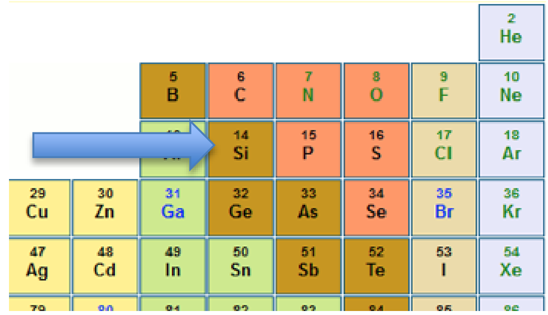
Chapter 3: Solar photovoltaics

Silicon



3.1 Introduction

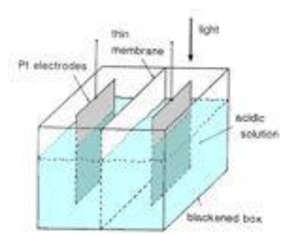
• The net solar power input to Earth is more than **8,000-times** humanity's current rate of fossil and nuclear fuels use.

• The most common **photovoltaic** (PV) cell is made almost entirely from silicon. It is the second most abundant element in the Earth's crust. It has no moving parts and can therefore theoretically operate for an indefinite period without wearing out. Furthermore, its output is electricity, probably the most useful of all energy forms. (Remember the second law of thermodynamics and the concept of entropy!!! Heat energy is random and depends very much on temperature for it usefulness, and therefore has high entropy. Electricity is ready for action, and low entropy.)

3.2 A brief history of PV (Wikipedia Timeline)

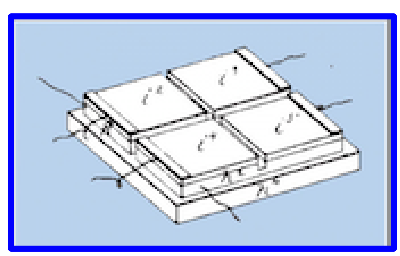
• 1800s: Physicist Count Allesandro Volta invented the battery. The word 'PhotoVoltaic' is derived by combining the Greek word for light, *photos*, with volt, the name of the potential difference (voltage) in an electrical circuit. Photovoltaics thus describes the generation of electricity from light.

• 1839: Physicist Edmond Becquerel publish information about his 'wet cell battery'. The photovoltaic effect is also credited to him because of his finding that the battery voltage increased when its silver plates were exposed to sunlight.



• 1877: The first report of the PV effect in a paper describing effects on selenium when exposed to light, a non-metallic element, like sulfur.

• 1883: Charles Fritts reported on something like the 'solar cell' effect, using a thin wafer of selenium covered with a grid of fine gold wires. Less than 1% of the solar energy incident on the wafer produced an electric current. Eventually it was widely used as a photographic exposure meter.



• 1953: A Bell Telephone laboratory team using doped silicon fabricated much more efficient solar cells that produced electricity from light. Eventually up to 6%. Bell Laboratories demonstrate their possible use in for instance rural telephones. But too expensive for most applications.

• 1954: At Bell Laboratories researchers were studying the effects of light on 'semiconductors', such as silicon and germanium, which have physical properties between that of 'conductors' and 'insulators'. In 1948 other researchers had discovered the 'transistor' using semiconductors in extremely pure crystalline form. These were 'doped' impurities, such as boron and phosphorus, which dramatically altered their performance in a productive way.

• 1958: Solar cells used to power a small transmitter on the second U.S. space satellite. Following this initial demonstration they went on to become the standard power supply for space craft.

• In the following decades, along with significant improvements they have come to be used in may aspects of technology and society, and even in power grids.

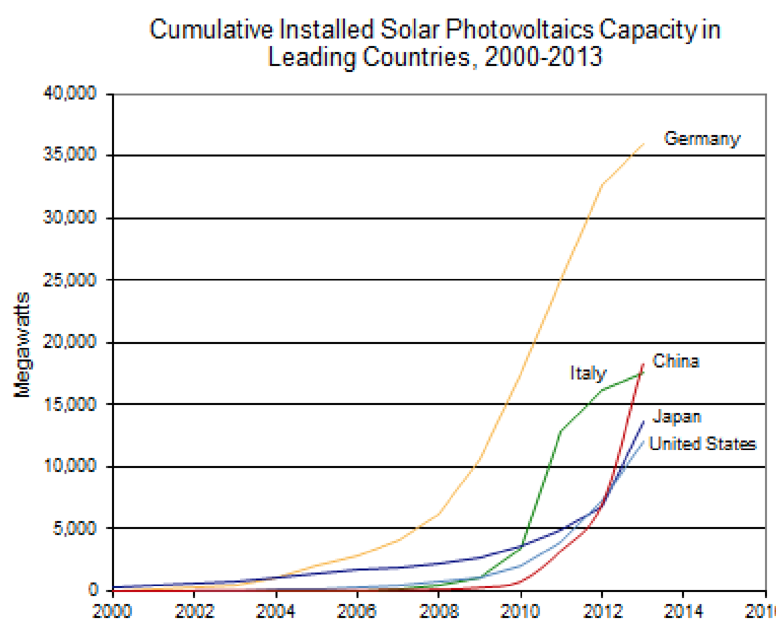
• The efficiently of the BEST silicone cells have now reached 25%, with the usual commercially available ones reaching abut 20%.

• The International Space Station is powered by large arrays of PV panels with a combined output of around 130 kW.

It is indeed interesting how in the 1970's Japan was the world leader in PV R&D as well as such consumer products as PV calculators.

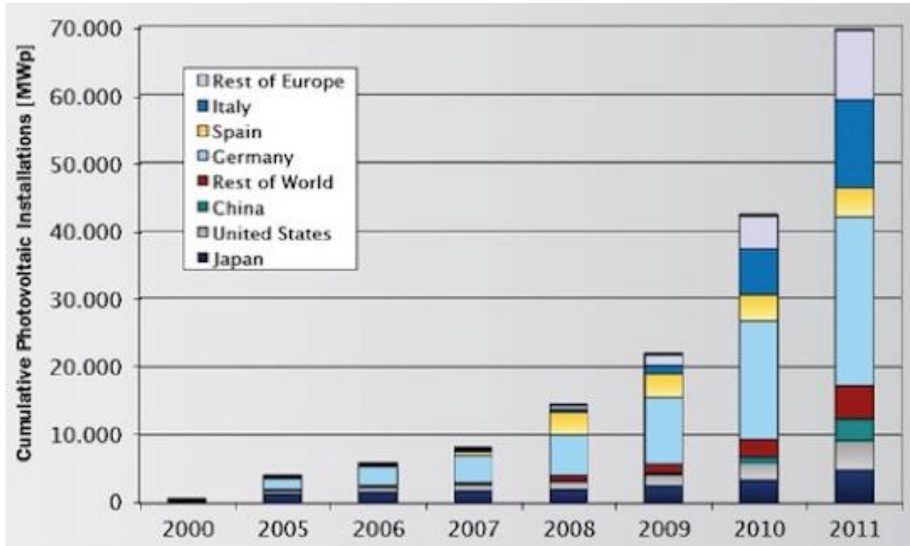
BUT, German took the lead in applying to the electric grid through huge government subsidies and the 'feed-in' concept .

