on spacecraft, as they offer the highest ratio of generated power per kilogram lifted into space. MJ-cells are compound semiconductors and made of gallium arsenide (GaAs) and other semiconductor materials. Another emerging PV technology using MJ-cells is concentrator photovoltaics (CPV).

Thin film

In rigid thin-film modules, the cell and the module are manufactured on the same production line. The cell is created on a glass substrate or superstrate, and the electrical connections are created in situ, a so-called "monolithic integration". The substrate or superstrate is laminated with an encapsulant to a front or back sheet, usually another sheet of glass. The main cell technologies in this category are CdTe, a-Si, a-Si+uc-Si tandem, and CIGS. Amorphous silicon has a sunlight conversion rate of 6–12%.

Flexible thin film cells and modules are created on the same production line by depositing the photoactive layer and other necessary layers on a flexible substrate. If the substrate is an insulator (e.g. polyester or polyimide film) then monolithic integration can be used. If it is a conductor then another technique for electrical connection must be used. The cells are assembled into modules by laminating them to a transparent colourless fluoropolymer on the front side, typically ethylene tetrafluoroethylene (ETFE) or fluorinated ethylene propylene (FEP), and a polymer suitable for bonding to the final substrate on the other side.

Mounting and tracking

Large utility-scale solar power plants usually use ground-mounted photovoltaic systems. Their solar modules are held in place by racks or frames that are attached to ground-based mounting supports.[18][19] Ground based mounting supports include:

- Pole mounts, which are driven directly into the ground or embedded in concrete.
- Foundation mounts, such as concrete slabs or poured footings
- Ballasted footing mounts, such as concrete or steel bases that use weight to secure the solar module system in position and do not require ground penetration. This type of mounting system is well suited for sites where excavation is not possible such as capped landfills and simplifies decommissioning or relocation of solar module systems.

Roof-mounted solar power systems consist of solar modules held in place by racks or frames attached to roof-based mounting supports.[20] Roof-based mounting supports include:

- Rail mounts, which are attached directly to the roof structure and may use additional rails for attaching the module racking or frames.
- Ballasted footing mounts, such as concrete or steel bases that use weight to secure the panel system in position and do not require through penetration. This mounting method allows for decommissioning or relocation of solar panel systems with no adverse effect on the roof structure.
- All wiring connecting adjacent solar modules to the energy harvesting equipment must be installed according to local electrical codes and should be run in a conduit appropriate for the climate conditions

Solar Canopy

Portable

Portable solar panels can ensure electric current, enough to charge devices (mobile, radio, ...) via USB-port or to charge a powerbank f.e. Special features of the panels include high flexibility, high durability & waterproof characteristics. They are good for travel or camping.

Tracking

Solar trackers increase the energy produced per module at the cost of mechanical complexity and increased need for maintenance. They sense the direction of the Sun and tilt or rotate the modules as needed for maximum exposure to the light.[21][22]

Alternatively, fixed racks can hold modules stationary throughout the day at a given tilt (zenith angle) and facing a given direction (azimuth angle). Tilt angles equivalent to an installation's latitude are common. Some systems may also adjust the tilt angle based on the time of year.[23]

On the other hand, east- and west-facing arrays (covering an east–west facing roof, for example) are commonly deployed. Even though such installations will not produce the maximum possible average power from the individual solar panels, the cost of the panels is now usually cheaper than the tracking mechanism and they can provided more economically valuable power during morning and evening peak demands than north or south facing systems.[24]

Concentrator

Some special solar PV modules include concentrators in which light is focused by lenses or mirrors onto smaller cells. This enables the cost-effective use of highly efficient, but expensive cells (such as gallium arsenide) with the trade-off of using a higher solar exposure area. Concentrating the sunlight can also raise the efficiency to around 45%.[25]

Light capture

The amount of light absorbed by a solar cell depends on the angle of incidence of whatever direct sunlight hits it. This is partly because the amount falling on the panel is proportional to the cosine of the angle of incidence, and partly because at high angle of incidence more light is reflected. To maximize total energy output, modules are often oriented to face south (in the Northern Hemisphere) or north (in the Southern Hemisphere) and tilted to allow for the latitude. Solar tracking can be used to keep the angle of incidence small.

