EEE124 – Energy in the Home

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Room E135, Mappin Building

PV lecture outline

Lecture 1: The sun as a source of energy. Applications in remote locations.

Lecture 2: Solar energy at the earth's surface. Semiconductors. Absorption of light. Creation of electrons and holes.

Lecture 3:. Power developed by solar cell. Parallel and series connections. Interpreting PV panel data sheet.

Lecture 4: Calculating PV system requirements. Typical PV system. Types of PV technologies available.

Outcomes:
Students should understand how energy from the sun is converted into electricity. How simple p-n junction semiconductors can produce power. How to do simple calculations about the type and size of PV required for home applications.

PV (or Photovoltaics)

- PV is ideal in applications where traditional sources of power are difficult to access – provided you have sunshine.
- Some facts about our sun:
  - It is 4.5 billion years old, and should continue to shine for a further 4-5 billion years.
  - Distance from earth – 150 million kilometers.

How is the light produced?

- Energy generated by fusion process – Hydrogen converted to Helium
- Energy is in gamma radiation but as it travels to the outside of the sun, it becomes visible radiation

- Temperature at sun’s centre – 15,000,000K
- Temperature at sun’s surface – 5,800K
- Temperature of tungsten halogen bulb – 3,000K

Some units of energy

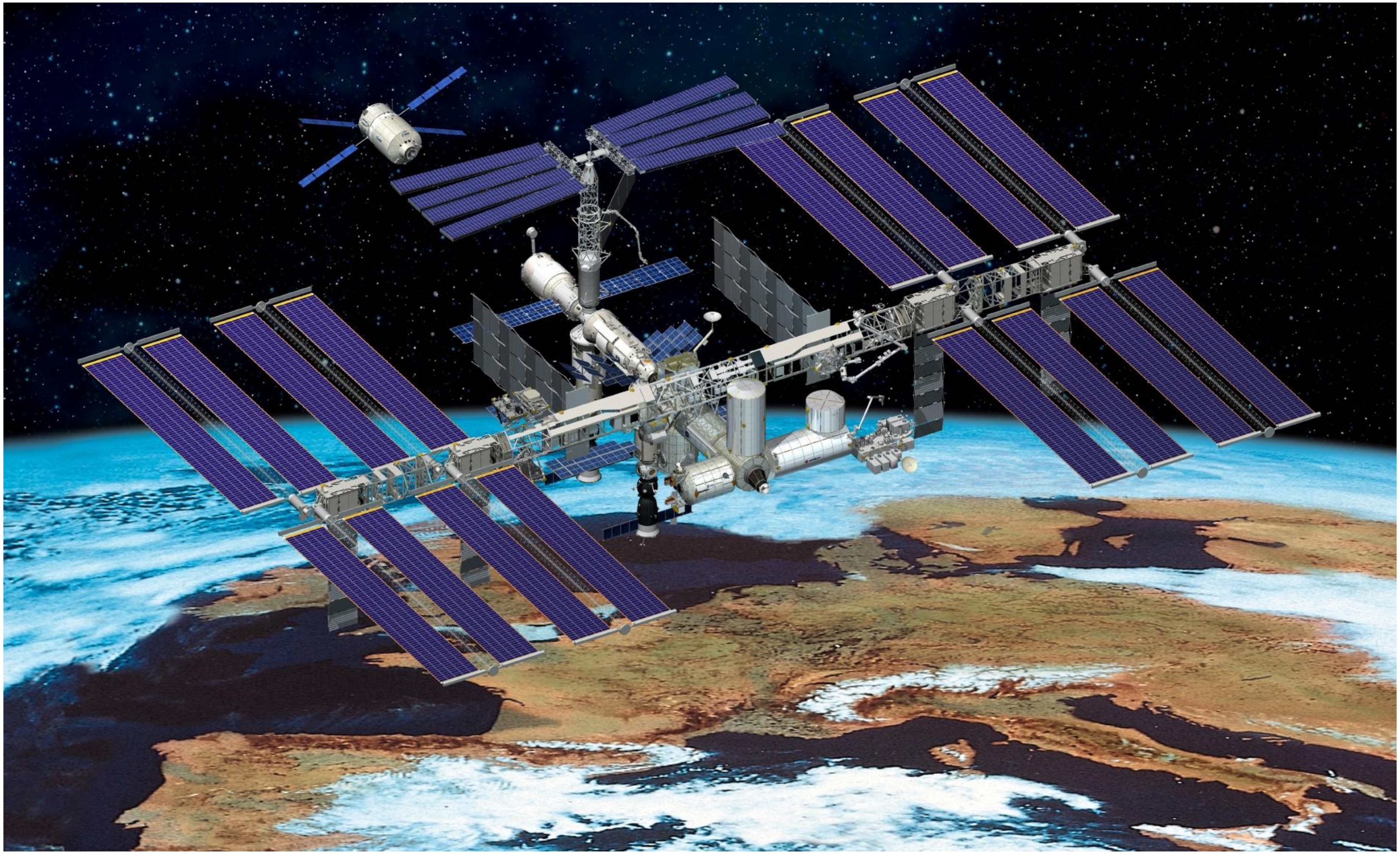
- Units of energy: Joules, watt-hr, BTU, erg
- Energy = watts x time
- What can you do with 5-6kW kettle in 1 minute? - boil 1 litre of water.
- A 110 watt kettle will do the same but in the 50mins of this lecture.

- Total power of the sun ~ 10^{23} kW, or
  - 100,000,000,000,000,000,000,000,000 Watts

Power at earths atmosphere is: 1360 W/m^2

The power received by the earth in 1 minute is enough to satisfy the world's energy needs for 1 year!

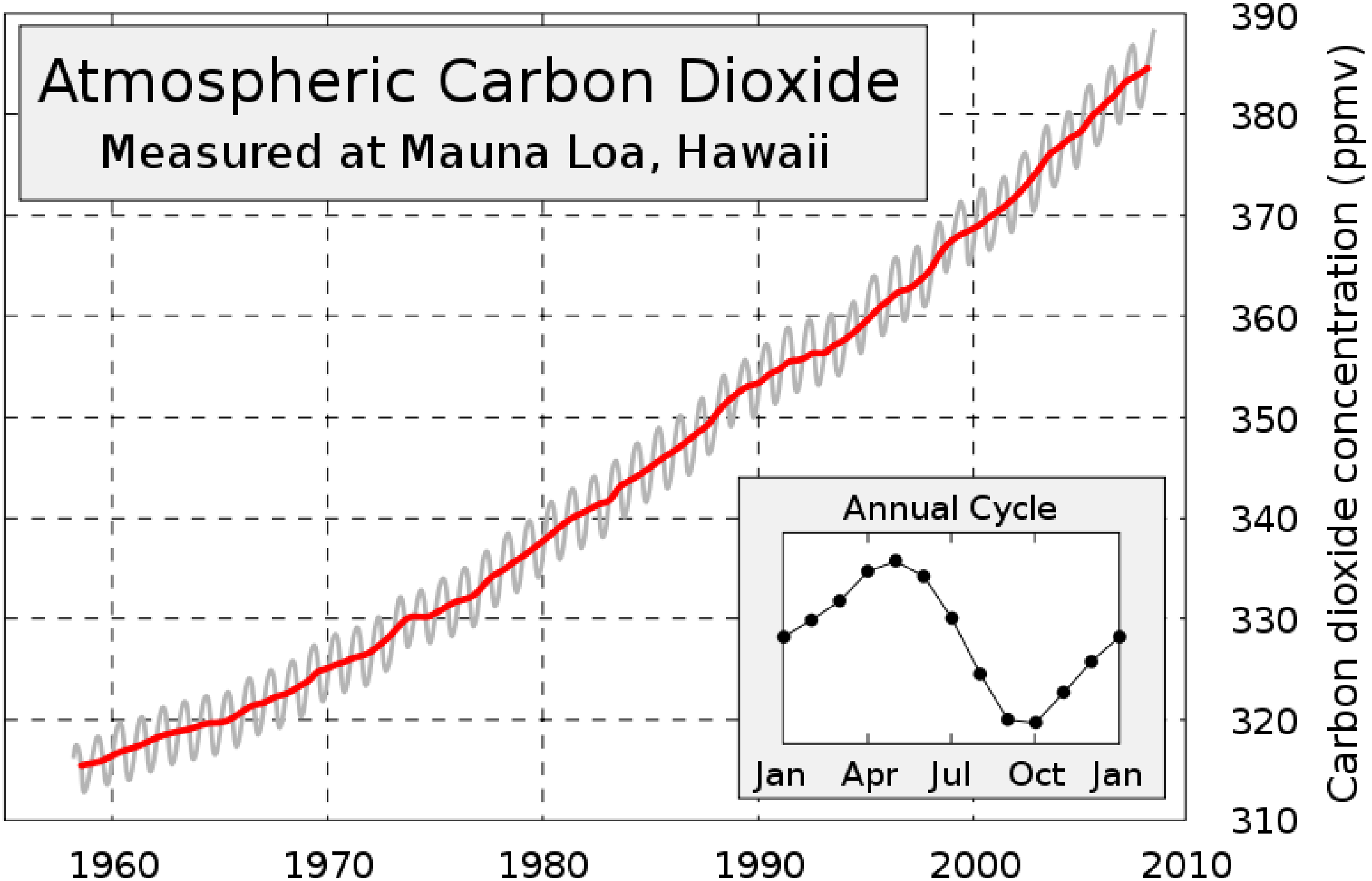
Traditional PV use



More recently.......