Stranger still is the fact that Chinese entrepreneurs took the lead in the manufacturing of cheap PV cells, and was able to supply German growth in PV electricity. Thus the charts!!

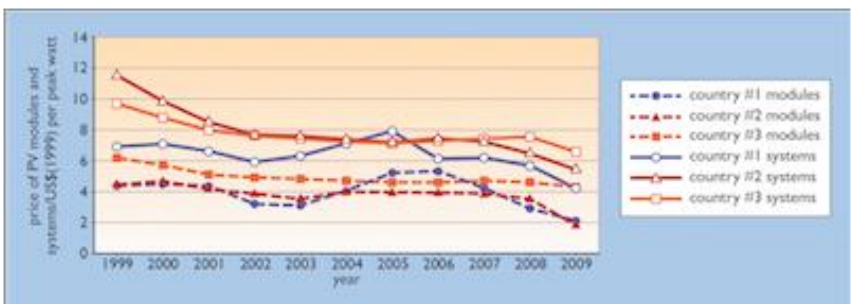


Cumulative Photovoltaic Installations

Domestic use of PV cells ➔



Price of PC modules

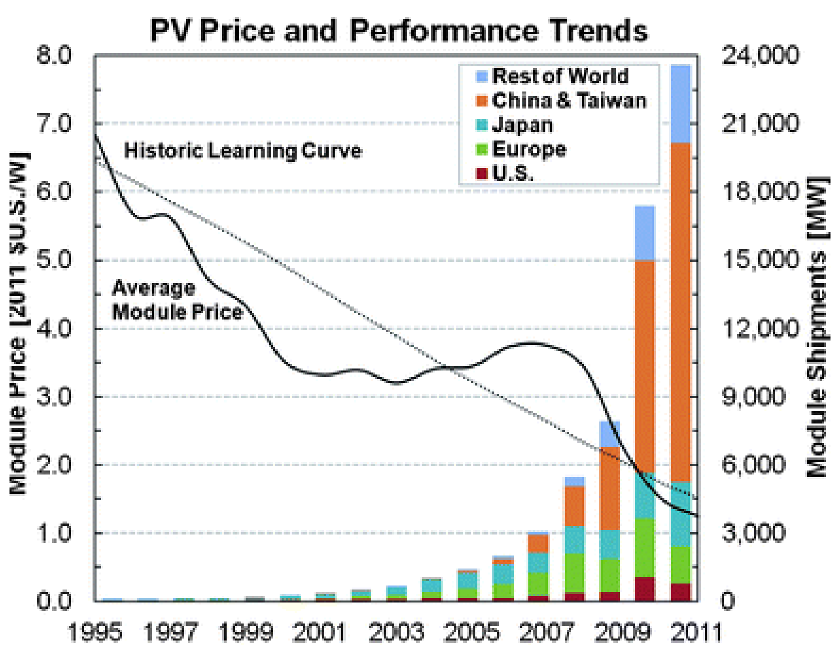


• Evolution of the price of PC modules and small-scale PV systems in three reporting countries. Prices in watt are shown on constant US$ (1999); i.e. they are corrected for the effects of inflation

🡐PRICE EVOLUTION

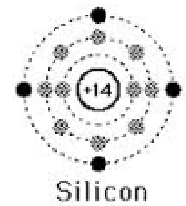
• From 2000 to 2010 the total installed power capacity of PV systems increased more than 20-fold, module costs dropped to around US$2 per pear watt and overall systems costs fell to around US$4 per watt. Such improvements are likely to continue-------

SHIPMENTS of PV cells ➔

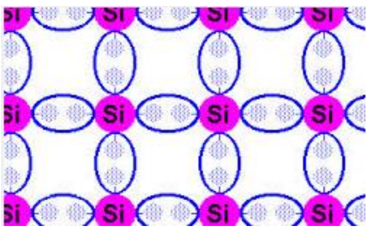


3.3 The PV effect in crystalline silicon: basic principles (Overview)

Semiconductors and doping (Overview)

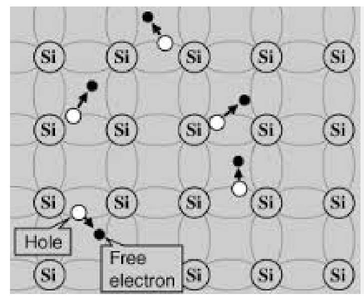


• A silicon atom has a nucleus with 14 protons and 14 neutrons, around which orbit 14 electrons.



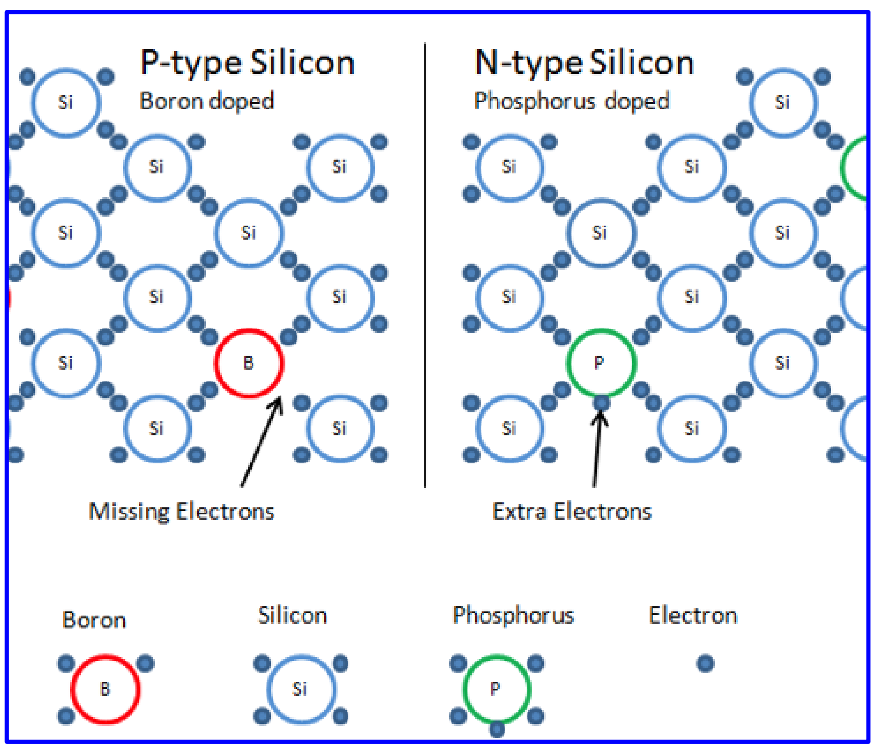
• A pure silicon crystal has a lattice structure of silicon atoms. Each atom has 4 electrons in the outer orbit, called 'valence electrons'. A crystal of silicon has an ordered structure where the 4 outer electrons are shared by 4 neighboring atoms. Their energy is within the so-called 'valence band'.