Solar panels are often coated with an anti-reflective coating, which is one or more thin layers of substances with refractive indices intermediate between that of silicon and that of air. This causes destructive interference in the reflected light, diminishing the amount. Photovoltaic manufacturers have been working to decrease reflectance with improved anti-reflective coatings or with textured glass.[26][27]

Power curve

In general with individual solar panels, if not enough current is taken, then power isn't maximised. If too much current is taken then the voltage collapses. The optimum current draw is roughly proportional to the amount of sunlight striking the panel. Solar panel capacity is specified by the MPP (maximum power point) value of solar panels in full sunlight.

Inverters
Solar inverters convert the DC power provided by panels to AC power.

MPP (Maximum power point) of the solar panel consists of MPP voltage (V_{mpp}) and MPP current (I_{mpp}). Performing maximum power point tracking (MPPT), a solar inverter samples the output (I-V curve) from the solar cell and applies the proper electrical load to obtain maximum power.

Micro-inverters work independently to enable each panel to contribute its maximum possible output for a given amount of sunlight, but can be more expensive.[28]

Module interconnection
Module electrical connections are made with conducting wires that take the current off the modules and are sized according to the current rating and fault conditions, and sometimes include in-line fuses.

Panels are typically connected in series of one or more panels to form strings to achieve a desired output voltage, and strings can be connected in parallel to provide the desired current capability (amperes) of the PV system.

In string connections the voltages of the modules add, but the current is determined by the lowest performing panel. This is known as the "Christmas light effect". In parallel connections the voltages will be the same, but the currents add. Arrays are connected up to meet the voltage requirements of the inverters and to not greatly exceed the current limits.

Blocking and bypass diodes may be incorporated within the module or used externally to deal with partial array shading, in order to maximize output. For series connections, bypass diodes are placed in parallel with modules to allow current to bypass shaded modules which would otherwise severely limit the current. For paralleled connections, a blocking diode may be placed in series with each module's string to prevent current flowing backwards through shaded strings thus short-circuiting other strings.

Connectors
Outdoor solar panels usually include MC4 connectors. Automotive solar panels may also include an auxiliary power outlet and/or USB adapter. Indoor panels (including solar pv glasses, thin films and windows) can integrate a microinverter (AC Solar panels).

Efficiency
Each module is rated by its DC output power under standard test conditions (STC) and hence the on field output power might vary. Power typically ranges from 100 to 365 Watts (W). The efficiency of a module determines the area of a module given the same rated output – an 8% efficient 230 W module will have twice the area of a 16% efficient 230 W module. Some commercially available solar modules exceed 24% efficiency.[30][31] Currently, the best achieved sunlight conversion rate (solar module efficiency) is around 21.5% in new commercial products[32] typically lower than the efficiencies of their cells in isolation. The most efficient mass-produced solar moduleshave power density values of up to 175 W/m² (16.22 W/ft²).[33]

The current versus voltage curve of a module provides useful information about its electrical performance.[34] Manufacturing processes often cause differences in the electrical parameters of different modules photovoltaic, even in cells of the same type. Therefore, only the experimental measurement of the I–V curve allows us to accurately establish the electrical parameters of a photovoltaic device. This measurement provides highly relevant information for the design, installation and maintenance of photovoltaic systems. Generally, the electrical parameters of photovoltaic modules are measured by indoor tests. However, outdoor testing has important advantages such as no expensive artificial light source required, no sample size limitation, and more homogeneous sample illumination.

Scientists from Spectrolab, a subsidiary of Boeing, have reported development of multi-junction solar cells with an efficiency of more than 40%, a new world record for solar photovoltaic cells.[35] The Spectrolab scientists also predict that concentrator solar cells could achieve efficiencies of more than 45% or even 50% in the future, with theoretical efficiencies being about 58% in cells with more than three junctions.

Capacity factor of solar panels is limited primarily by geographic latitude and varies significantly depending on cloud cover, dust, day length and other factors. In the United Kingdom, seasonal capacity factor ranges from 2% (December) to 20% (July), with average annual capacity factor of 10–11%, while in Spain the value reaches 18%.[36] Globally, capacity factor for utility-scale PV farms was 16.1% in 2019.[37]

Overheating is the most important factor for the efficiency of the solar panel.[38]

Radiation-dependent efficiency
Depending on construction, photovoltaic modules can produce electricity from a range of frequencies of light, but usually cannot cover the entire solar radiation range (specifically, ultraviolet, infrared and low or diffused light). Hence, much of the incident sunlight energy is wasted by solar modules, and they can give far higher efficiencies if illuminated with monochromatic light. Therefore, another design concept is to split the light into six to eight different wavelength ranges that will produce a different color of light, and direct the beams onto different cells tuned to those ranges.[39]

