

Chapter 4

SOLAR TECH

How Solar Technologies Harvest Energy From the Sun

This chapter considers the processes and technologies needed to turn light into power: first for solar photovoltaics, and then for solar-thermal. It then considers the relative strengths and weaknesses of these two ways of harvesting the sun's power. The aim is to provide a good technological background for the solar case histories in the following two chapters.

The photovoltaic effect

The photovoltaic effect is the ability of a semiconducting material to convert light directly into electrical energy. (A semiconductor is a solid with an intermediate electrical conductivity somewhere between a conductor and an insulator). The photovoltaic phenomenon was discovered by Edmond Becquerel, who noticed when experimenting with batteries in 1839 that the amount of electricity produced would vary with light. In 1876 William Grylls Adams and Richard Evans Day discovered that selenium produces electricity when exposed to light. Selenium solar cells were thereafter used for extremely low power applications, such as photographic exposure meters, right up until the 1970s. Although there was a lot of scientific research on the photovoltaic effect in the first half of the twentieth century, including a paper by Albert Einstein which won a Nobel Prize, the breakthrough happened in 1954 at Bell Laboratories. Scientists working there made the first silicon photovoltaic cell, increasing the energy output to a much more useful level.

This groundbreaking cell achieved 6% efficiency: that is, it converted 6% of the potential energy in the sunlight into electricity. Over time, the technology was developed further to achieve 15% and then over 20% efficiency. Crystalline silicon solar cells in use today commonly have an efficiency of around 16%, though the best performers reach 25% in the

laboratory. (Note that the cells are used in panels, also known as modules, as described later in the chapter. These have slightly lower efficiencies than the cells they contain, because not all the panel area is covered in cells, and because there is slight variability in performance between individual cells).

Initially, the silicon photovoltaic cell struggled to find a market, but in the late 1950s and 1960s it became the default power source for spacecraft and satellites. The next big step forward came from Elliot Berman's Solar Power Corporation, where the production cost was reduced by a factor of five using a less pure grade of silicon. This 80% cost reduction made photovoltaics a cost-competitive technology for remote areas without access to the grid. As a result, they began to be used for applications such as telecommunications. Today there is a fully established global photovoltaics industry, worth around \$50 billion in 2008, which has been growing at a rate well in excess of 50% per year for the last three years – driving costs ever lower, as we'll soon see.

How a photovoltaic cell works

The basic structure of a photovoltaic cell is shown in Figure 13. Photovoltaic power generation happens when light is absorbed in a semiconductor material to release positive and negative charge carriers which are extracted from the material as an electric current. The material in most cells used today is silicon, one of the most abundant elements on earth. Silicon combines with oxygen readily to form minerals called silicates, such as quartz (silicon dioxide, or SiO_2), which is the main mineral in sand. Pure silicon can be separated from sand, in a manner described below, and this is the material used in silicon solar cells.

Generation of an electric current comes about as follows. Each silicon atom has four bonding electrons in its outer shell and, in the high-purity crystals needed to make a solar cell, neighbouring silicon atoms join together by forming electron bond pairs. Light is capable of breaking these bonds, freeing an electron, and raising the electron to an energy level where it can move through the silicon crystal. The free electron leaves behind a positively charged hole in the crystal lattice which will also move around. The electrons are negatively charged and the holes are positively charged. Their motion is random but if the electrons can be

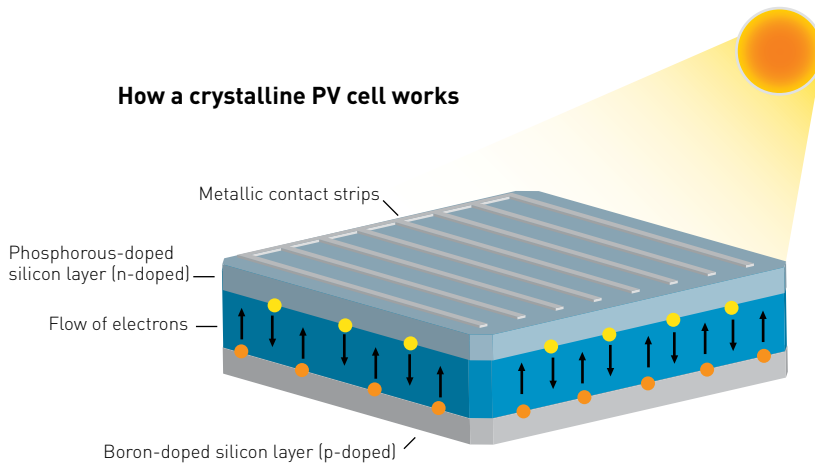


Figure 13: How a photovoltaic cell works.