• This is a pure silicon crystal.



• Being a '**semiconductors**' some electrons are tightly bound and others - with higher energy - are somewhat free to wander around in the crystal, so-called 'free electrons' in the so-called 'conduction band'.

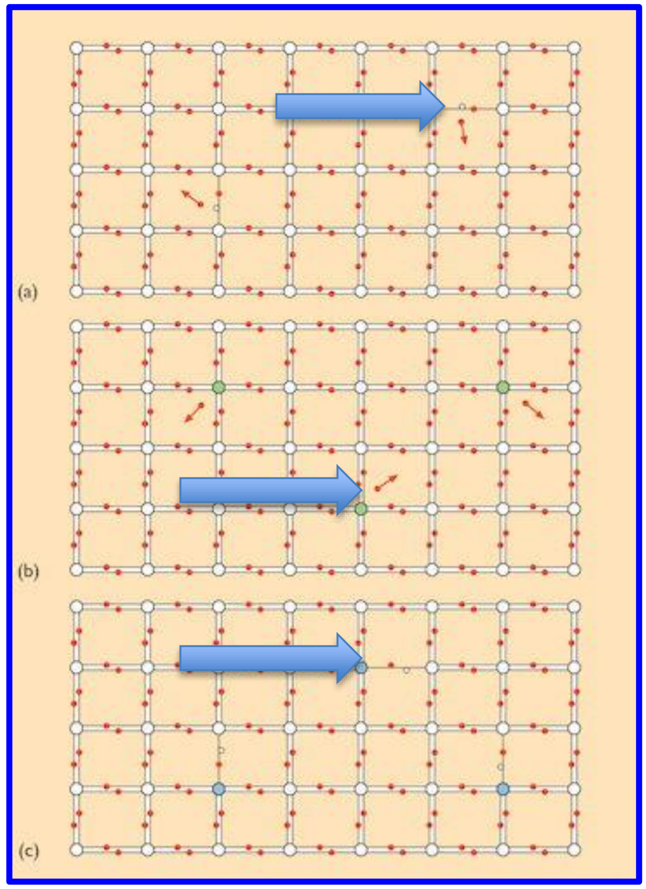
• Sometimes it is very useful and practical to add impurities, meaning small quantities of other types of atoms.



• **p-type** semiconductors are made from crystalline silicon, but are doped with very small amounts of an impurity (**usually boron, with only three valence electrons**). The doped material has a deficit of free electrons. These 'missing electrons' are called '**holes**'. This over abundance of positive charge makes this a **p-type** semiconductor.

• **n-type** semiconductors are made from crystalline silicon, doped with very small amounts of another impurity (usually **phosphorus, with 5 valence electrons**). The doped material possesses a surplus of free electrons. **Electrons** are sub-atomic particles with a negative electrical charge, so silicon doped in this way is known as **n-type (negative-type)**

Here is another view of a doped silicon crystal:

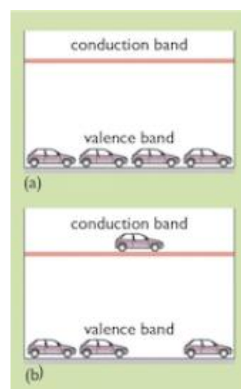


a) White circles are silicon atoms. Two red dots •• between two silicon atoms are the bonding 'valence electrons'. **If an electron spontaneously receives *sufficient energy from a photon or vibration energy of the crystal* it can become a 'free electron'**, and can wander around within the crystal. These are indicated by one independent •. This leaves a "hole", the small white dot. Thus, Si is a semiconductor.

b) If the crystal is doped with phosphorous (•), which has 5 valence electrons, it becomes n-type silicon. This produces extra free electrons wandering in the crystal: indicated as a single •

c) A crystal of p-type silicon can be created by doping the silicon with trace amounts of boron (as already mentioned). Each boron atom, • , has only 3 valence electrons, so that it shares two electrons with three of its silicon neighbors and one with the fourth. Thus the p-type crystal contains more holes • than conduction electrons •.

Here are two video clips about doped silicon crystals: 1, 2 ➔



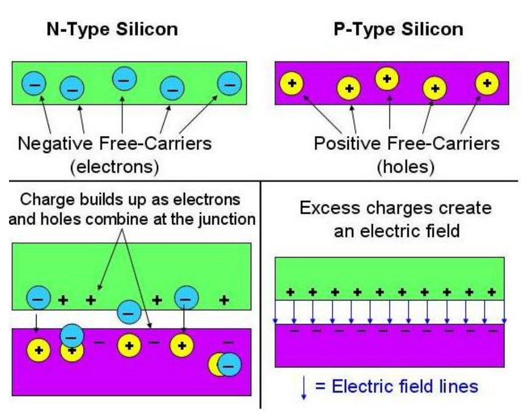
• If p-type and n-type crystals are put side by side a 'junction' is formed. Here is a simplified illustration to show what happens.

When light – photons - of appropriate wavelength fall within the p-n junction, they transfer energy to some **valence electrons**, while 'promoting' them to higher energy levels; from the lower energy 'valance bands' (holding atoms together) to higher energy, excited, states of the '**conduction band'** (higher energy where electrons are 'free'. When they move they leave behind 'holes' in the martial. which can move.

• When the p-n junction is formed, some **electrons** in the intermediate region are attracted from the n-side to combine with holes on the nearby p side.

• The net effect of this is to set up around the junction a layer on the n-side that is more positively charged than it would otherwise be, and, on the p-side a layer that is more negatively charged than it would otherwise be. Thus, an ***REVERSE*** electric field is set up around the junction: negative on the p-side and positive on the n-side. Because the region around the junction is also depleted of charge carriers (electrons and holes) it is known as the **depletion region**.