Performance and degradation
Module performance is generally rated under standard test conditions (STC): irradiance of 1,000 W/m², solar spectrum of AM 1.5 and module temperature at 25 °C.[40] The actual voltage and current output of the module changes as lighting, temperature and load conditions change, so there is never one specific voltage at which the module operates. Performance varies depending on geographic location, time of day, the day of the year, amount of solar irradiance, direction and tilt of modules, cloud cover, shading, soiling, state of charge, and temperature. Performance of a module or panel can be measured at different time intervals with a DC clamp meter or shunt and logged, graphed, or charted with a chart recorder or data logger.

For optimum performance, a solar panel needs to be made of similar modules oriented in the same direction perpendicular to direct sunlight. Bypass diodes are used to circumvent broken or shaded panels and optimize output.

These bypass diodes are usually placed along groups of solar cells to create a continuous flow.[41]

Electrical characteristics include nominal power (P_{MAX}, measured in W), open-circuit voltage (V_{OC}), short-circuit current (I_{SC}, measured in amperes), maximum power voltage (V_{MPP}), maximum power current (I_{MPP}), peak power, (watt-peak, W_p), and module efficiency (%).

Open-circuit voltage or V_{OC} is the maximum voltage the module can produce when not connected to an electrical circuit or system.[42] V_{OC} can be measured with a voltmeter directly on an illuminated module's terminals or on its disconnected cable.

The peak power rating, W_p, is the maximum output under standard test conditions (not the maximum possible output). Typical modules, which could measure approximately 1 by 2 metres (3 ft × 7 ft), will be rated from as low as 75 W to as high as 600 W, depending on their efficiency. At the time of testing, the test modules are binned according to their test results, and a typical manufacturer might rate their modules in 5 W increments, and either rate them at +/- 3%, +/-5%, +3/-0% or +5/-0%.[43][44][45]

Influence of temperature

The performance of a photovoltaic (PV) module depends on the environmental conditions, mainly on the global incident irradiance G in the plane of the module. However, the temperature T of the p–n junction also influences the main electrical parameters: the short circuit current ISC, the open circuit voltage VOC and the maximum power Pmax. In general, it is known that VOC shows a significant inverse correlation with T, while for ISC this correlation is direct, but weaker, so that this increase does not compensate for the decrease in VOC. As a consequence, Pmax decreases when T increases. This correlation between the power output of a solar cell and the working temperature of its junction depends on the semiconductor material, and is due to the influence of T on the concentration, lifetime, and mobility of the intrinsic carriers, i.e., electrons and gaps. inside the photovoltaic cell.

Temperature sensitivity is usually described by temperature coefficients, each of which expresses the derivative of the parameter to which it refers with respect to the junction temperature. The values of these parameters can be found in any data sheet of the photovoltaic module; are the following:

- β: VOC variation coefficient with respect to T, given by ∂VOC/∂T.
- α: Coefficient of variation of ISC with respect to T, given by ∂ISC/∂T.
- δ: Coefficient of variation of Pmax with respect to T, given by ∂Pmax/∂T.

Techniques for estimating these coefficients from experimental data can be found in the literature[46]

Degradation

The ability of solar modules to withstand damage by rain, hail, heavy snow load, and cycles of heat and cold varies by manufacturer, although most solar panels on the U.S. market are UL listed, meaning they have gone through testing to withstand hail.[47]

Potential-induced degradation (also called PID) is a potential-induced performance degradation in crystalline photovoltaic modules, caused by so-called stray currents.[48] This effect may cause power loss of up to 30%.[49]

Advancements in photovoltaic technologies have brought about the process of "doping" the silicon substrate to lower the activation energy thereby making the panel more efficient in converting photons to retrievable electrons.[50]

Chemicals such as boron (p-type) are applied into the semiconductor crystal in order to create donor and acceptor energy levels substantially closer to the valence and conductor bands.[51] In doing so, the addition of boron impurity allows the activation energy to decrease twenty-fold from 1.12 eV to 0.05 eV. Since the potential difference (E_B) is so low, the boron is able to thermally ionize at room temperatures. This allows for free energy carriers in the conduction and valence bands thereby allowing greater conversion of photons to electrons.