forced to move in one direction and the holes in the opposite direction then they will form an electric current. The breakthrough at Bell Labs was to find a way to modify the silicon to ensure this separation occurs.

If impurities are introduced in controlled quantities into the crystal lattice – a process known as ‘doping’ – the crystal structure can be primed for electricity generation. A phosphorus atom has one electron more than silicon in its outer shell, and a boron atom has one electron less. This makes them perfect for the job. The cell can be thought of as a sandwich of two layers, one phosphorus-doped and one boron-doped. At the junction between the phosphorus-doped silicon layer (the negative-doped or n-doped layer, as the technologists call it) and the boron-doped layer (the positive-doped or p-doped layer) there is an electric field which makes the electrons produced by the sunlight go one way and the holes the other. This makes a current, which can be picked up in a circuit if wires are connected to the cell. Because the electrons are at higher energy levels than the holes, a voltage is created which drives the electrons and holes round the circuit in opposite directions and gets them to do work. For power, both current and voltage are required.

Light needs to pass through into the cell, and so in most crystalline silicon cells the metallic contacts on the front are thin strips, usually screen-printed as a grid onto the cell. At the back contact, in most crystalline silicon cells, the metallic layer can cover the whole surface.¹

What we have just described is the process as it happens in a crystalline silicon solar cell. In thin-film photovoltaic cells the basic physics is the same, but charges are separated in a different way, which we describe in the

section on thin-film cells below. First let us consider the manufacturing process for crystalline silicon cells, which make up around 90% of the global photovoltaics market today.

Crystalline silicon: from sand to solar

The photovoltaics industry can best be thought of as a chain of industrial activities, each quite different but entirely dependent on the one before. Let's take a look at these stages in turn, starting at the top of the chain.

Solar feedstock

The journey begins with the melting of sand to provide feedstock for the industry. A mix of silicates and carbon is heated to over 1,900°Celsius in a furnace. The carbon bonds with the oxygen from the silicates and the result is liquid silicon plus carbon dioxide or carbon monoxide. The liquid silicon left at the bottom of the furnace is 98% pure and known as metallurgical-grade silicon. Usually, if this is made into solar cells, it must first be purified into solar-grade silicon, which is 99.99999% pure.

To purify silicon it is converted into an intermediate silicon-rich gas. The most common is trichlorosilane, although silicon tetrachloride and silane are also used. The gases are blown over 'seeds' of pure silicon at high temperatures. The seeds can be rods or smaller particles which drop through the heated silicon-rich gas. Either way, the gases deposit so-called solar-grade silicon around the seeds.

The Siemens process is one of the most common methods of making solar-grade silicon. In this process the trichlorosilane gas is heated to 1,150°Celsius and exposed to high purity silicon rods which grow as the silicon is deposited onto them. Another method is to use a so-called fluidised bed reactor, which makes use of small particle-type seeds.

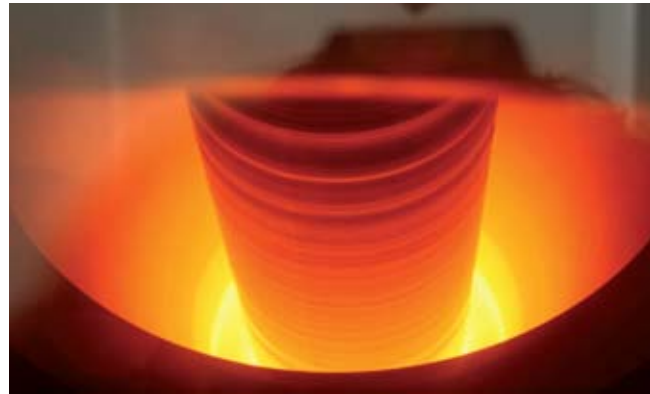
Silicon feedstock production is an energy- and capital-intensive business. It costs between \$600,000 and \$1.1 million to produce enough silicon for each megawatt of solar capacity, and it takes three–four years to build each new plant.² This means that historically this part of the value chain has been the domain of big chemical companies. Until recently, there were only half a dozen main players. But with the rapid growth of the solar photovoltaics industry, and the huge influx of investment this has entailed, the situation is changing. Silicon production for the solar