Wafer 0.2 – 0.3 mm thick ➔

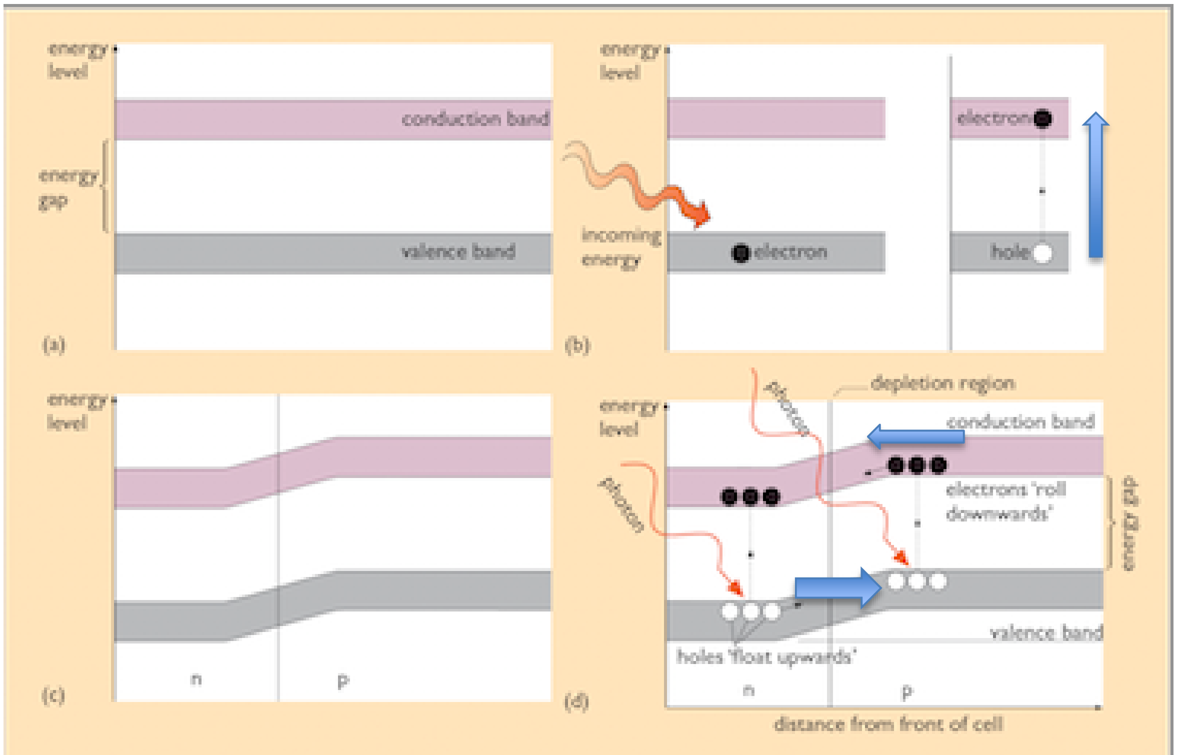


Now look at the same process drawn in the standard form with bands and electrons:

➔Here, (a) shows the energy bands in a normal ('intrinsic') semiconductor.

(b) An electron can be 'promoted' to the conduction band upon absorbing energy from light (or heat), leaving behind a 'hole' in the valance band.

(c) When n-type and p-type semiconductors are combined into a p-n junction, their different energy bands combine to give a new distribution, and a built-in electric field is created



(d) In the p-n junction, **photons** of light can excite electrons from the valence band to the conduction band. The electrons 'roll downwards' to the n–region, and the holes 'float upwards' to the p-region.

Thus the word 'photo-voltaic' ➔ photons result in a 'voltage'

The flow of electrons in the n-region is, by definition, an electric current. If there is an external circuit for the current to flow through, the moving electrons will flow out of the semiconductor via one of the metallic contacts on the top of the cell. The holes in the meantime move in the opposite direction through the material until they reach another metallic contact on the bottom of the cell, where they are then 'filled' by electrons entering from the external circuit.

- In order to produce power, the PV cell must generate voltage as well as the current provided by the flow of electrons. The voltage is, in effect, provided by the internal electric field set up at the p-n junction. Individual crystalline silicon PV cells are typically about 150 x 150 mm in size, produce a voltage of just over 0.5 volts and give a peak power of approximately 4 watts.

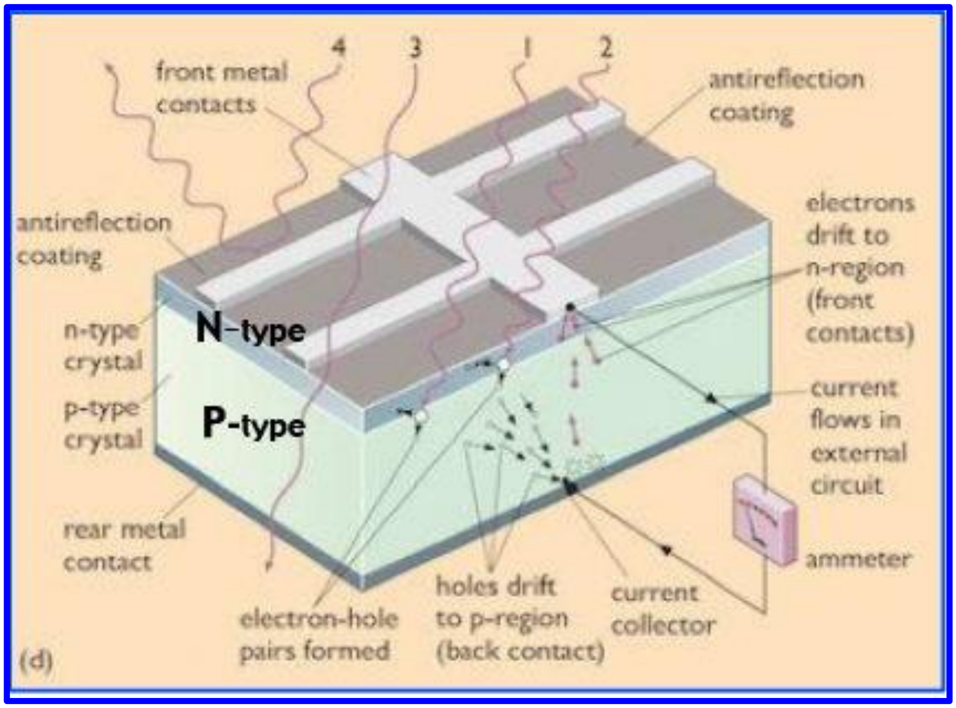
• A silicon solar cell is a wafer of p-type silicon with a thin layer of n-type silicon on one side.