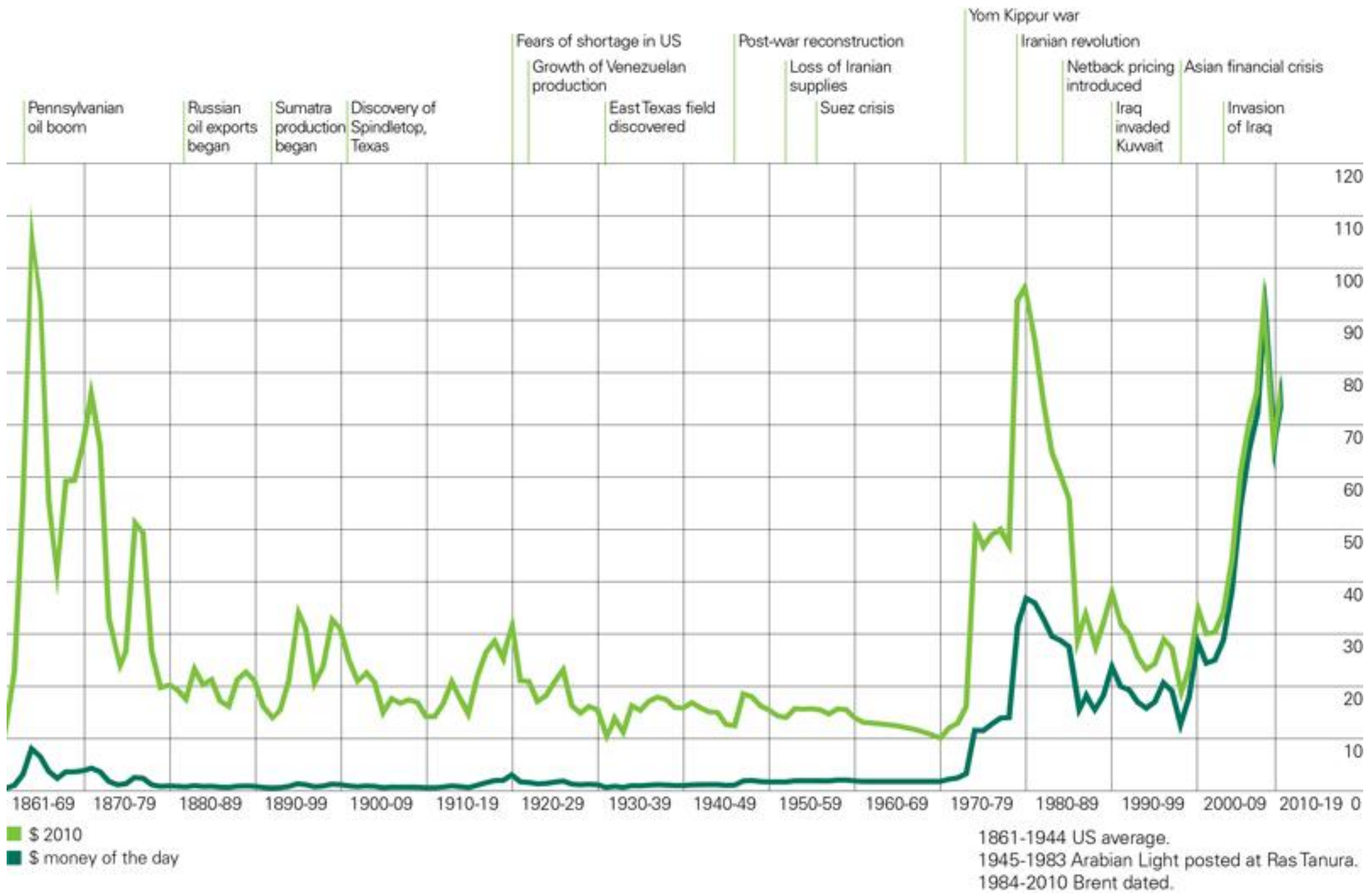
And now….

Why bother?



http://www.greentechmedia.com/articles/read/ten-power-point-slides-that-shook-the-earth/

If saving the planet is not enough....