The power output of a photovoltaic (PV) device decreases over time. This decrease is due to its exposure to solar radiation as well as other external conditions. The degradation index, which is defined as the annual percentage of output power loss, is a key factor in determining the long-term production of a photovoltaic plant. To estimate this degradation, the percentage of decrease associated with each of the electrical parameters. The individual degradation of a photovoltaic module can significantly influence the performance of a complete string. Furthermore, not all modules in the same installation decrease their performance at exactly the same rate. Given a set of modules exposed to long-term outdoor conditions, the individual degradation of the main electrical parameters and the increase in their dispersion must be considered. As each module tends to degrade differently, the behavior of the modules will be increasingly different over time, negatively affecting the overall performance of the plant.

There are several studies dealing with the power degradation analysis of modules based on different photovoltaic technologies available in the literature. According to a recent study,[52] the degradation of crystalline silicon modules is very regular, oscillating between 0.8% and 1.0% per year.

On the other hand, if we analyze the performance of thin-film photovoltaic modules, an initial period of strong degradation is observed (which can last several months and even up to 2 years), followed by a later stage in which the degradation stabilizes, being then comparable to that of crystalline silicon.[53] Strong seasonal variations are also observed in such thin-film technologies because the influence of the solar spectrum is much greater. For example, for modules of amorphous silicon, micromorphic silicon or cadmium telluride, we are talking about annual degradation rates for the first years of between 3% and 4%.[54] However, other technologies, such as CIGS, show much lower degradation rates, even in those early years.

Solar panel conversion efficiency, typically in the 20% range, is reduced by the accumulation of dust, grime, pollen, and other particulates on the solar panels, collectively referred to as soiling. "A dirty solar panel can reduce its power capabilities by up to 30% in high dust/pollen or desert areas", says Seamus Curran, associate professor of physics at the University of Houston and director of the Institute for NanoEnergy, which specializes in the design, engineering, and assembly of nanostructures.[55] The average soiling loss in the world in 2018 is estimated to be at least 3% – 4%.[56]

Paying to have solar panels cleaned is a good investment in many regions, as of 2019.[56] However, in some regions, cleaning is not cost-effective. In California as of 2013 soiling-induced financial losses were rarely enough to warrant the cost of washing the panels. On average, panels in California lost a little less than 0.05% of their overall efficiency per day.[57]

There are also occupational hazards with solar panel installation and maintenance. A 2015–2018 study in the UK investigated 80 PV-related incidents of fire, with over 20 "serious fires" directly caused by PV installation, including 37 domestic buildings and 6 solar farms. In $^1/_3$ of the incidents a root cause was not established and in a majority of others was caused by poor installation, faulty product or design issues. The most frequent single element causing fires was the DC isolators.[58]

A 2021 study by kWh Analytics determined median annual degradation of PV systems at 1.09% for residential and 0.8% for non-residential ones, almost twice that previously assumed.[59] A 2021 module reliability study found an increasing trend in solar module failure rates with 30% of manufacturers experiencing safety failures related to junction boxes (growth from 20%) and 26% bill-of-materials failures (growth from 20%).[60]

Cleaning methods for solar panels can be divided into 5 groups: manual tools, mechanized tools (such as tractor mounted brushes), installed hydraulic systems (such as sprinklers), installed robotic systems, and deployable robots. Manual cleaning tools are by far the most prevalent method of cleaning, most likely because of the low purchase cost. However, in a Saudi Arabian study done in 2014, it was found that "installed robotic systems, mechanized systems, and installed hydraulic systems are likely the three most promising technologies for use in cleaning solar panels".[61]

Waste and recycling

There were 30 thousand tonnes of PV waste in 2021, and the annual amount was estimated by Bloomberg NEF to rise to more than 1 million tons by 2035 and more than 10 million by 2050.[62] For comparison 750 million tons of fly ash waste was produced by coal power in 2022.[63] In the United States, around 90% of decommissioned solar panels end up in landfills as of 2023.[64] Most parts of a solar module can be recycled including up to 95% of certain semiconductor materials or the glass as well as large amounts of ferrous and non-ferrous metals.[65] Some private companies and non-profit organizations are currently engaged in take-back and recycling operations for end-of-life modules.[66] EU law requires manufacturers to ensure their solar panels are recycled properly. Similar legislation is underway in Japan, India, and Australia.[67] A 2023 Australian report said that there is a market for quality used panels and made recommendations for increasing reuse.[68]:33