When a photon of light with the appropriate amount of energy penetrates the cell near through the thin n-type layer near to the junction and encounters a silicon atom:

(**1**) It dislodges one of the electrons, which leaves behind a hole. The energy needed to promote the into the conduction band is known as the band gap.

The electron thus promoted tends to migrate into the layer of the n-type silicon, and the hole tends to migrate to the layer of the p-type silicon. The electron then travels to a current collector on the front surface of the cell, generates an electric current in the external circuit and then re-emerges in the layer of the p-type silicon, where it can combine with the waiting holes.

(**2**) For a photon of energy greater than band gap, an electron-hole par is generated and excess energy into heat.

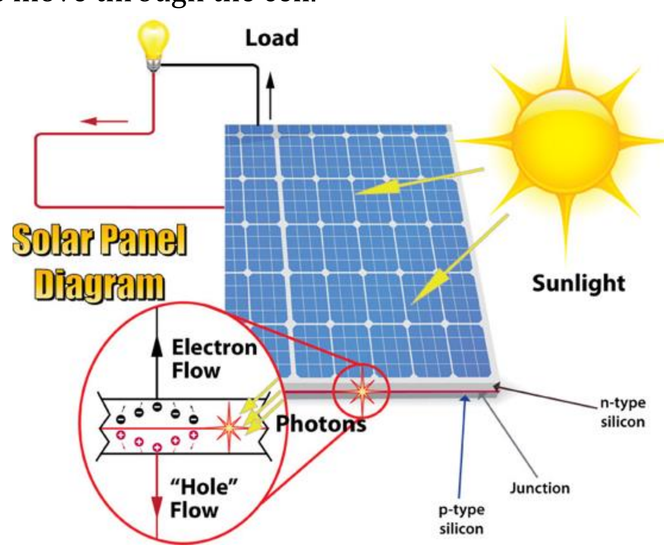


video clip: overview of p-n junction solar cell

(**3**) If photon energy is less than band gap, photons move through the cell.

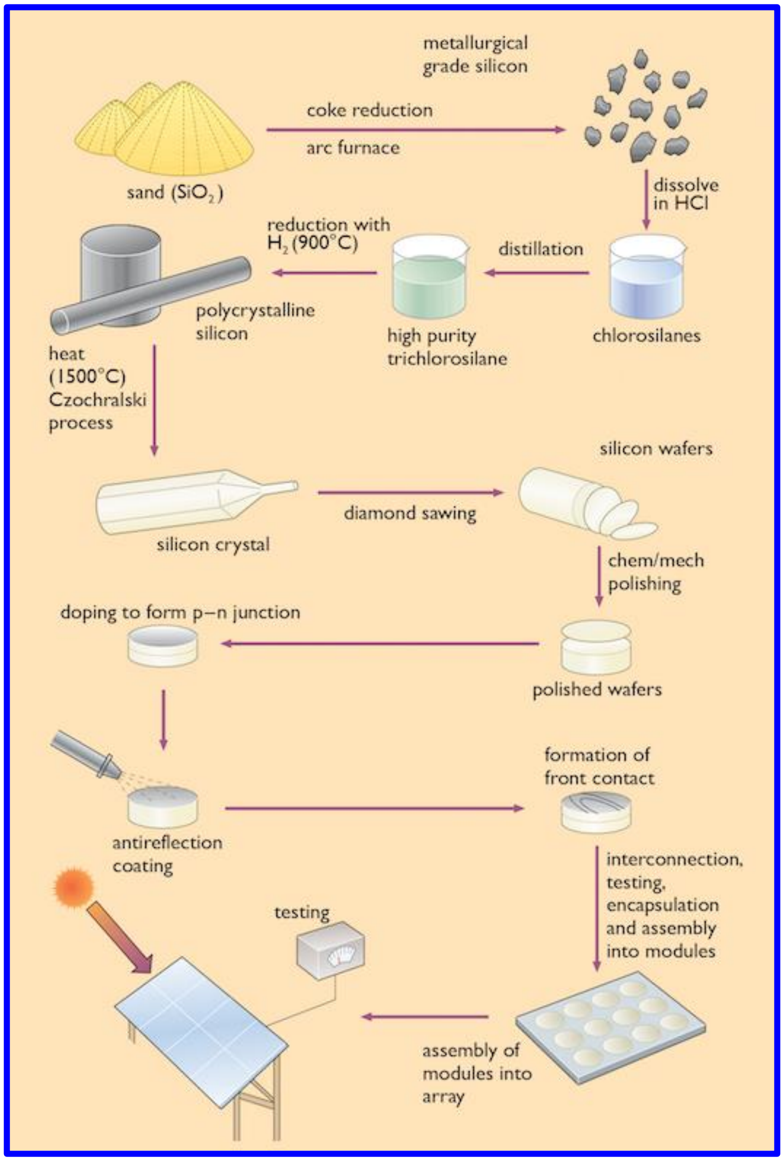
(**4**) Other photons are lost by being blocked by current collectors on the front surface.

Remember glass???



Monocrystalline silicon cells

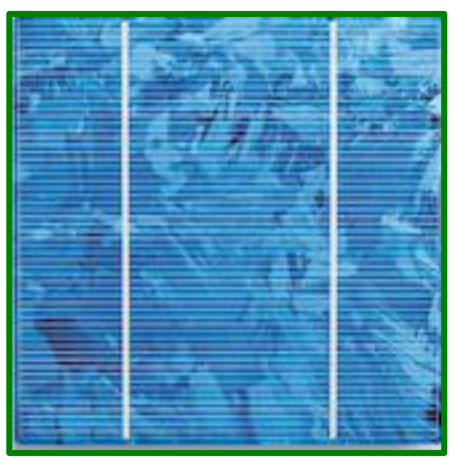
• Until fairly recently, the majority of solar cells were made from extremely pure monocrystalline silicon (Si), that is silicon with a single, continuous crystal lattice structure. Having virtually no defects or impurities



Monocrystalline silicon is usually grown from a small seed crystal that is slowly pulled out of a molten mass, or 'melt', of *polycrystalline silicon*, in the sophisticated but expensive **Czochralski process,** developed initially as part of the process for manufacturing 'silicon chips' for the electronics industry. The process of crystal growth is known as an **epitaxial** process. And can be used for other PV semiconductors. The entire process of *monocrystalline silicon solar cell* and module production is summarized to the right.

3.4 Crystalline PV: reducing costs and raising efficiency

• Although monocrystalline silicon PV modules are highly efficient, they are expensive because the Czochralski process is slow, requires highly skilled operators, and labor and energy intensive. Also, until recently, all cells were fabricated from extremely pure 'electronics-grade silicon', including recycled leftovers from silicon chip manufacturers. Now less expensive methods have been developed, such as using slightly less efficient **polycrystalline silicon**.