industry exceeded silicon production for the semiconductor industry for the first time in 2006. By 2008, global solar feedstock production amounted to 71,000 tonnes. (As a rule of thumb, 1 tonne of silicon can produce cells that can generate 10 megawatts of solar-photovoltaic power, and 10 grams will produce 1 watt). The amount of solar feedstock production expected in 2009 by the more optimistic industry analysts is in excess of 120,000 tonnes.³ Sixteen companies account for 85% of that anticipated production.⁴

Wafers

The solar-grade silicon needs to be made into wafers. There are two types of wafer: polycrystalline (sometimes also referred to as multicrystalline) and mono-crystalline. The solar-grade silicon pieces, which can include off-cuts and breakages from other parts of the production process, are melted in a large crucible, with boron generally added to start the doping process. For polycrystalline silicon, the molten silicon is cooled into a large block which is then sawn into bricks with a square cross section, typically 150 millimetres by 150 millimetres. Wire saws are then used to slice the polycrystalline silicon brick into very thin wafers, typically 200–300 microns thick. A micron is a thousandth of a millimetre, so the wafers are around a quarter of a millimetre each – or twice the width of a human hair.

The monocrystalline approach, by contrast, involves drawing a single crystal of silicon from a bath of liquid silicon, usually using the so-called Czochralski process. This results in an ingot (a block of silicon) with a circular cross section. Before the ingot is sawn into wafers the edges are trimmed to produce a pseudo square cross section that results in wafers which appear to have had the corners knocked off.



The production of a monocrystalline solar cell PV cell - the molten silicon being drawn from the crucible (above) and the cooled ingot before slicing into wafers (left). (images: Trina Solar)





A completed solar cell, before assembly into a module
(Image: Trina Solar)

Whilst solar cells made from polycrystalline silicon are generally less efficient than those made from monocrystalline silicon, the fact that the cells are truly square and can be packed together in a module without any wasted space means that the modules generally have the same power density. One company, Evergreen Solar, has developed a technology that has no need for sawing of ingots. Two thin ribbons of monocrystalline silicon are pulled slowly from a crucible, and these can be cut directly into wafers.

Wafer production requires capital expenditure of between \$300,000 and \$800,000 per megawatt, and it takes nine–eighteen months to build a plant, with a further six months or so for equipment installation and set-up. The range in these figures (and those quoted for cells and modules below) is due to differences in technology, geography, vendor and level of automation.⁵

Wafers to cells

The silicon wafers are now ready to be converted into solar cells. The first stage is to prepare the surface of the wafer following the sawing. The cell is etched to clean up the surface and increase light capture. The silicon is then doped on the light-facing side with phosphorus, and an anti-reflective coating is added. Without this, the silicon would reflect up to 35% of sunlight, making it much less efficient. Finally, electrical connectors are printed on to the top and bottom of the cell, and conductive ribbons are attached to allow the cells to be connected together.

The typical efficiency of a monocrystalline cell today is 16%. The most efficient cells available commercially at the time of writing are produced by a manufacturer called Sunpower, which has designed a cell without metallic contacts on the front. These aesthetically pleasing black cells reach an efficiency of 22%. In Sunpower laboratory work, efficiency has been lifted to 23.4%. The world laboratory record for cell efficiency at the time of writing is 24.7%, held by the University of New South Wales.