Recycling possibilities depend on the kind of technology used in the modules:

- Silicon based modules: aluminum frames and junction boxes are dismantled manually at the beginning of the process. The module is then crushed in a mill and the different fractions are separated – glass, plastics and metals.[69] It is possible to recover more than 80% of the incoming weight.[70] This process can be performed by flat glass recyclers since morphology and composition of a PV module is similar to those flat glasses used in the building and automotive industry. The recovered glass, for example, is readily accepted by the glass foam and glass insulation industry.
- Non-silicon based modules: they require specific recycling technologies such as the use of chemical baths in order to separate the different semiconductor materials.[71] For cadmium telluride modules, the recycling process begins by crushing the module and subsequently separating the different fractions. This recycling process is designed to recover up to 90% of the glass and 95% of the semiconductor materials contained.[72] Some commercial-scale recycling facilities have been created in recent years by private companies.[73] For aluminium flat plate reflector: the trendinessof the reflectors has been brought up by fabricating them using a thin layer (around 0.016 mm to 0.024 mm) of aluminum coating present inside the non-recycled plastic food packages.[74]

Since 2010, there is an annual European conference bringing together manufacturers, recyclers and researchers to look at the future of PV module recycling.[75][76]

Production

Top producers of PV systems, by shipped capacity in gigawatts	
Module producer	Shipments in 2019 (GW)[77]
Jinko Solar	14.2
JA Solar	10.3
Trina Solar	9.7
LONGi Solar	9.0
Canadian Solar	8.5
Hanwha Q Cells	7.3
Risen Energy	7.0
First Solar	5.5
GCL System	4.8
Shunfeng Photovoltaic	4.0

The production of PV systems has followed a classic learning curve effect, with significant cost reduction occurring alongside large rises in efficiency and production output.[78]

With over 100% year-on-year growth in PV system installation, PV module makers dramatically increased their shipments of solar modules in 2019. They actively expanded their capacity and turned themselves into gigawatt GW players.[79] According to Pulse Solar, five of the top ten PV module companies in 2019 have experienced a rise in solar panel production by at least 25% compared to 2019.[80]

The basis of producing solar panels revolves around the use of silicon cells.[81] These silicon cells are typically 10–20% efficient[82] at converting sunlight into electricity, with newer production models now exceeding 22%.[83]

In 2018, the world's top five solar module producers in terms of shipped capacity during the calendar year of 2018 were Jinko Solar, JA Solar, Trina Solar, Longi solar, and Canadian Solar.[84]

Price

The price of solar electrical power has continued to fall so that in many countries it has become cheaper than fossil fuel electricity from the electricity grid since 2012, a phenomenon known as grid parity.[87] With the rise of global awareness, institutions such as the IRS have adopted a tax credit format, refunding a portion of any solar panel array for private use.[88] The price of a solar array only continues to fall.

Average pricing information divides in three pricing categories: those buying small quantities (modules of all sizes in the kilowatt range annually), mid-range buyers (typically up to 10 MWp annually), and large quantity buyers (self-explanatory—and with access to the lowest prices). Over the long term there is clearly a systematic reduction in the price of cells and modules. For example, in 2012 it was estimated that the quantity cost per watt was about US$0.60, which was 250 times lower than the cost in 1970 of US$150.[89][90] A 2015 study shows price/kWh dropping by 10% per year since 1980, and predicts that solar could contribute 20% of total electricity consumption by 2030, whereas the International Energy Agency predicts 16% by 2050.[91]

Real-world energy production costs depend a great deal on local weather conditions. In a cloudy country such as the United Kingdom, the cost per produced kWh is higher than in sunnier countries like Spain.

Following to RMI, Balance-of-System (BoS) elements, this is, non-module cost of non-microinverter solar modules (as wiring, converters, racking systems and various components) make up about half of the total costs of installations.

For merchant solar power stations, where the electricity is being sold into the electricity transmission network, the cost of solar energy will need to match the wholesale electricity price. This point is sometimes called 'wholesale grid parity' or 'busbar parity'.[87]

Some photovoltaic systems, such as rooftop installations, can supply power directly to an electricity user. In these cases, the installation can be competitive when the output cost matches the price at which the user pays for their electricity consumption. This situation is sometimes called 'retail grid parity', 'socket parity' or 'dynamic grid parity'.[93] Research carried out by UN-Energy in 2012 suggests areas of sunny countries with high electricity prices, such as Italy, Spain and Australia, and areas using diesel generators, have reached retail grid parity.[87]

Standards

Standards generally used in photovoltaic modules:

- IEC 61215 (crystalline silicon performance), 61646 (thin film performance) and 61730 (all modules, safety), 61853 (Photovoltaic module performance testing & energy rating)
- ISO 9488 Solar energy—Vocabulary.
- UL 1703 from Underwriters Laboratories
- UL 1741 from Underwriters Laboratories
- UL 2703 from Underwriters Laboratories
- CE mark
- Electrical Safety Tester (EST) Series (EST-460, EST-22V, EST-22H, EST-110).