Polycrystalline silicon

• These are easier and cheaper to manufacture, but tend to be less efficient. However, research has found that the efficiency can be increased by special processing, and now reaching efficiencies of 16%.

Polycrystalline silicon film

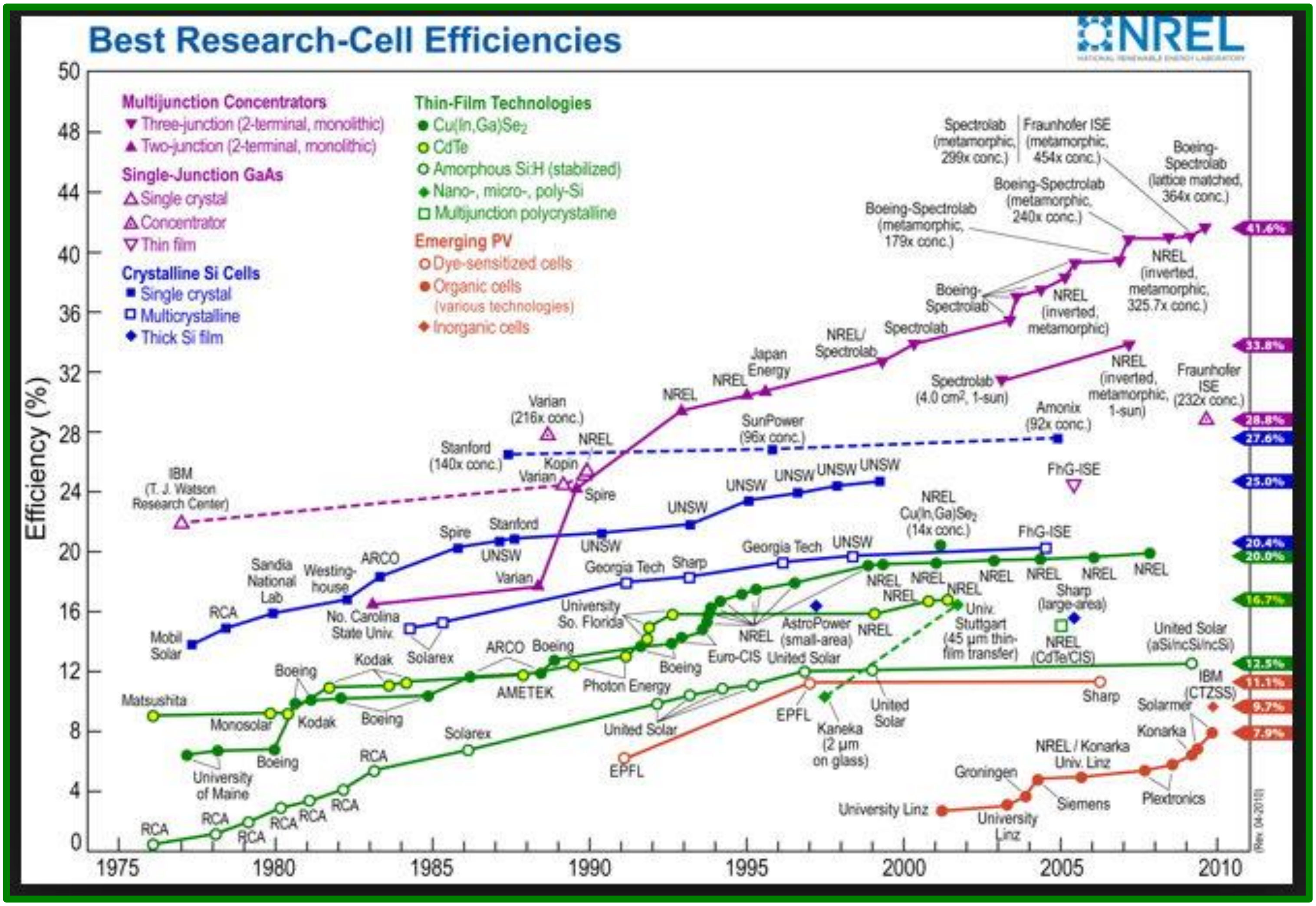
• By developing special 'light-trapping' techniques, it is possible to maximize the interactions of photons with the material, thus allowing much thinner 'film' layers of silicon to be used, deposited onto ceramic or glass substrates. About 8% efficiency.

Gallium arsenide

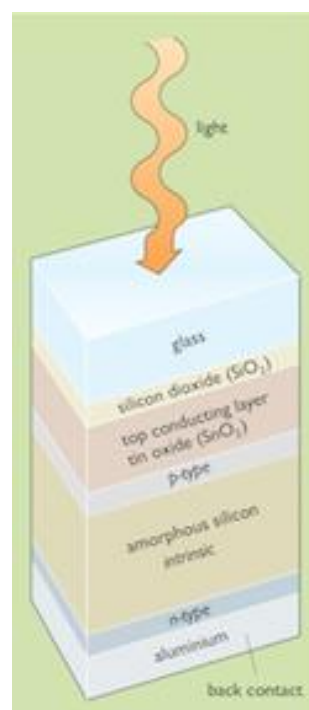
• GaAs is a so-called compound semiconductor, but consisting of alternating gallium and arsenic atoms. Because it has a high light absorbing coefficient, thin films can be used. And because the band gap is wider than that of silicon, it is great for absorbing the light spectra in our atmosphere, and a higher efficiency is obtainable. Can also operate at high temperature, and thus good for concentrating systems. They are more expensive.

• GaAs cells have often been used when very high efficiency is required, as in many space applications and solar racing cars.

• The winner of the 2009 World Solar Challenge race across Australia was the Tokai Challenger, designed and tested by students from Tokai University together with several Japanese automotive companies. It covered 2,998 km in 29 hours 49 minutes at an average speed of 100.54 km per hour. Used Sharp triple-junction III-V PV cells of the type used in space applications. Peak power output of 1.8 kW and an efficiency of 30%.



3.5 Thin film PV



• Crystalline wafers are not the only materials suitable for photovoltaics. PV cells can also be made from ‘thin films’ of various kinds, the most common of which are:

Amorphous silicon

• Thin films of silicon known as amorphous silicon (a-Si) in which the atoms are much less ordered than in the crystalline forms. Atoms not all fully bonded. These are cheaper produce since made at lower temperature, and thus energy. Suitable for continuous production; and it allows large areas of cell to be deposited on to a wide variety of both ridged and flexible substrates, including steel, glass and plastics. Maximum efficiencies of 10%. Useful in a variety of applications where the requirement is not so much for high efficiency as low cost.