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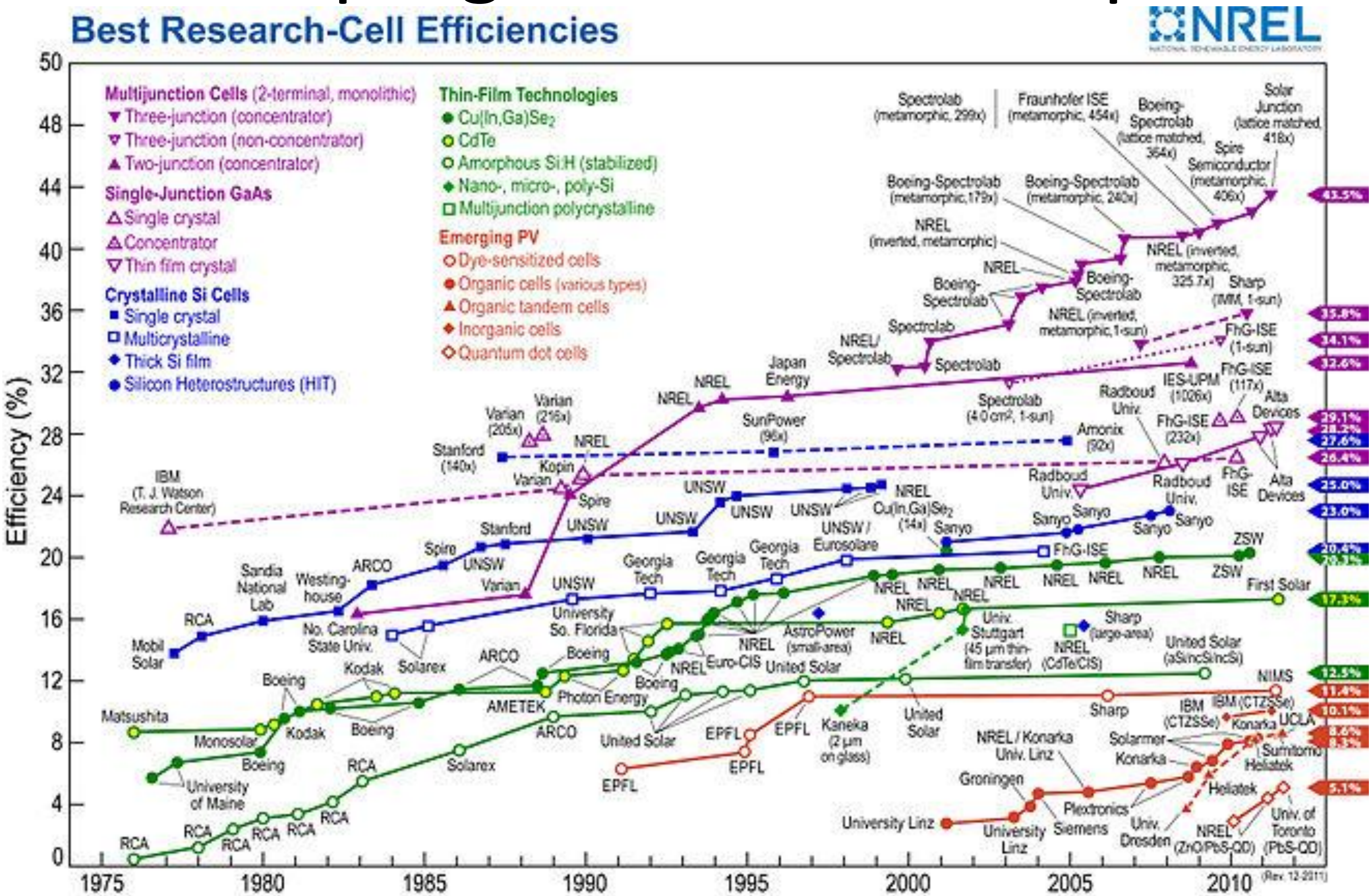
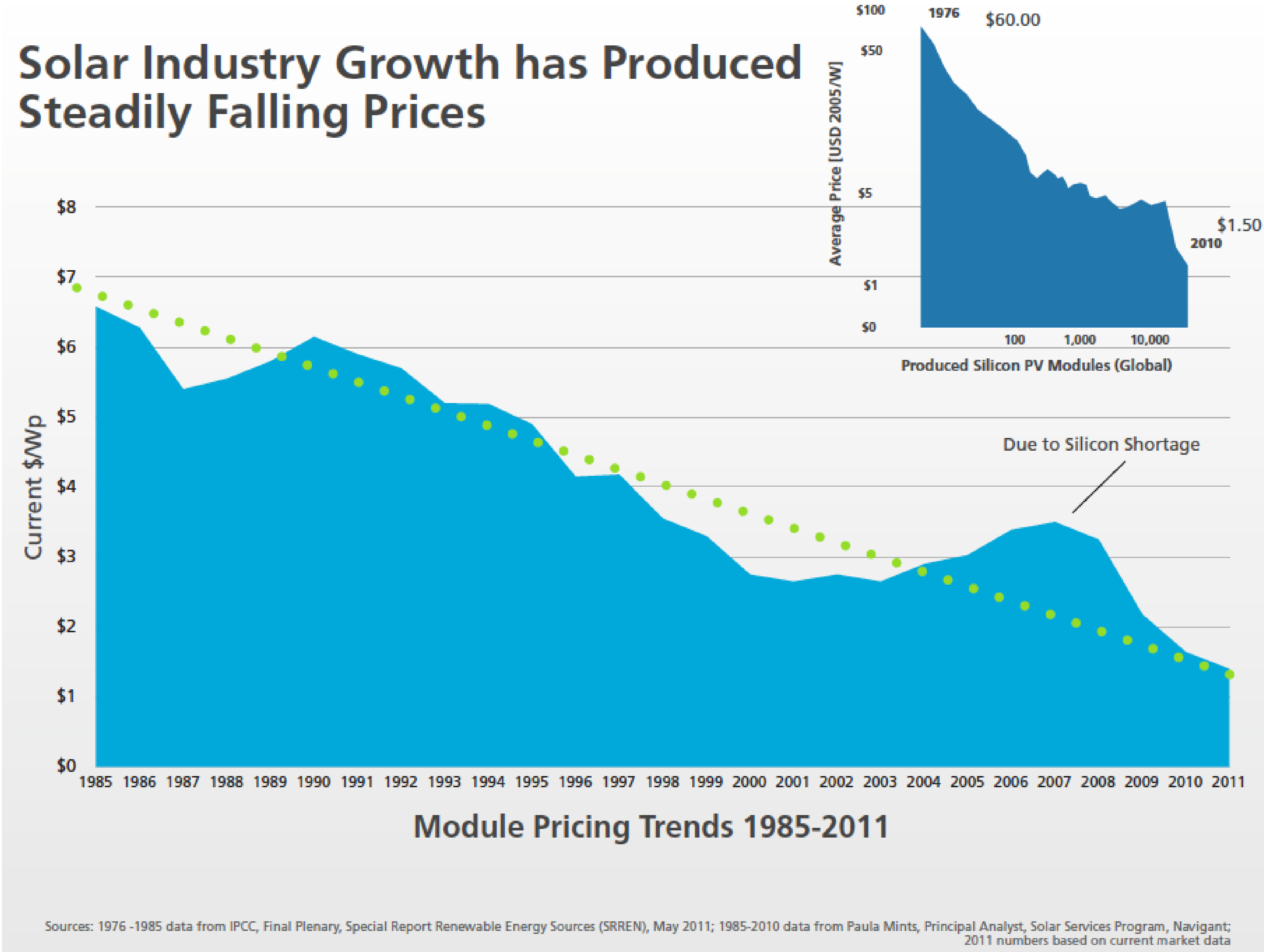
PV – A recent renewable technology (c.f. solar, wind..)

- 1839 - Edmund Becquerel, a French experimental physicist, discovered the photovoltaic effect while experimenting with an electrolytic cell.
- 1883 - Charles Fritts, an American inventor, described the first solar cells made from selenium wafers.ll made up of two metal electrodes.
- 1904 - Einstein published his paper on the photoelectric effect.
- 1954 – production of 4.5% efficient silicon cells by Bell labs and AT&T.
- 1964 – Nimbus spacecraft launched with 470W PV array.

Recent progress has been rapid…





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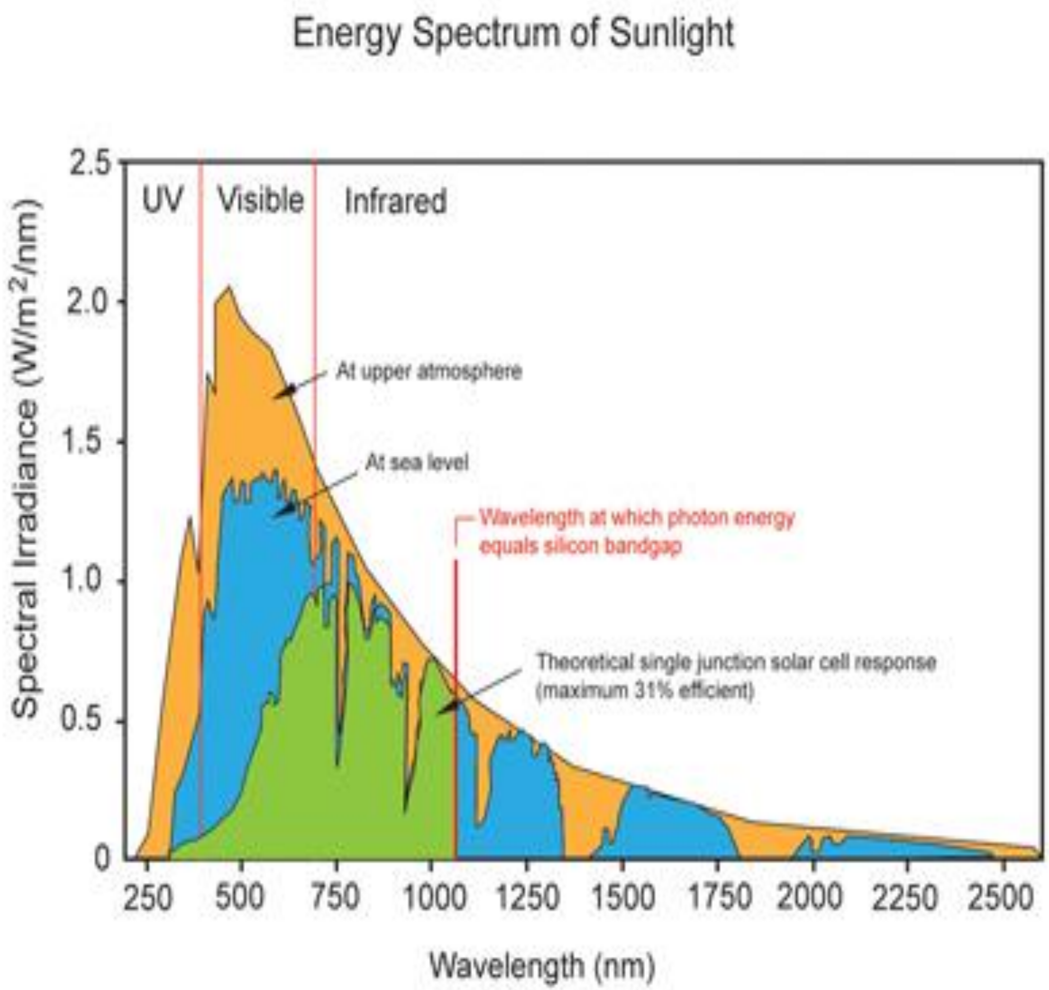
Some key efficiency numbers....