Applications

There are many practical applications for the use of solar panels or photovoltaics. It can first be used in agriculture as a power source for irrigation. In health care solar panels can be used to refrigerate medical supplies. It can also be used for infrastructure. PV modules are used in photovoltaic systems and include a large variety of electric devices:

- Solar canals
- Photovoltaic power stations
- Rooftop solar PV systems
- Standalone PV systems
- Solar hybrid power systems
- Concentrated photovoltaics
- Floating solar; water-borne solar panels
- Solar planes
- Solar-powered water purification
- Solar-pumped lasers
- Solar vehicles
- Solar water heating
- Solar panels on spacecraft and space stations
- Solar landfill

Limitations

Impact on electricity network

With the increasing levels of rooftop photovoltaic systems, the energy flow becomes 2-way. When there is more local generation than consumption, electricity is exported to the grid. However, an electricity network traditionally is not designed to deal with the 2- way energy transfer. Therefore, some technical issues may occur. For example, in Queensland Australia, more than 30% of households used rooftop PV by the end of 2017. The duck curve appeared often for a lot of communities from 2015 onwards. An over-voltage issue may result as the electricity flows from PV households back to the network.[94] There are solutions to manage the over voltage issue, such as regulating PV inverter power factor, new voltage and energy control equipment at the electricity distributor level, re-conducting the electricity wires, demand side management, etc. There are often limitations and costs related to these solutions.

For rooftop solar to be able to provide enough backup power during a power cut a battery is often also required.[95]

Solar module quality assurance

Solar module quality assurance involves testing and evaluating solar cells and Solar Panels to ensure the quality requirements of them are met. Solar modules (or panels) are expected to have a long service life between 20 and 40 years.[96] They should continually and reliably convey and deliver the power anticipated. modules presented to a wide exhibit of climate conditions alongside use in various temperatures. Solar modules can be tested through a combination of physical tests, laboratory studies, and numerical analyses.[97] Furthermore, solar modules need to be assessed throughout the different stages of their life cycle. Various companies such as Southern Research Energy & Environment, SGS Consumer Testing Services, TÜV Rheinland, Sinovoltaics, Clean Energy Associates (CEA), CSA Solar International and Enertis provide services in solar module quality assurance. "The implementation of consistent traceable and stable manufacturing processes becomes mandatory to safeguard and ensure the quality of the PV Modules" [98]

Stages of testing

The lifecycle stages of testing solar modules can include: the conceptual phase, manufacturing phase, transportation and installation, commissioning phase, and the in-service phase. Depending on the test phase, different test principles may apply.

Conceptual phase

The first stage can involve design verification where the expected output of the module is tested through computer simulation. Further, the modules ability to withstand natural environment conditions such as temperature, rain, hail, snow, corrosion, dust, lightning, horizon and near-shadow effects is tested. The layout for design and construction of the module and the quality of components and installation can also be tested at this stage.

Manufacturing phase

Inspecting manufacturers of components is carried through visitation. The inspection can include assembly checks, material testing supervision and Non Destructive Testing (NDT). Certification is carried out according to ANSI/UL1703, IEC 17025, IEC 61215, IEC 61646, IEC 61701 and IEC 61730-1/-2.

AC module

An AC (Alternating Current) module is a photovoltaic module which has a small DC to AC microinverter mounted onto its back side which produces AC power with no external DC connector.

AC modules are defined by Underwriters Laboratories as the smallest and most complete system for harvesting solar energy.[99]

CONCLUSION

The theory of solar cells explains the process by which light energy in photons is converted into electric current when the photons strike a suitable semiconductor device. The theoretical studies are of practical use because they predict the fundamental limits of a solar cell, and give guidance on the phenomena that contribute to losses and solar cell efficiency.