Copper indium (gallium) diselenide

- Has obtained the highest laboratory efficiencies of all thin film devices, around 19%, and modules with stable efficiencies of 15% are available.

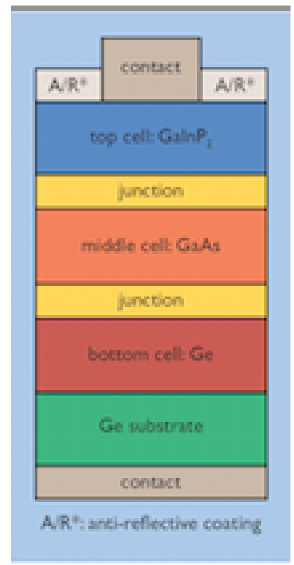
Cadmium telluride

- Interesting, but uses a toxic substance, so stringent precautions need to be taken during their manufacture, use and eventual disposal or recycling.

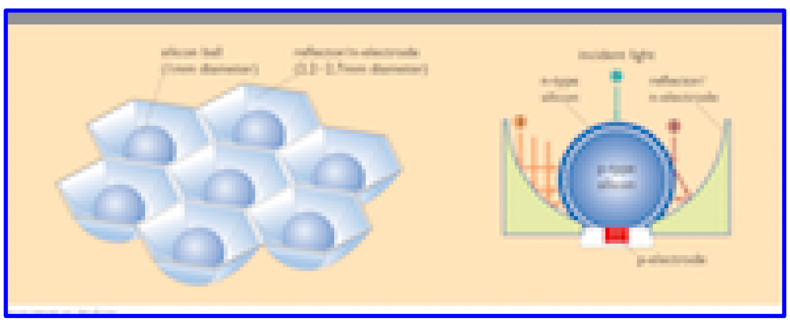
3.6 Other PV technologies

Multi-junction PV cells and modules

- Stacked films allow the use of many different wavelengths. Result in high efficiencies of 28% to 40%. **But expensive**. Such cells are mainly used in space applications and in concentrating PV systems, and are designed to resist radiation exposure and high operating temperatures.



Concentrating PV systems



Emerging and novel PV technologies: Nanotechnologies and may other

Lectures about solar photovoltaics

Purdue University: Introduction to Solar Cells. Lecture 1, 2, 3, 4, 5, 6, 7

Purdue University: Introduction to Near-equilibrium Transport. Lecture 1, 2, 3

MIT: Introduction to Fundamentals of Photovoltaics: Lecture 1, 2, 3, 4, 5

MIT lecture: The MIT Energy Initiative: Sustainable Energy and Terawatt-Scale Photovoltaics: 1,

Documentary: Solar Power Revolution - Here Comes The Sun – Documentary: 1,

Documentary: How does it work: Solar photovoltaic energy: 1,

3.8 PV systems for remote power

• PV modules are now widely used in 'industrialized countries' to provide electrical power to locations where it would be inconvenient or expensive to connect to the conventional grid supplies. They often charge batteries to insure continuity of power.

Here is a PV parking meter, PV navigational buoy and PV telemetry system

• In many 3rd-world countries power grids are often nonexistent, particularly in rural areas, and all forms of energy are usually very expensive. Applications include: PV water pumping, PV refrigerators to keep vaccines stored safely in health centers, PV systems for homes and community centers, providing energy for lights, radios, audio and video systems, PV-powered telecommunication systems, computers and Internet, and PV- powered street lighting.

• India has a plan to provide safe, clean lighting using efficient compact fluorescent lamps or light emitting diode lamps (LED) The solar lantern batteries can be recharged at solar PF charging stations in villages, run by selected local entrepreneurs ➔

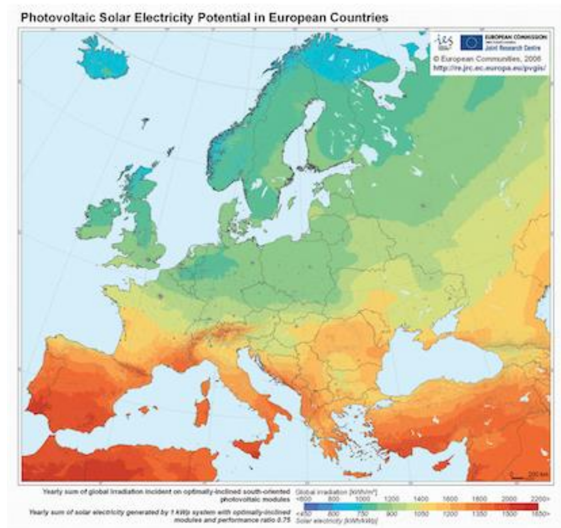
3.9 Grid connected PV systems

PV systems for homes

• In most parts of the developed world, grid electricity is easily available as a convenient backup to PV or other fluctuating renewable energy supplies. Here it makes sense for PV energy systems to use the grid as a giant 'battery'. The grid can absorb PV power which is surplus to current needs (say on sunny summer afternoons), making it available for use by other customers and reducing the amount that has to be generated by conventional means; and at night or on cloudy days, when the output of the PV system is insufficient, it can provide backup energy from conventional sources.

• In these grid-connected PV systems, a so-called 'grid-commutated inverter' (or 'synchronous inverter') transforms the direct current (DC) power from the PV arrays into alternating current (AC) power at a voltage and frequency that can be accepted by the gird, while the 'debt' and 'credit' meters measure the amount of power brought from or sold to the utility. In many countries, **'Feed-in Tariffs (FiTs)'** have been introduced. These provide for premium payments to be made for power produced by grid-connected PV arrays and other renewable sources.

• UK recommends half of all roofs to be oriented for south facing PV arrays.



Energy yields from PV systems

• Solar radiation map of Europe, showing annual energy yields of optimally oriented PV arrays in various European locations. 'Performance Ratio' is the ratio of actual to theoretical maximum PV array output.

PV systems for non-domestic buildings

• PV arrays can also be integrated into the roofs and walls of commercial, institutional and industrial buildings, replacing some of the conventional wall cladding and roofing materials that would otherwise have been needed, and thus reducing the net costs of the PC system.

• There are now many examples of non-domestic buildings incorporating grid-connected PV systems, in countries like Germany, Japan, the Netherlands, Italy, the UK, and the USA.

• This large development at Amersfoor in the Netherlands has a total of 1 MW of PV array capacity installed on the roofs of houses, schools, and community buildings. The PV arrays are owned by the local electricity company, which pays home owners for the electricity they produce.