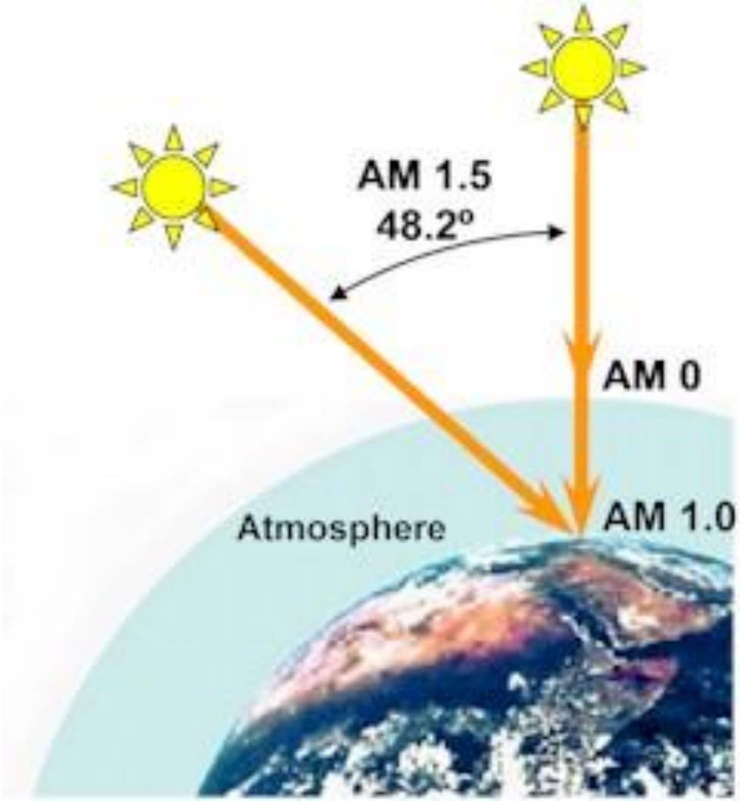
- Efficiency of good coal/oil power stations – 40%
- Combined gas-steam turbines – almost 60%
- Best PV cells – 44% (theoretical maximum is 67%)
- Standard silicon gives us ~16% (Shockley–Queisser thermodynamic limit is ~33%)

Sunlight is made up of many different wavelengths, and the intensity varies as can be seen..



Definition of Air Mass or AM

- When the sun is at its zenith (i.e. directly overhead), the distance the sunlight has to travel to the PV array is a minimum, known as Air Mass 1.

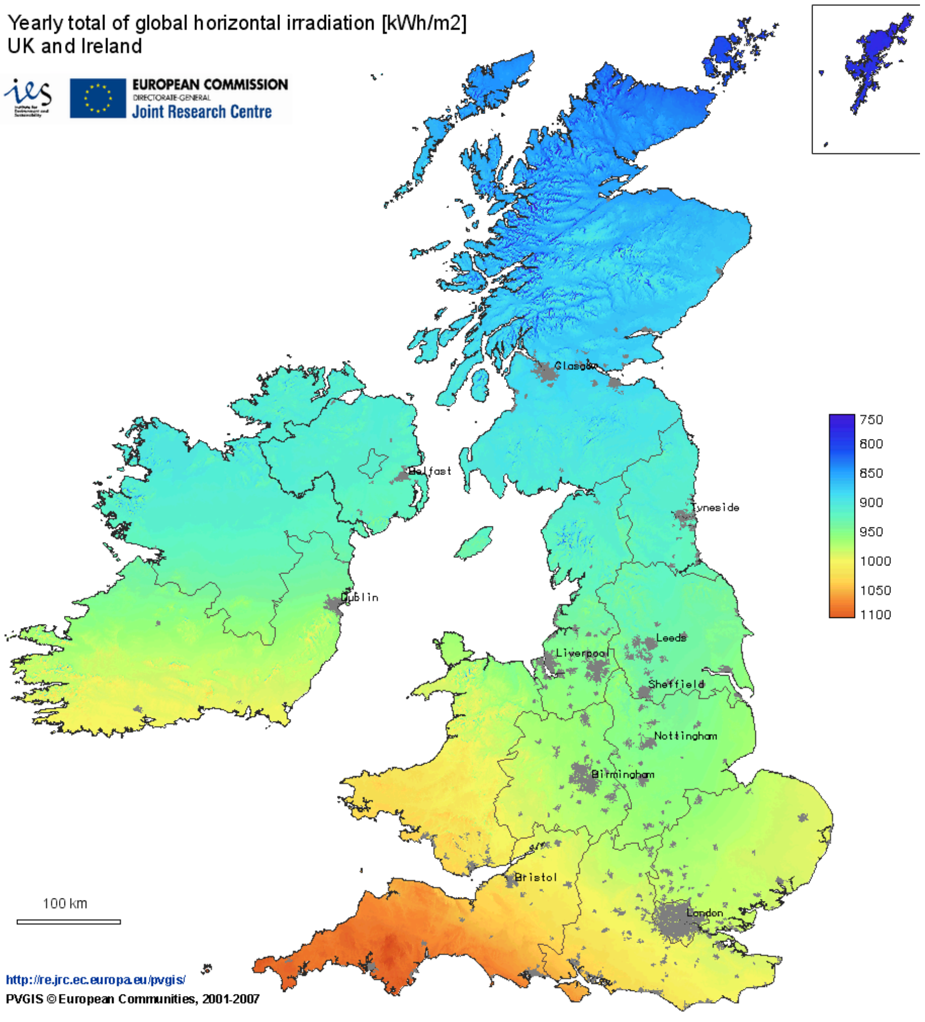


At other times of day, the sun is at an angle, and we need to take the extra distance the light has to travel in the atmosphere into account. Air Mass = $1/\cos(\vartheta)$.

AM 1.5 is a good average value for daytime conditions.