Working explanation

1. Photons in sunlight hit the solar panel and are absorbed by semi-conducting materials.
2. Electrons (negatively charged) are knocked loose from their atoms as they are excited. Due to their special structure and the materials in solar cells, the electrons are only allowed to move in a single direction. The electronic structure of the materials is very important for the process to work, and often silicon incorporating small amounts of boron or phosphorus is used in different layers.
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 semiconductor, one of three things can happen:

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

When a photon is absorbed, its energy is given to an electron in the crystal lattice. Usually this electron is in the valence band. The energy given to the electron by the photon "excites" it into the conduction band where it is free to move around within the semiconductor. The network of covalent bonds that the electron was previously a part of now has one fewer electron. This is known as a hole, and it has positive charge. The presence of a missing covalent bond allows the bonded electrons of neighboring atoms to move into the "hole", leaving another hole behind, thus propagating holes throughout the lattice in the opposite direction to the movement of the negatively electrons. It can be said that photons absorbed in the semiconductor create electron-hole pairs.

A photon only needs to have energy greater 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 about 5,800 K,[1] and as such, much of the solar radiation reaching the Earth is composed of photons with energies greater than the band gap of silicon (1.12eV), which is near to the ideal value for a terrestrial solar cell (1.4eV). These higher energy photons will be absorbed by a silicon 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.

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. n-type doping produces mobile electrons (leaving behind positively charged donors) while p-type doping produces mobile holes (and negatively charged acceptors) 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 close 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 into the p-type side, each one annihilates a hole, making that side net negatively charged (because now the number of mobile positive holes is now less than the number of negative acceptors). Similarly, holes diffusing to the n-type side make it more positively charged. However (in the absence of an external circuit) this diffusion current of carriers does not go on indefinitely because the charge build up on either side of the junction produces an electric field that opposes further diffusion of more charges. Eventually, an equilibrium is reached where the net current is zero, leaving a region either side of the junction where electrons and holes have diffused across the junction and annihilated each other called the depletion region because it contains practically no mobile charge carriers. It is also known as the space charge region, although space charge extends a bit further in both directions than the depletion region.

Once equilibrium is established, electron-hole pairs generated in the depletion region are separated by the electric field, with the electron attracted to the positive n-type side and holes to the negative p-type side, reducing the charge (and the electric field) built up by the diffusion just described. If the device is unconnected (or the external load is very high) then diffusion current would eventually restore the equilibrium charge by bringing the electron and hole back across the junction, but if the load connected is small enough, the electrons prefer to go around the external circuit in their attempt to restore equilibrium, doing useful work on the way.

Charge carrier separation

There are two causes of charge carrier motion and separation in a solar cell:

1. drift of carriers, driven by the electric field, with electrons being pushed one way and holes the other way

2. diffusion of carriers from zones of higher carrier concentration to zones of lower carrier concentration (following a gradient of chemical potential).

These two "forces" may work one against the other at any given point in the cell. For instance, an electron moving through the junction from the p region to the n region (as in the diagram at the beginning of this article) is being pushed by the electric field against the concentration gradient. The same goes for a hole moving in the opposite direction.

It is easiest to understand how a current is generated when considering electron-hole pairs that are created in the depletion zone, which is where there is a strong electric field. The electron is pushed by this field toward the n side and the hole toward the p side. (This is opposite to the direction of current in a forward-biased diode, such as a light-emitting diode in operation.) When the pair is created outside the space charge zone, where the electric field is smaller, diffusion also acts to move the carriers, but the junction still plays a role by sweeping any electrons that reach it from the p side to the n side, and by sweeping any holes that reach it from the n side to the p side, thereby creating a concentration gradient outside the space charge zone.

In thick solar cells there is very little electric field in the active region outside the space charge zone, so the dominant mode of charge carrier separation is diffusion. In these cells the diffusion length of minority carriers (the length that photo-generated carriers 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.[2]

Once the minority carrier enters the drift region, it is 'swept' across the junction and, at the other side of the junction, becomes a majority carrier. This reverse current is a generation current, fed both thermally and (if present) by the absorption of light. On the other hand, majority carriers are driven into the drift region by diffusion (resulting from the concentration gradient), which leads to the forward current; only the majority carriers with the highest energies (in the so-called Boltzmann tail; cf. Maxwell–Boltzmann statistics) can fully cross the drift region. Therefore, the carrier distribution in the whole device is governed by a dynamic equilibrium between reverse current and forward current.