Cell production requires capital expenditure of between \$200,000 and \$600,000 per megawatt, and it takes twelve–twenty-four months to build a plant, with a further three–nine months for equipment installation and set-up.⁶

Cells to modules

A silicon solar cell will have a voltage between the front and the back of the cell of just half

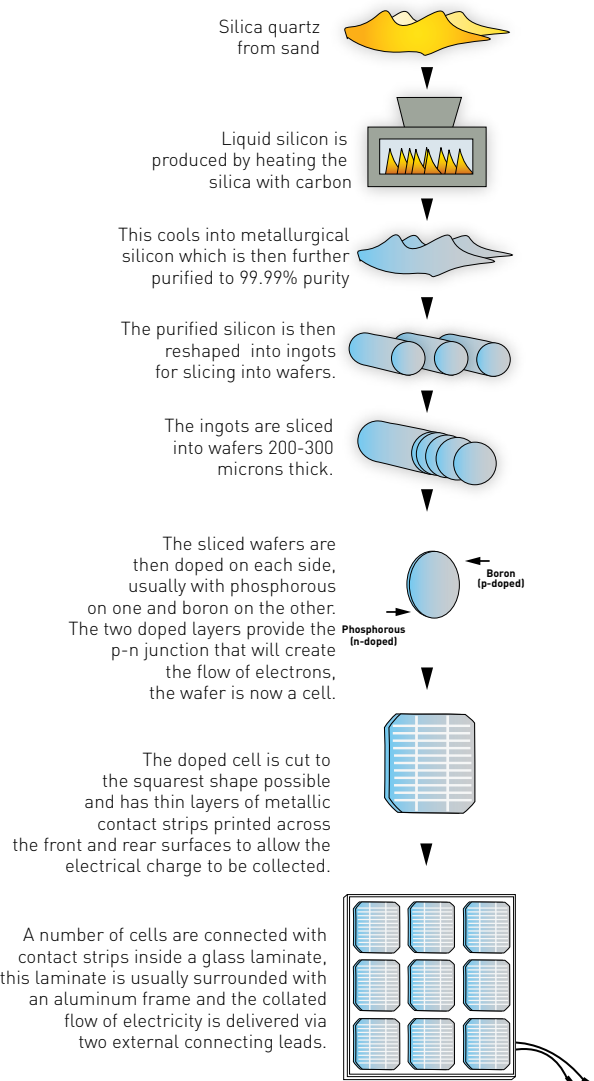


Figure 14: The production process for a crystalline silicon solar module.

a volt: less than half that of an AA battery. In order to provide a useful voltage from a panel, many cells need to be connected together in series – like a chain, one after the other. To protect the connected cells from contamination they must be encapsulated in a waterproof package. The most common form of encapsulation is a sheet of tempered glass on the front (to allow light through) and a protective film on the rear. This sandwich is held together with adhesive which is cured when the whole package thus far (called a laminate at this stage of the process) is heated and pressed in a solar laminator.

The final step is to put a frame around the laminate to protect the edge of the glass and provide a structure which allows the panel to be bolted to a suitable support structure. This is usually made of aluminium or stainless steel. Alternatively, the laminate can be inserted directly into a specially designed frame to make a roof tile, or some other element that can be attached to buildings.

Module production requires capital expenditure much lower than the earlier stages: between \$40,000 and \$230,000 per megawatt. It takes nine–eighteen months to build a plant, with a further three–nine months for equipment installation and set-up.⁷

Quality control is vital before modules are released to market. Each module undergoes testing in the factory for its electrical properties. There are many testing sites around the world where inferior manufacturing can quickly be exposed, and the commercial downsides for a manufacturer who produces a module that doesn't 'do what it says on the tin' are severe.

Thin-film photovoltaics

Thin-film solar cells have caused a lot of excitement, and received a lot of investment, over the previous few years. These cells exploit the photovoltaic effect in the same basic way that crystalline silicon cells do, but the manufacturer uses less material and requires lower processing temperatures to reach a finished product. Thin-film solar cells are made by building up super-thin layers of materials on a suitable substrate. The final layer can be as thin as a micron: 200–300 times thinner than a crystalline cell. The energy and material costs are lower and the potential for rapid scale-up of mass production is therefore



Thin film PV module manufacturing at First Solar's plant in Frankfury, Germany
(Image: First Solar)