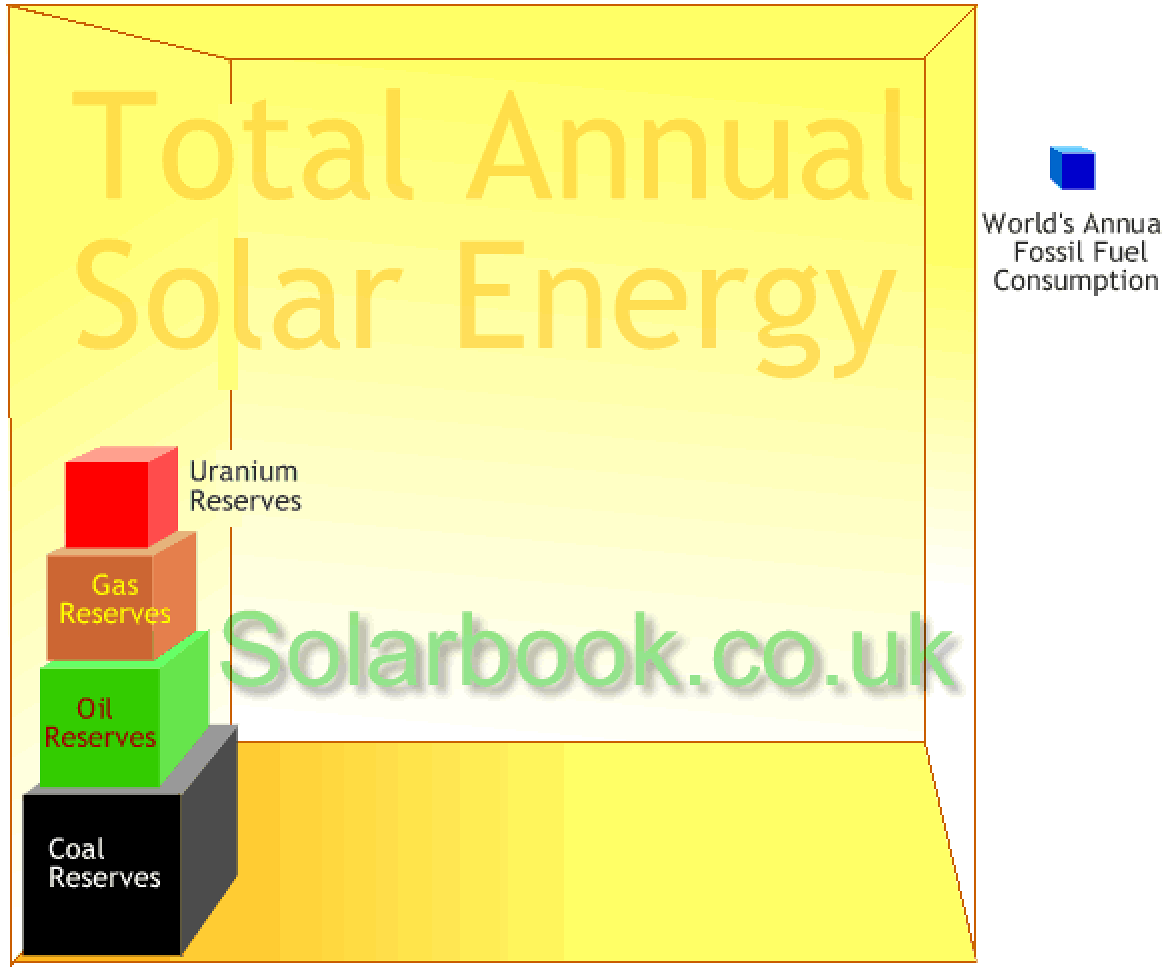
UK total irradiation

- The south-west is better than the north for PV



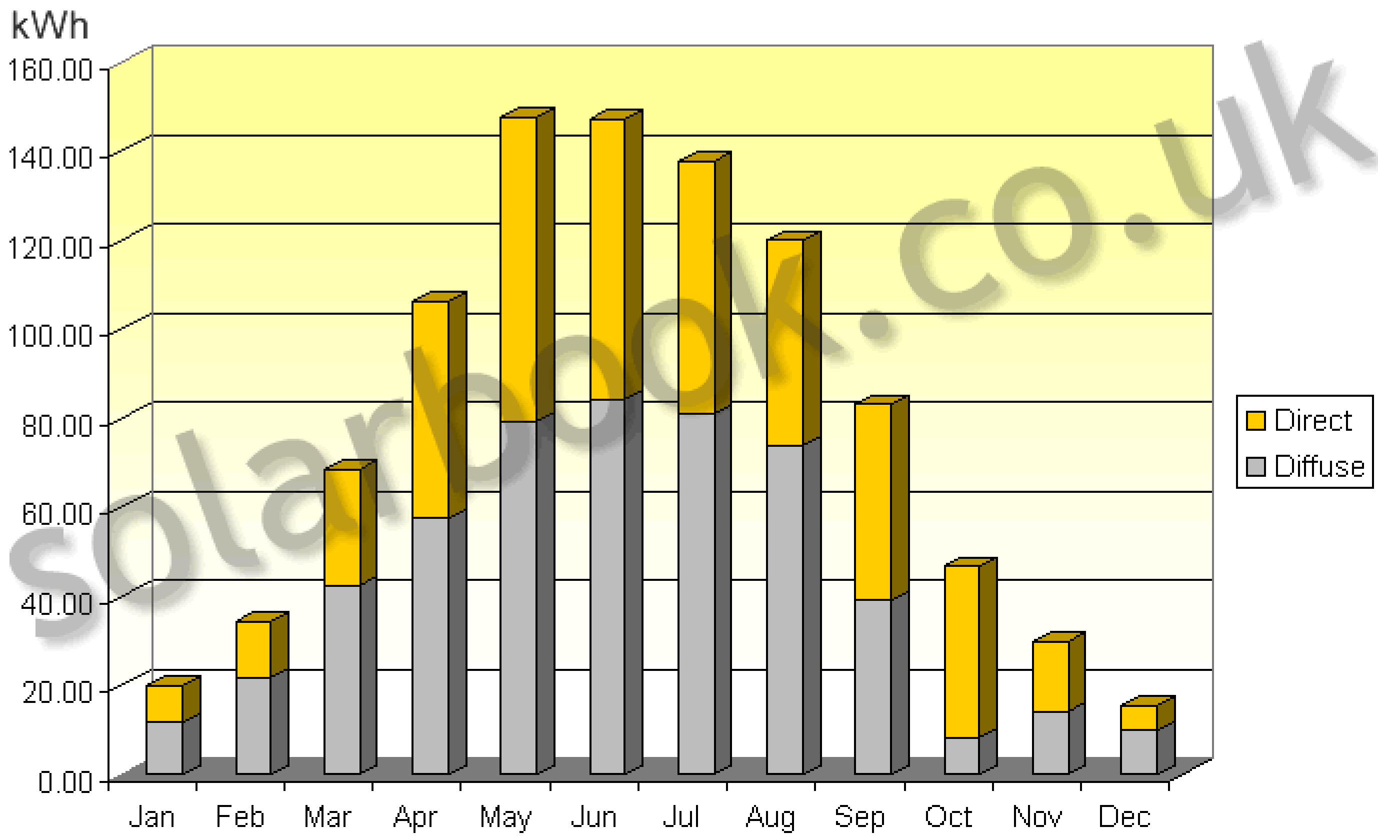
Solar energy vs. Other sources

- The potential of solar energy is obvious from this figure.