•This solar office building at Doxford, near Sunderland in the UK, has a 73 kW PV array integrated into its south-facing wall. The building incorporates energy-efficient and passive solar design features to minimize its need for heating and lighting.

This 30 kW crystalline PV array is installed on the roof of the central catering 'Hub' of the Open University in Milton Keynes, UK. OUR BOOK: 'Renewable Energy – Power for a Sustainable Future'

Large, grid-connected PV power plants

• Large, centralized PV power systems, at the multi-megawatt scale, have also been built to supply power for local or regional electricity grids in a number of countries, including Germany, Switzerland, Italy and the USA.

• These large stand-alone PV plants can take advantage of economies of scale in purchasing and installing large numbers of PV modules and associated equipment, and located at sites optimal for solar energy collection. Collected energy must be distributed by the grid, which means power line loss. Price must be negotiated with power companies.

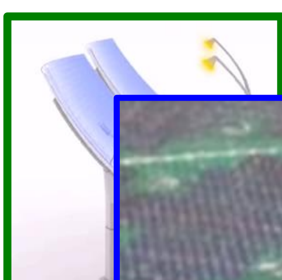
"Sempra generation", USA

Large amounts of land must be purchased or leased. Or on 'waste land' along motorways.

Highway photovoltaic noise barrier

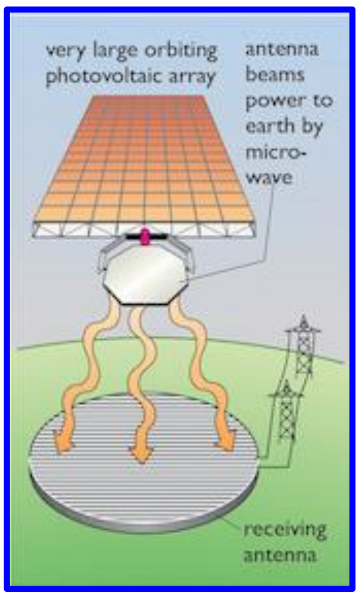
'Sun Farm" in U.K.

Both heat and power:



Solar Roads

• **Satellite Solar Power Systems**: First suggested in the 1970s, and given much consideration, a lingering concept is to put a solar energy collection station in orbit with huge arrays of over 50 km^2 each, and producing several GW of electrical power, and to microwave this energy to 10 km^2 receiving station on Earth, where it could be converted to AC and put on the grid. But many technical and economic difficulties. One estimate was US$ 79 billion and thirty years. This concept is still being explored. To the right is a recent article by Fred Myers in the journal Physics World.



"Solar Impulse" flying from San Francisco to New York in 2013---

Energy

Japan plans new space station as a solar energy source

The Japanese space agency, JAXA, is planning to test the possibility of generating solar power from space and transmitting it back to Earth via microwaves. The Space Solar Power System (SSPS), when launched in 2030, would have a power output of 1 GW and could provide electricity for as little as ¥8 per kilowatt-hour – six times cheaper than it would cost for ground-based solar power generation.

The SSPS involves using arrays of photovoltaic dishes several square kilometres in size placed in a geo-stationary orbit beyond Earth's atmosphere. The power from the array would be converted to microwaves, which would then be beamed to Earth. The advantage of microwaves is that they are not heavily absorbed or reflected by the Earth's atmosphere, allowing power to be generated even on cloudy days. The microwaves would then be collected on the ground via parabolic antennas – likely based at sea – and converted back into a voltage with an estimated conversion efficiency of about 85%. JAXA is also testing transmitting the energy via laser, but this would be more affected by cloud levels in the atmosphere.

Japan has long been at the forefront of solar and other renewable energy technologies, and some 130 researchers at JAXA's Institute for Unmanned Space Experiment Free Flyers have been studying SSPS as an alternative future energy resource since 1998. The Japanese government also recently selected several hi-tech giants, including Mitsubishi Electric, NEC, Fujitsu and Sharp, to build some of the prototype systems.

According to JAXA researcher Tatsuhito Fujita, a satellite will be launched in a few years' time to test the transmission of microwaves in low Earth orbit. The next step, expected in about 2020, would be to launch and test a large flexible photovoltaic structure with 10 KW power capacity, which will be closely followed by a 250 MW prototype. The final aim is to produce electricity cheaply enough to compete with other alternative energy sources using a 1 GW commercial system.

Fred Myers
Tokyo

3.11 Environmental impact and safety

Environmental impacts and safety of PV systems

• The environmental impact of PV is probably among the lowest of all renewable or non-renewable electricity generating system.

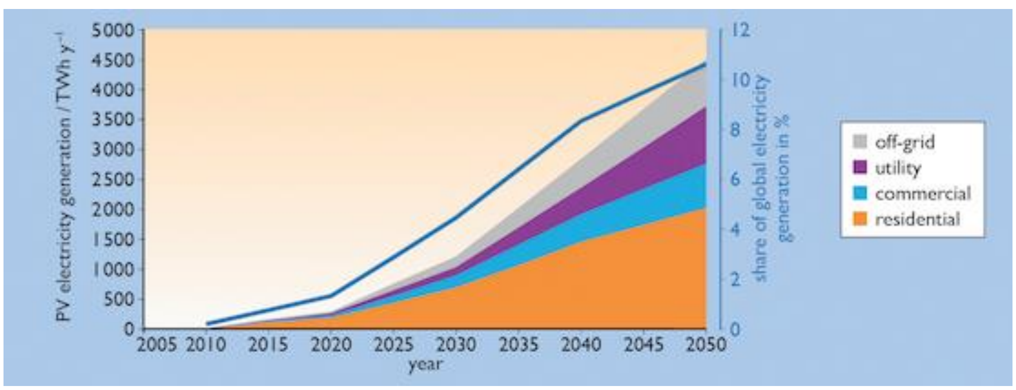
• It does have visual impact, which is negative to some.

• In some countries like Switzerland, the authorities are installing large PV arrays as noise barriers alongside motorways and railways. Arguably PV is here reducing the overall environmental impact.

The energy balance of PV systems and potential materials constraints

• In the early history of PV an enormous amount of energy input was necessary in the production process. But this has greatly changed in the favor of PV. Now the payback time is about 1.2 to 1.8 years.

3.12 PV integration, resources and future prospects



Integration

Everything depends on location: amount of expected solar radiation, time of year, weather patters and clouds, pollution. Integration must take all of this into account, and be prepared to switch over to more advantageous systems when necessary.

The growing world photovoltaic market

• If the present growth continues we can expect a DOUBLING of world PV production every two to three years. Presently, about ¾ of this capacity is installed in the EU