Fundamental

SERIES 9 MODULE 08

CURRENT THINKING ON...

Photovoltaic systems

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Photovoltaic (PV) systems use photovoltaic cells to capture energy from sunlight and convert it into direct current (DC) electricity. This electricity can then be used as DC (often stored in a battery) or converted into alternating current (AC) via an inverter. A PV module or 'panel' is formed from a number of cells which are connected within the module into sub-strings. Modules are normally connected together into one or more strings to form what is known as an array.

The amount of energy in the sunlight reaching the earth's surface is equivalent to around 10,000 times the world's energy requirements[1]. On average, the UK receives around 1,000kWh per m^2 each year[2] (this figure is larger in the south of England than Scotland). However, only a small portion of this incident energy can be converted to electricity by photovoltaic panels due to their relatively low energy conversion efficiency.

The intensity of daylight (irradiation) at any point on the earth's surface at any time varies hugely depending on the time of year, time of day and cloud conditions. When the sun is highest in the sky and there are fewest clouds the least energy is reflected back into space or absorbed before it reaches the earth. Therefore, maximum light intensity (irradiance) is most likely in the UK at around midday near summer solstice (when the sun is highest in the sky). In the UK, monthly irradiation in winter is roughly one quarter of that in summer due to the shorter days and the sun being lower in the sky[3].

As light passes through the atmosphere gases and particles absorb different frequencies by various amounts. The absorption due to the length of the path through the atmosphere is described by the air mass factor which describes the distance perpendicular to the earth's surface and allows for the change in spectrum of light.

Irradiation incident

A solar panel will receive the maximum energy when it is perpendicular to incident daylight (irradiation). The irradiation incident on a surface such as a solar panel depends on its elevation (normally measured from the horizontal) and azimuth (e.g. south) and the position of the sun. For example, a solar panel lying horizontally will capture more energy at summer solstice than a vertical panel facing east.

As the position of the sun is constantly changing it is not possible for a fixed solar panel to be perpendicular to the incident energy all of the time. The optimal angle for a fixed solar panel is that which captures the most energy over the course of a year. In the UK this is facing south at an angle of elevation of between 300 and 400.

Sunlight comprises beam and diffuse components. The beam portion comes direct from the sun and casts hard shadows while the diffuse portion has been scattered on its journey through the atmosphere. In the UK around 60 per cent of sunlight (irradiation) is diffuse[2]. This means that if a panel does not face in the best direction, the reduction in yield is not as significant as one might expect. For example, panels facing east or west (at an elevation of 30°) are predicted by the Standard Assessment Protocol (SAP) to have an output of around 20 per cent less than if they had faced south.

Photovoltaic modules (commonly known as PV panels) comprise semi-conductor materials that absorb photons of light energy and liberate direct current (DC) by releasing charge (electron-hole pairs). The most common types of modules are made of crystalline silicon although thin-film technology is becoming increasingly popular.

Crystalline modules are made from a number of cells (often 60) connected together in series to give the required voltage (e.g. 30V). Each cell comprises a junction of positively and negatively dopes silicon. If one cell is shaded it can cause a hot-spot due to the current flowing through it from the illuminated cells, therefore the cells within a module are connected into substrings, each of which has a bypass diode to prevent over-heating. The modules provide electrical connection points and mechanical protection for the cells, typically through the use of an aluminium frame, tempered glass and encapsulation. Commercially available crystalline modules have a typical efficiency of around 14 per cent.

Photovoltaic cells require very high purity silicon which is made by the melting of silica sand at extremely high temperatures followed by further chemical processing. The silicon can be made into either mono- or poly-crystalline cells. Mono-crystalline has a very regular structure and is grown slowly by drawing a crystal at high temperatures. Poly-crystalline is produced faster and has a less regular structure which gives lower energy conversion efficiency (due to faster hole – pair recombination). Mono- and poly-crystalline are visibly different

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as mono-crystalline cells are cut to be semi-round and have a uniform appearance (*see photo below*) while poly-crystalline cells are square and the individual crystals can be seen (*see photo right*).

Efficiency drops

Electrical contacts are required on the front and back of the cell to take charge away from the junction. Roughly half of the energy in the incident radiation is not captured by the cell as the photon energy is too high or low to be absorbed. Further losses are due to electrical factors (potential difference and recombination losses) and shading from the contacts. Solar cells have negative temperature coefficients meaning their efficiency drops with temperature.

Thin film modules are made by deposition of a thin layer of semi-conductor onto a substrate (typically glass). Their manufacture can take place at far lower temperatures than silicon cells and requires considerably less material, meaning production costs are lower. Thin film modules have considerably lower efficiency but offer better performance in diffuse light and have a better tolerance of shading. During their initial period of operation the efficiency of the panels drops due to light-induced degradation. Despite this, thin film modules can be very useful for building integration as they can be semi-transparent and incorporated into glazing or cladding materials. Commercially available modules have an efficiency of around 7 per cent.