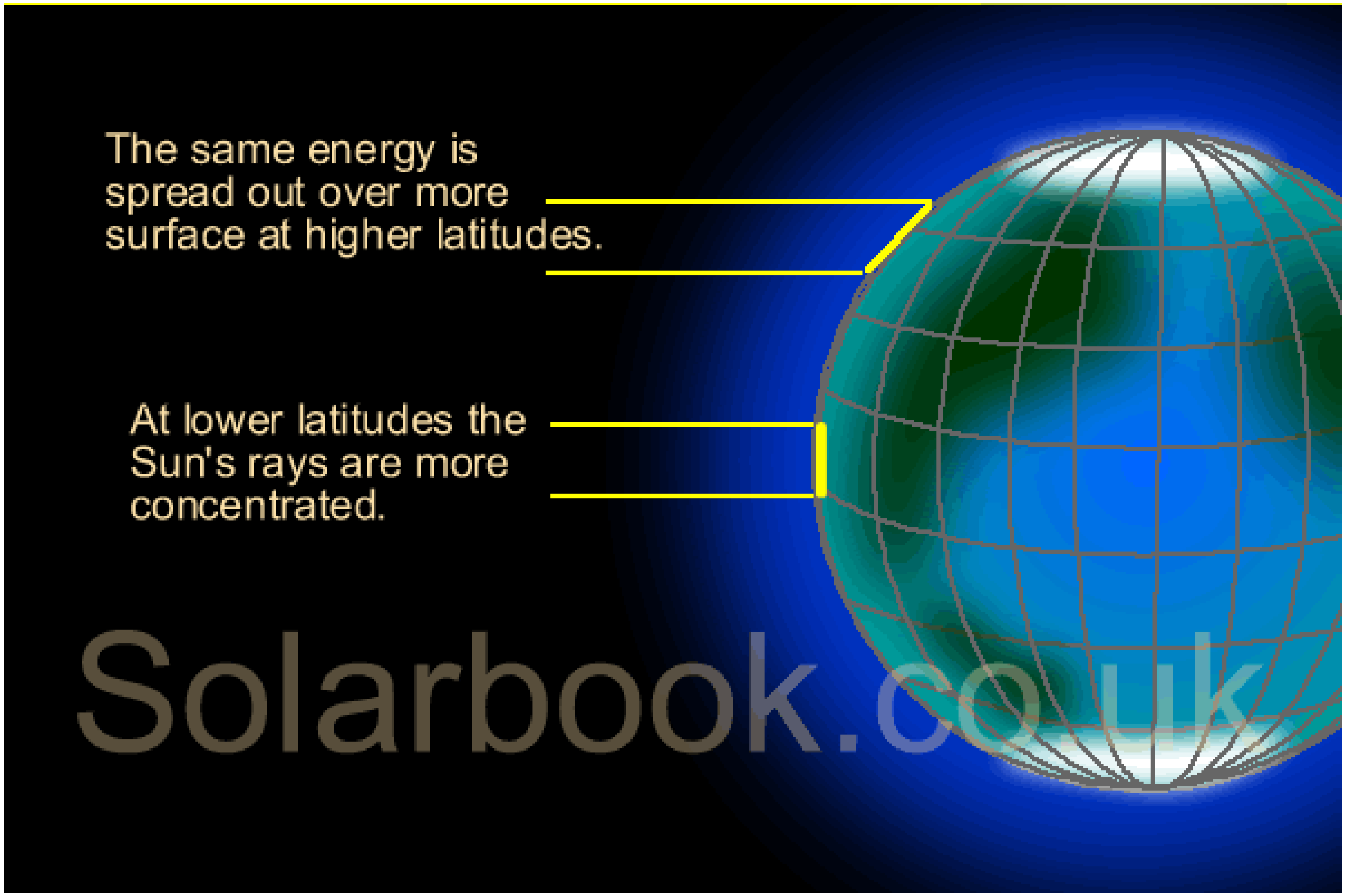
http://www.solarbook.co.uk/

Variation in sunlight during the year

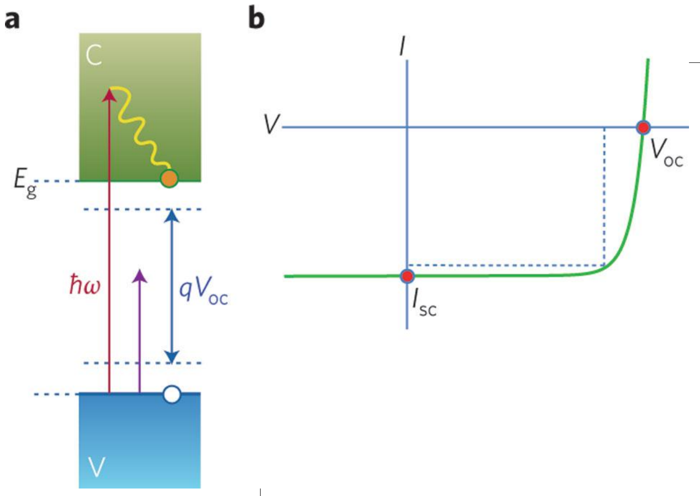


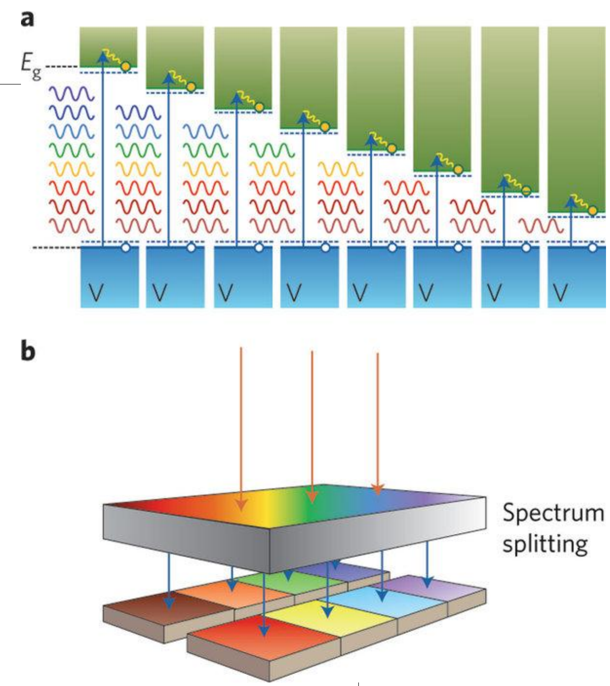
http://www.solarbook.co.uk/

Latitude and time of year affects the power density



How does light create carriers in a semiconductor?





If the light has an energy > Eg (band-gap energy of the semiconductor), an electron can be promoted into the conduction band while leaving behind a hole (a positively charged version of the electron).

As Eg increases, shorter wavelengths of light (higher energy) is required to create charge carriers.

How/Why does a semiconductor p-n junction generate current & voltage when illuminated?

- Need to understand some basic semiconductor theory. A full semiconductor band and an empty semiconductor band cannot conduct electricity.

No carriers to move on upper floor

Too many carriers for movement on lower floor

Image from www.wsi.tum.de

How/Why does a semiconductor p-n junction generate current & voltage when illuminated?

- Energy (in the form of light) can move some charge carriers from lower level to higher level. This allows movement of charge on both levels – i.e. current can flow.

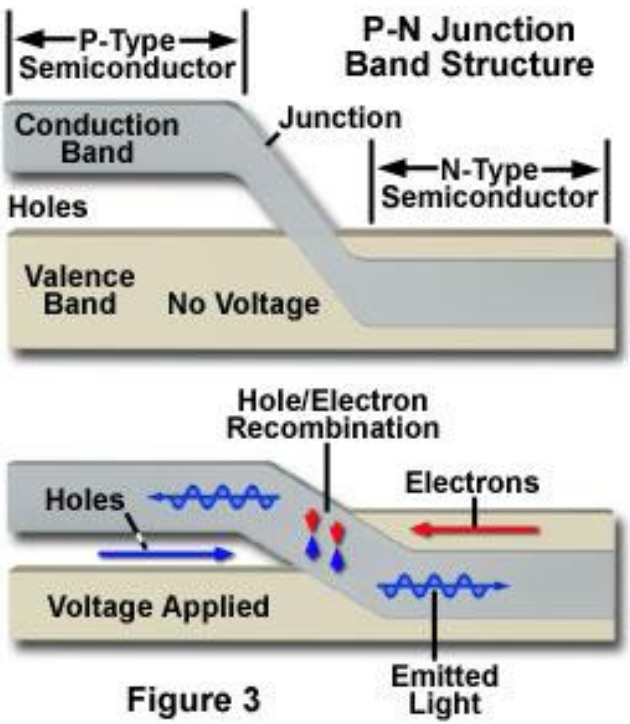
Some charge carriers can move on upper floor

Some charge carriers can now also move on lower floor

Image from www.wsi.tum.de

Where does the voltage come from?

- As charge is now moving across the p-n junction, there is a voltage developed across the p-n junction.



In the dark, there is no movement of the conduction and valence bands

Under illumination, the conduction band moves down and the valence band moves up so that charge can move.

Image from www.olympusfluoview.com

Once you have current AND voltage, you have power being generated. Power = current x voltage

- You can have different values of current and voltage in a p-n junction under illumination, depending on the resistance of the 'load'.

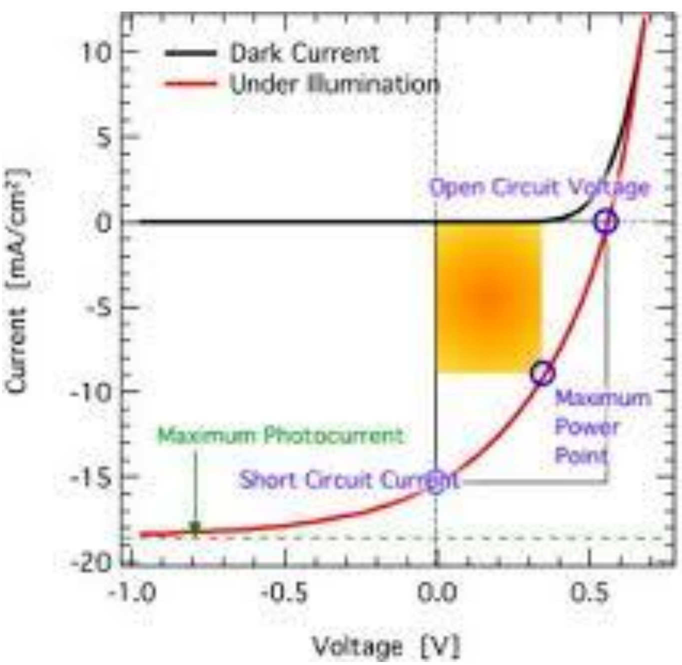


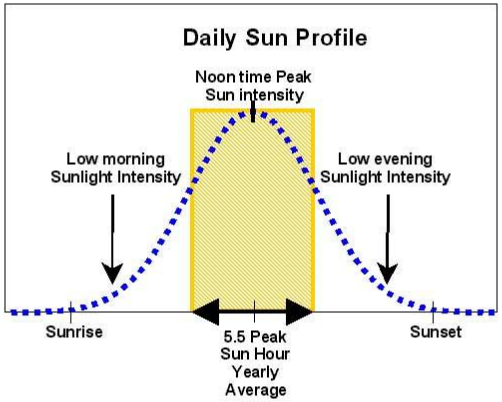
Image from blog.disorderedmatter.eu

Operating point has to be on the red line in 3rd quadrant.