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 created on the p-type side, "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 majority carriers (electrons in the n-type portion and holes in the p-type portion) at the two terminals.[3]

Equivalent circuit 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 ideal electrical components whose behavior is well defined. 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.[4] The resulting equivalent circuit of a solar cell is shown on the right. Also shown, on the left, is the schematic representation of a solar cell for use in circuit diagrams.

REFERENCES

[1] Solar Cells. chemistryexplained.com

[2] "Solar cells – performance and →use". solarbotic s.net.

[3] Al-Ezzi, Athil S.; Ansari, Mohamed Nainar M. (8 July 2022). "Photovoltaic Solar Cells: A Review". Applied System Innovation. 5 (4): 67. doi:10.3390/asi5040067. ISSN 2571-5577.

[4] Connors, John (21–23 May 2007). "On the Subject of Solar Vehicles and the Benefits of the Technology". 2007 International Conference on Clean Electrical Power. Capri, Italy. pp. 700–705. doi:10.1109/ICCEP.2007.384287.

[5] Arulious, Jora A; Earlina, D; Harish, D; Sakthi Priya, P; Inba Rexy, A; Nancy Mary, J S (1 November 2021). "Design of solar powered electric vehicle". Journal of Physics: Conference Series. 2070 (1): 012105. Bibcode:2021JPhCS2070a2105A. doi:10.1088/1742-6596/2070/1/012105. ISSN 1742-6588.

[6] Nivas, Mandakuriti; Naidu, Rambilli Krishna Prasad Rao; Mishra, Debani Prasad; Salkuti, Surender Reddy (March 2022). "Modeling and analysis of solar-powered electric vehicles". International Journal of Power Electronics and Drive Systems. 13 (1): 480–487. doi:10.11591/ijpeds.v13.i1.pp480-487. ISSN 2722-256X.

[7] "Technology Roadmap: Solar Photovoltaic Energy" (PDF). IEA. 2014. Archived (PDF) from the original on 1 October 2014. Retrieved 7 October 2014.

[8] "Photovoltaic System Pricing Trends – Historical, Recent, and Near-Term Projections, 2014 Edition" (PDF). NREL. 22 September 2014. p. 4. Archived (PDF) from the original on 26 February 2015.

[9] "Documenting a Decade of Cost Declines for PV Systems". National Renewable Energy Laboratory (NREL). Retrieved 3 June 2021.

[10] Gevorkian, Peter (2007). Sustainable energy systems engineering: the complete green building design resource. McGraw Hill Professional. ISBN 978-0-07-147359-0.

[11] "Julius (Johann Phillipp Ludwig) Elster: 1854 - 1920". Adventures in Cybersound. Archived from the original on 8 March 2011. Retrieved 15 October 2016.

[12] "The Nobel Prize in Physics 1921: Albert Einstein", Nobel Prize official page

[13] Lashkaryov, V. E. (2008). "Investigation of a barrier layer by the thermoprobe method" (PDF). Ukr. J. Phys. 53 (Special Issue): 53–56. ISSN 2071-0194. Archived from the original (PDF) on 28 September 2015.

Translated and reprinted from Izv. Akad. Nauk SSSR, Ser. Fiz. 5, No. 4–5, pp. 442–446 (1941)

[14] "Light sensitive device" U.S. Patent 2,402,662 Issue date: June 1946

[15] Lehovec, K. (15 August 1948). "The Photo-Voltaic Effect". Physical Review. 74 (4): 463–471. Bibcode:1948PhRv...74..463L. oi:10.1103/PhysRev.74.463.

[16] Lau, W.S. (October 2017). "Introduction to the World of Semiconductors". ULSI Front-End Technology: Covering from the First Semiconductor Paper to CMOS FINFET Technology. p. 7. doi:10.1142/10495. ISBN 978-981-322-215-1.

[17] "April 25, 1954: Bell Labs Demonstrates the First Practical Silicon Solar Cell". APS News. American Physical Society. 18 (4). April 2009.

[18] Tsokos, K. A. (28 January 2010). Physics for the IB Diploma Full Colour. Cambridge University Press. ISBN 978-0-521-13821-5.

[19] Garcia, Mark (31 July 2017). "International Space Station Solar Arrays". NASA. Retrieved 10 May 2019.

[20] David, Leonard (4 October 2021). "Air Force's X-37B robotic space plane wings past 500 days in Earth orbit". LiveScience. Retrieved 6 November 2021.