Hybrid modules are available that comprise mono-crystalline cells and a thin film layer to provide a high module efficiency (e.g. 17 per cent for Sanyo HIT modules).

Electrical characteristics are defined at standard test conditions (STC) which are: irradiance of 1,000W per m^2, air mass factor of 1.5 and cell temperature of 25°C. The efficiency of a module is defined as the electrical output power of the module divided by the solar power incident on it. A higher efficiency module can produce more electricity from a fixed area (under standard test conditions).

Panels are described in terms of their voltage and current characteristic.

The maximum voltage (Voc) occurs when the module is not connected to anything (known as open circuit). When the module connections are joined (short circuited) the maximum current occurs (Isc). The instantaneous power from the module is the product of voltage and current and has a maximum value for any one irradiance level. As the incident irradiance reduces the current drops. The voltage also reduces with irradiance (to a smaller extent) but is mainly determined by temperature.

To obtain the maximum power from a module in any given light level, the current drawn must be chosen to achieve the maximum power voltage (Vmp). Most modern inverters and charge regulators adapt dynamically to operate at the current which maximises the transfer of electrical power. This technique is known as maximum power point tracking.

Panel data sheets give the following electrical parameters which are used in system design:

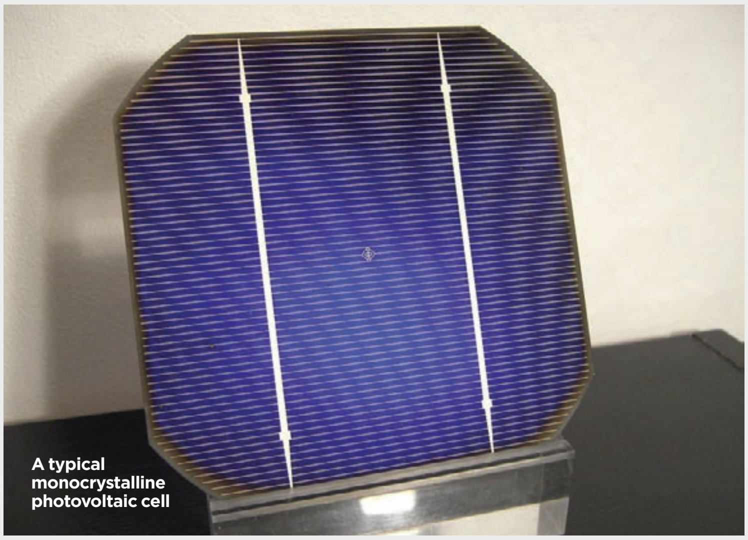
• electrical output e.g. 240W;
• open circuit voltage and short circuit current e.g. 37V and 9A; and
• maximum power current and voltages e.g. 30V and 8A.

These parameters are measured at standard test conditions during a 'flash test'. However, modules perform under a variety of conditions (typically at lower irradiance). Also, when modules are subject to high levels of irradiance they are often hotter than 25°C. This means that the temperature coefficient of the module is important as it determines the drop in efficiency with increase in temperature. Daylight levels in the UK are rarely more than 1,000W per m^2 meaning that panels seldom perform at the rated output.

The income that can be generated from a system depends on the annual yield which is determined by the system size, irradiation (determined by location, orientation, elevation and shading), and panel performance. Yields are often normalised to enable comparison of performance i.e. kWh per year from one kW of installed capacity. Expected yields in the UK can be calculated using the Standard Assessment Procedure (SAP). SAP takes into account orientation, shading and elevation but does not allow for location or panel technology e.g. systems of the same size using panels located in Scotland and England are estimated as having the same yield. The Standard Assessment Procedure gives an expected annual yield of around 800kWh per kW of installed panel capacity for well-located systems such as those facing roughly south at standard roof pitch and with little shading. Based on this a 4kW domestic system can produce over 3,000kWh each year (over half of typical domestic electricity demand).

As mentioned above, panels are tested under standard test conditions but perform under a variety of conditions. For this reason the yields from 1kW of photovoltaic modules at any one site in any one year will vary between technologies and even manufacturers. This can be shown through simulation using software such as PVSol and by data from independent trials such as that undertaken by Photon Magazine.

Yields can be reduced by small levels of shading as systems typically comprise modules in series: shading of one module will reduce the performance of the entire string in which it is connected. This can be minimised through the use of micro-inverters (one per panel). In addition, if one cell in a module is shaded (e.g. by a leaf) the entire sub-string in which it is located will be by-passed by internal diodes. Even partial shade has a disproportionately large impact on performance.