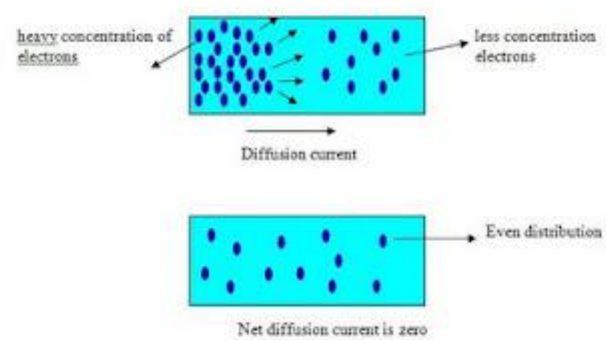
Yellow square is the power produced. You cannot have a large current simultaneously with a high voltage.

Load refers to the object being supplied with power (e.g. heater, TV, lamp..).

Current developed by PV cell – depends on a number of factors



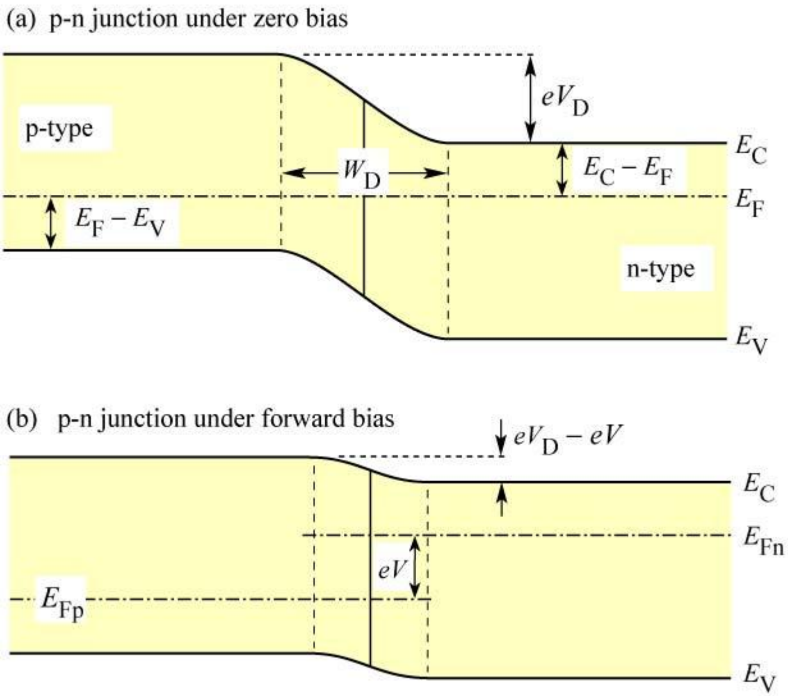
Illumination varies with time of day – so does current.
www.solarexpert.com



Longer diffusion length gives higher currents.
Freeengineeringnotes.blogspot.com

If the illumination is constant, then larger area cells generate higher current.

Voltage developed by PV cell



In dark, no voltage across p-n junction

Fig. 4.1. P-n junction under (a) zero bias and (b) forward bias. Under forward bias conditions, minority carriers diffuse into the neutral regions where they recombine.

With illumination, a voltage *V* develops across the p-n junction

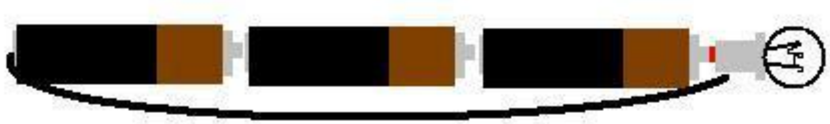
E. F. Schubert
Light-Emitting Diodes (Cambridge Univ. Press)
www.LightEmittingDiodes.org

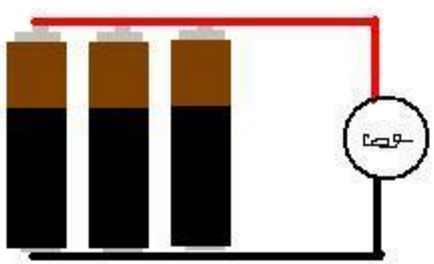
The light forward biases the p-n junction and the voltage *V* appears across the terminals. The typical value of *V* is about 0.3-0.7 of the band-gap. As Si has a band-gap energy of 1.1eV, *V*~0.6 volts is typical.

http://www.ecse.rpi.edu/~schubert/Light-Emitting-Diodes-dot-org/chap04/chap04.htm

PV has to produce high current and high voltage simultaneously

1.5 volts + 1.5 volts + 1.5 volts = 4.5 Volts





1.5 Volts

We do this routinely with batteries for torches, radios, etc.

A series connection gives increased voltage but not current.

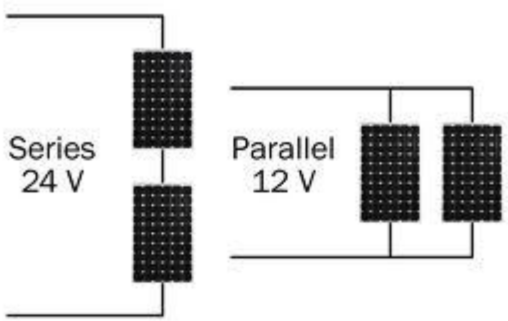
A parallel connection gives increased current but not voltage.

One battery going open circuit is a serious problem for series connection.

One battery going short circuit is a serious problem for parallel connection.

PV has to produce high current and high voltage simultaneously

Example shows 9 x 4 cell panel. 36 silicon cells connected in series can easily produce a voltage between 12V – 18V.



We can now connect these panels in series to increase voltage and in parallel to increase current. The total number of panels required will depend on the application it is used for and the power required. Same problems as batteries if one cell goes open circuit or short circuit.

![SHARP]

ND Series (60 cells)
220 W | 210 W

Polycrystalline silicon photovoltaic modules

Say yes to solar power!

Because it protects the climate.

Innovations from a photovoltaic pioneer

As a solar specialist with 50 years' experience in photovoltaics (PV), Sharp makes significant contributions to ground-breaking progress in solar technology.

Sharp photovoltaic modules in the ND series are designed for applications with high power requirements. These quality polycrystalline modules produce a continuous, reliable yield, even under demanding operational conditions.

All Sharp ND series modules offer system integration which is optimal both technically and economically, and are suitable for installations in on and off-grid PV systems.

Brief details for the installer

- 156.5 mm × 156.5 mm polycrystalline solar cells
- 60 cells in series
- 2,400 N/m² mechanical load-bearing capacity (245 kg/m²)
- 1,000 V DC maximum system voltage
- IEC/EN 61215, IEC/EN 61730, Class II (VDE: 40021391)

Product features

- High-performance photovoltaic modules made of polycrystalline (156.5 mm)² silicon solar cells with module efficiencies of up to 13,4 %.
- Bypass diodes which minimise the loss in output when shading occurs.
- Textured cell surface for particularly high electricity yields.
- BSF structure (Back Surface Field) to optimise cell efficiency.
- Use of tempered white glass, EVA plastic, and weather protection film, as well as an anodised aluminium frame with drainage holes for long-term use.
- Output: connection cable with waterproof plug connector.

Quality from Sharp

Benchmarks are set by the quality standards of Sharp Solar. Continual checks guarantee a consistently high level of quality. Every module undergoes visual, mechanical, and electrical inspection. This is recognisable by means of the original Sharp label, the serial number, and the Sharp guarantee:

- 5 year product guarantee
- 10 year performance guarantee for a power output of 90 %
- 25 year performance guarantee for a power output of 80 %

The detailed guarantee conditions and additional information can be found at **www.sharp.eu**.