A typical monocrystalline photovoltaic cell

Consider shading

When considering system design the location of any sources of shading must be carefully considered. The impact of shade will be greatest if it occurs at the middle of the day and / or the middle of the year when light levels are at typically at their highest.

Off-grid systems generate electricity and either use it directly (e.g. in a water pump) or store it in a battery for use as required. Such systems must be carefully sized so that the number of panels and batteries are correctly selected to meet the required energy demand while minimising cost. The system sizing must take into account the profile of both irradiance and electricity demand. This is because the batteries cannot provide energy storage for many months (i.e. the panels must be sized to meet winter demand) and irradiance varies on a daily basis (i.e. several days energy storage is required).

A typical off-grid system comprises several panels, a charge regulator and batteries. The charge regulator links the panels and batteries to prevent over-charging and under-charging of the batteries. The energy stored in the batteries can be used as direct current (DC) or converted to alternating current power (AC) via an inverter. Inverters allow standard electrical appliances to be used and power to be transmitted longer distances more efficiently (due to the higher voltages) but introduce additional conversion losses.

For grid-connected systems

the number of panels is normally determined by physical constraints (such as roof space) or financial considerations. Typical domestic systems are 2- 4kW. The panels are connected into strings to provide a voltage and current suitable for an inverter of the appropriate rating. The system must be designed so that the voltage of the string is less than the maximum value for the inverter but with the maximum power point voltage within the maximum power point tracking range of the inverter. The inverter manufacturer's software should be used to ensure the best unit is selected for the array and the correct number of strings used. For a typical domestic installation the panels are connected as one string of modules providing, for example, 7A of direct current (DC) at 500V.

The panels are connected to an inverter which converts the DC electricity to standard mains electricity (230V AC). Inverters are available with or without transformers. Transformers offer the advantage of electrical separation between the DC and AC circuits but add weight and energy losses. The use of transformerless inverters in the UK currently requires bonding of the system to earth.

In a typical PV installation the AC electricity from the inverter is fed into the property's electrical system. Electricity generated is used on-site with any surplus exported to the grid. Under Engineering Recommendation G83/1, certain microgeneration systems smaller than 16A per phase can be installed without prior permission from the distribution network operator as long as type approved equipment is used and the installations meet the requirements of G83/1 (e.g. disconnection on under/over voltage and frequency). For larger systems permission should be

A typical polycrystalline photovoltaic cell system

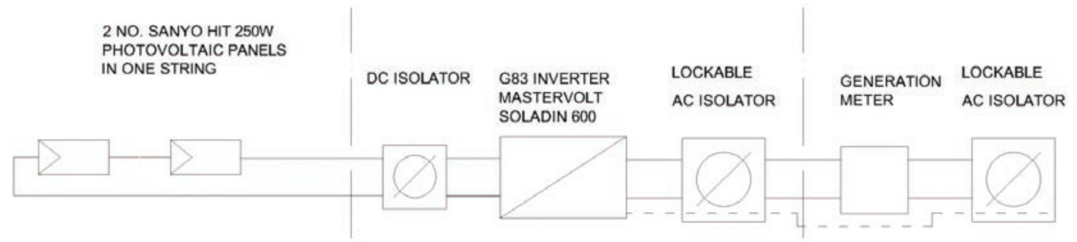
sought prior to connection but the use of G83 approved equipment is often allowed. Large systems (e.g. over 30kW) may require the use of G59 approved equipment which has tighter operating parameters.

Lower systems costs

Photovoltaic systems are becoming increasingly popular for grid-connected systems due to lower systems costs, higher energy prices, financial incentives and environmental drivers. Encouraged by the successful use of subsidies in Germany the UK Government introduced the Feed in Tariff to provide incentives for a number of renewable technologies including photovoltaics. Since the introduction of the Feed In Tariff there has been a huge increase in the number of systems installed. There have also been significant reductions in installed costs (mainly due to lower equipment costs) meaning that photovoltaic systems provide higher returns on investment than envisaged by Government when the scheme was introduced. The scheme has been so popular that the rates paid have been reduced, leading to uncertainty in the sector about future uptake.

Photovoltaic modules currently cost less than £1 per watt and the typical cost of a domestic sized system is around £3 per watt (including balance of plant and installation). Income is earned from:

Electrical schematic for a small grid-connected PV system



- bill reduction (value of imports offset by on-site generation);
- generation tariff (paid for all electricity generated regardless of where it is used); and
- export tariff (paid for exports – typically 'deemed' at 50 per cent but can be measured).

The Feed In Tariff comprises the Generation and Export Tariffs and is paid by an electricity supplier. To obtain the FiT the system (assuming it is smaller than 50kW) must be installed by a Microgeneration Certification Scheme (MCS) approved installer.

There is a very large amount of solar energy reaching the UK each year and it has significant variation throughout both the year and the day. Despite the low energy conversion efficiency of PV modules a typical domestic PV system can produce enough electricity to make a significant contribution towards a home's electricity consumption.

Further reading

- Choosing Solar Electricity: A Guide to Photovoltaic Systems – Brian Goss.
- Photovoltaics in Buildings – Guide to the installation of PV systems 2nd edition (2006).
- Planning and installing Photovoltaic Systems. A guide for installers, architects and engineers (2nd edition 2008).
- Photovoltaics in the UK: An introductory guide for new consumers: http://www.eci.ox.ac.uk/research/energy/downloads/pv-inthe-uk.pdf

References

1) Planning and installing Photovoltaic Systems. A guide for installers, architects and engineers (2nd edition 2008).
2) Photovoltaic Geographical Information System (PVGis): http://re.jrc.ec.europa.eu/pvgis/apps4/pvest.php#
3) The Government's Standard Assessment Procedure (SAP) for Energy rating of Dwellings 2009 - Appendix M. (Department of Energy and Climate Change).
4) Photovoltaics in Buildings – Guide to the installation of PV systems 2nd edition (2006).
5) Engineering Recommendation G83/1-1 June 2008 (Energy Networks Association).

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This is the eighth module in the ninth series and focuses on photovoltaic systems. It is accompanied by a set of multiple-choice questions. To qualify for a CPD certificate readers must submit at least eight of the ten sets of questions from this series of modules to ***Energy in Buildings and Industry*** for the Energy Institute to mark. Anyone achieving at least eight out of ten correct answers on eight separate articles qualifies for an Energy Institute CPD certificate. This can be obtained, on successful completion of the course and notification by the Energy Institute, for a fee of £15 (for members) or £25 (for non-members).

The articles, written by a qualified member of the Energy Institute, will appeal to those new to energy management and those with more experience of the subject.

The forthcoming modules in the ninth series will focus on: refrigeration, and motors and drives. If you missed any of the modules in this series (the previous modules focused on monitoring and targeting, air conditioning, underfloor heating, biomass boilers, building energy management systems, heat pumps, and first steps in energy management) please let EiBI know (mark.thrower@btinternet.com) and we will send you the missing modules in 'pdf' format either by e-mail or on a CD.

The previous 80 modules from the first eight series are also available free of charge on CD.

MARK THROWER, MANAGING EDITOR

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Completed answers should be mailed to:

The Education Department, Energy in Buildings & Industry, P. O. Box 825, GUILDFORD, GU4 8WQ

SERIES 9 MODULE 08: QUESTIONS

Photovoltaic systems

Please mark your answers on the sheet below by placing a cross in the box next to the correct answer. Only mark one box for each question. You may find it helpful to mark the answers in pencil first before filling in the final answers in ink. Once you have completed the answer sheet in ink, return it to the address below. Photocopies are acceptable.

1. Which is the smallest component of a typical photovoltaic system?

☐ module ☐ Array ☐ Inverter ☐ Cell

2. What yield might one expect from a well-positioned 10kW PV system in the UK?

☐ 8,000 kWh per year
☐ 10,000 kWh per m2
☐ 14,000 kWh per year
☐ 30,000 kWh per year

3. Which pair of panel azimuth and elevation gives the best yield in the UK?

☐ Any direction, horizontal
☐ South facing, 36°
☐ South facing, 50°
☐ South facing, vertical

4. Estimate the reduction in output caused by the shading of 1% of a panel.

☐ 1 per cent
☐ 10-50 per cent
☐ 80 per cent
☐ 100 per cent

5. What is the reduction in yield from a PV panel facing east rather than south (300 elevation)

☐ 5 per cent
☐ 20 per cent
☐ 50 per cent
☐ 70 per cent

6. What does the Feed In Tariff provide an income for:

☐ Generation only
☐ Export into the grid only
☐ Generation and export
☐ On-site use only

7. What factor would NOT affect the annual yield from a 250W PV panel:

☐ Efficiency at Standard Test Conditions
☐ Temperature
☐ Shading
☐ Location

8. What is the most common type of photovoltaic module currently used in the UK?

☐ Amorphous ☐ Crystalline ☐ Hybrid ☐ Thin-film

9. What is the function of an inverter in an off- grid photovoltaic system?

☐ Charges the battery from the panels
☐ Measures the energy produced by the photovoltaic modules
☐ Converts the DC from the panels to AC for the grid
☐ Converts DC electricity to AC electricity

10. In what way would you expect 250W PV panels of varying efficiencies to vary?

☐ Energy produced at Standard Test Conditions
☐ Predicted annual energy yield
☐ Area
☐ Rated power