Mechanical data

Cell	Polycrystalline (156.5 mm)² silicon solar cells
Quantity and wiring of cells	60 in series
Dimensions	1,652 × 994 × 46 mm (1.64 m²)
Weight	21 kg
Connection type	Cable with plug connector (MC-3)

Limit values

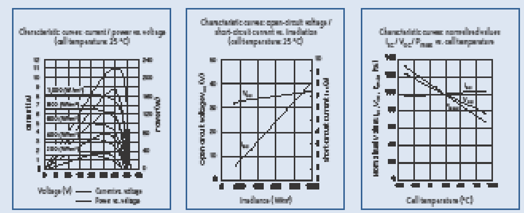
Operating temperature (cell) Storage temperature	– 40 to + 90	°C
Storage air humidity (relative)	up to 90	%
Maximum system voltage	1,000	V DC
Maximum mechanical load	2,400	N/m²
Over-current Protection	15	A

Electrical data

		ND-220 (E1F)	ND-210 (E1F)	
Maximum power	P_{max}	220 W_p	210 W_p	
Open-circuit voltage	V_{oc}	36.5	36.4	V
Short-circuit current	I_{sc}	8.20	8.03	A
Voltage at point of maximum power	V_{mpp}	29.2	28.8	V
Current at point of maximum power	I_{mpp}	7.54	7.3	A
Module efficiency	η_m	13.4	12.8	%
NOCT		47.5	47.5	°C
Temperature coefficient – open-circuit voltage	αV_{oc}	– 130	– 130	mV / °C
Temperature coefficient – short-circuit current	αI_{sc}	+0.053	+0.053	% / °C
Temperature coefficient – power	αP_{max}	– 0.485	– 0.485	% / °C

The electrical data applies under standard test conditions (STC): irradiation 1,000 W/m² with light spectrum AM 1.5 and a cell temperature of 25 °C. The rated electrical characteristics are subject to a manufacturing tolerance of – 5 % / + 10 %. NOCT conditions: irradiation of 800 W/m², ambient temperature of 20 °C and wind speed of 1 m/sec.

Characteristic curves ND-220 (E1F)

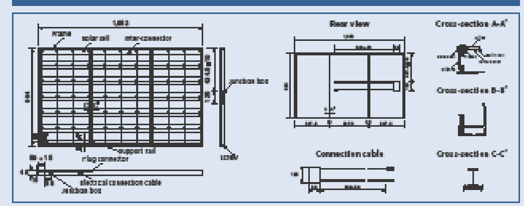


Applications

- On-grid PV systems
- Off-grid PV systems
- On-roof PV systems
- Ground-mounted PV systems

Please read our detailed installation manual carefully before installing the photovoltaic modules.

Exterior dimensions



Note

Technical data is subject to change without prior notice. Before using Sharp products, please request the latest data sheets from Sharp. Sharp accepts no responsibility for damage to devices which have been equipped with Sharp products on the basis of unverified information.

The specifications may deviate slightly and are not guaranteed. Installation and operating instructions are to be found in the corresponding handbooks, or can be downloaded from www.sharp.eu.

This module should not be directly connected to a load.

The reference image on the front page shows an 1 MWp system of Sunline AG in Forth, Germany.

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SHARP

SolarND_60_E1109

Interpreting Sharp PV panel data:

There are 60 polycrystalline Silicon cells connected in series for each panel. As the Open Circuit Voltage (Voc) = 36.5 volts, each cell must be producing about 0.61 volts. This is reasonable for a good silicon cell.

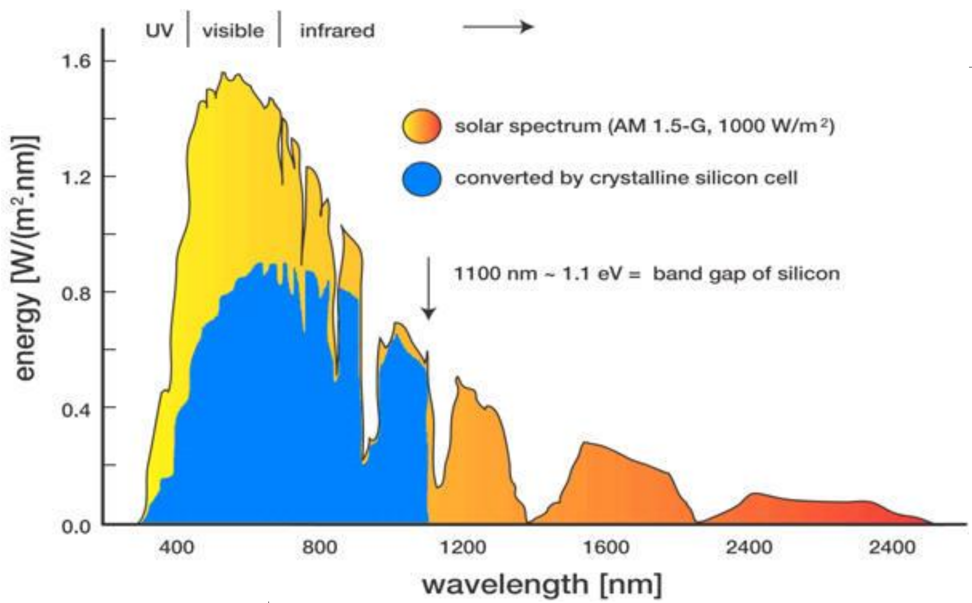
When exposed to light (1000 W/m^2 with AM1.5 spectrum and at 25C) the panel produces 8.2 Amps of current. As this is a series connection, each cell must produce this current.

Each cell is 156mm x 156mm, so the sunlight power falling on a cell is 24.3 watts. As there are 60 cells in the panel, the power on all the cells is 24.3 x 60 =1460 watts.

When matched to the optimum load, the panel provides 29.2 volts (V_{mpp}) and 7.54 amps (I_{mpp}). So the optimum power developed is 29.2 x 7.54 = 220 watts.

The panel efficiency is therefore 220/1460 = 15%. This calculation gives a figure close to that stated of 13.4%.

Why is the PV efficiency not 100%?



www.vicphysics.org

Not all the sunlight is captured effectively by silicon and converted to charge carriers.

Not all the charge carriers will contribute to current.

Current world record for silicon is ~25%, but most commercial cells are around the 15-17% efficiency mark.

Electrical Appliances in a Home

- Fridge Freezer -250-350 kWh/year
- Washing machine -1-2 kWh/cycle
- Tumble dryer -4kWh/cycle
- Kettle -2-3kW
- Computer -200W
- Hair dryer -2kW
- TV -125W

- Typical household uses 3,300kWh/year
- Calculate how much electricity you use in a year in kWh.

Roof area needed for PV system

- Typical panel is 1.6mx1m, @220W output
- Need 12 for 2.6kW
- Need ~20m^2 roof area
- Typical cost ~£9K

Is PV a sensible choice for a home?

Q1: How much electricity is used in a year? - typical house 3300kWh

Q2: How much sunshine do you get in a year? - typically 900kWh/m^2

Q3: What is the cell/panel efficiency? – typically 15%

Q4: How much south facing roof space is available? – typically 15-25m^2

Calculation: You will only get 135W/m^2 of useful power with standard cells/panels. Therefore will need 24.4m^2 of panels to cover the electricity use by PV.

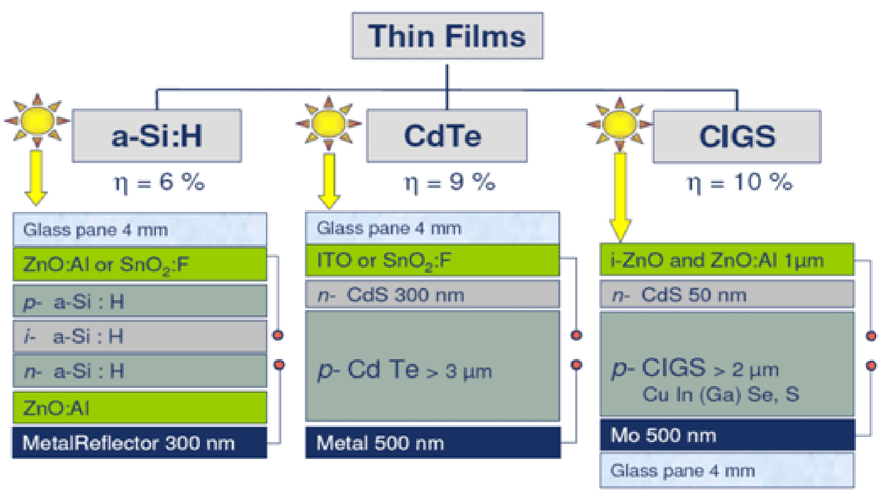
As 1kWh is ~16p, you spend £528/annum on electricity.
Over 20 years you spend £10560 on electricity – about the same as installation cost.
Increasing cost of energy with time & Government subsidies (FIT) mean that it is currently a good deal for most people in appropriate locations.

Key components of a PV system

- Besides the solar panel, we need a number of other components as shown.
- Battery for storing energy
- Inverter for converting DC to AC
- MPPT controller or regulator

Different types of PV modules

Mono-crystalline is highest quality but most expensive. Amorphous sililcon is cheap and easy to deposit in large areas but has lower efficiency.



Alternatives to crystalline forms of silicon have lover efficiencies but are cheap as they can be deposited on plastic, glass etc.