1. Introduction
Perhaps the title should be “inflexible solar cells” because that is the common perception of most available photovoltaic (PV) modules on the market today (Fig. 1). These extremely visible additions to buildings around the world are not beloved of architects or planners, despite their environmental credentials. Even when a building is designed with an integrated PV array there is a limited choice of system. To appreciate this we should understand the manner in which PV modules convert sunlight into electricity, which requires certain features in common across all photovoltaic devices.

We may then be able to realise the restrictions placed on PV scientists and engineers in developing new types of solar cell, and critically appraise suggestions for novel designs. Certainly there is a need for truly flexible modules, whether this is to assist in transporting and mounting them or whether it is to enable fixing to non-rigid structures.
2. Sunshine to electricity: the photovoltaic conversion process

Solar cells absorb sunlight to generate electrical current directly by the photovoltaic effect, without a thermal or mechanical mediator. To do this effectively they must be optically dense for much of the solar spectrum, which explains their dark blue or black appearance (Fig. 2 and 3). The three features that all solar cells possess are: an optical absorber that converts light to electrical charge; an in-built electrical field that separates these pairs of positive and negative electrical charges before they are lost by recombination; electrical contacts that deliver these charges to the external work load. The first two of these features are provided by a semiconducting material, commonly silicon, which has the ability of controlled electrical conductivity by the addition of very small amounts of selected impurities. In this manner, two types of semiconductor are formed; p-type and n-type, which together generate an electrical field at any p-n junction without the addition of an external power supply.

As with any power conversion device, the conversion will be less than 100% efficient, determined by unavoidable losses and ultimately set by thermodynamics. Solar cell output power is the product of electrical current and voltage, which can be optimised only by a compromise between generating maximum current and maximum voltage. The current depends on the particular semiconductor chosen from a diverse family of elements and compounds but it is also directly dependent on the illuminated area – the reason for most solar panels being as large as possible. The voltage is dependent on the p-n junction structure, and its magnitude is the same for all cell areas, but also ultimately depends on the particular semiconductor. Without introducing too many concepts, we should appreciate that the solar spectrum encompasses ultraviolet through to infrared wavelengths, and that a semiconductor has a threshold wavelength for optical absorption, above which it will be transparent: to absorb most of the solar spectrum would require a material with an infrared threshold wavelength.

Unfortunately this means that its p-n junction field is weak, giving an unavoidably low output voltage. Semiconductors that give the best combination of voltage and current have a threshold wavelength just into the infrared end of the visible spectrum, which means that they are opaque to visible light. The remainder of the absorbed energy merely heats up the cells.

How we select a suitable semiconductor for solar cells requires scientific consideration, of course, but must also factor in such economic issues as the processing of the basic material into p-n junctions and the abundance or scarcity of the materials required.
In contrast, thin-film cells are generally more sparing in their use of semiconductor material but may be less perfect in structure than the traditional bulk crystalline materials, hence giving a lower performance. The first of this type to gain a significant market share used amorphous silicon films, currently having efficiencies of ~10% from a thickness only one 200th of a standard silicon cell. More efficient thin-film solar converters use compound semiconductors such as those based on combinations of copper, indium, gallium, and selenium (“CIGS” cells), attaining almost 20% efficiency whilst still saving on the use of material. Currently the lowest thin film module price is around 62 euro cents per watt.

3. Solar cell operational considerations

Regardless of the type of solar cell, it is necessary to connect them in series and parallel arrangements, much as is done for conventional batteries. Each cell typically generates only half a volt, thus it is essential to connect several in series to produce a useful voltage, and this is true for modules which themselves may produce only low voltage outputs. Whereas the voltage increases only slowly with intensity, the output current is directly dependent on the illumination intensity (and as noted above depends on the collection area). This has an immediate consequence for real installations, as the solar input will change according to the time of day, the season, and the weather. Temperature changes also impact on solar cell performance, with current increasing somewhat with temperature, and voltage decreasing at a rate of ~0.4% per °C rise. If the generated power is to be fed into the electrical grid, then an inverter (to be added to the installation cost) will convert the generated DC power into 50Hz AC and will take care of synchronisation and timing issues required by supply network regulations, as well as ensuring that the electrical load is matched to the generated current and voltage to the greatest effect.

This matter of variation in illumination becomes a planning consideration when the question of the orientation and inclination of an array of modules is to be decided. For the highest output, the solar cells should be normal to the rays of the Sun, but to avoid frequent adjustments (solar tracking is essential for optical concentrators) it is usual to select an orientation close to south-facing in the northern hemisphere, and compromise with a fixed inclination several degrees less than the angle of latitude (around 36° in the UK). However, building regulations may override this, by requiring that modules are within a few degrees of the roof angle.
Shadowing of all or part of a solar cell array will also have considerable effects on the output power. If local topography or adjacent structures will cause shadowing of part of an array at any time, it may be effective to divide the array into separate sectors, each having its own inverter, to prevent the shadowed components from reducing the generated current: whilst this increases capital costs, new developments in micro-inverters afford a solution for each module to have its own inverter.

Valuable guidance on designing and installing solar modules (including safety, testing and commissioning) is provided by the DTI Guide to the Installation of PV Systems ("Photovoltaics in Buildings"). This is required guidance for installers to gain certification for the Microgeneration Installation Standard (MIS 3002 for PV), which is essential for any householder to apply for the UK Feed in Tariff. The second edition of 2006 requires installers to supply an estimate of performance based on the Standard Assessment Procedure for Energy Rating of Dwellings (SAP 2005), which provides a simple formula for the energy produced per year according to the installed peak power rating, orientation, tilt and shadowing. The new third edition will provide a more accurate and detailed model, which is closer to the models employed by many installers today. This estimate will be of interest to anyone wishing to know the financial payback period.

Another payback period should be considered by those concerned with energy accounting, namely the pay-back period for solar cells to deliver the energy embedded in them during their manufacture and installation. Cells based on single-crystalline materials such as conventional silicon cells have the longest pay-back time, of several years, depending on the actual location. Thin-film cells repay their lower energy consumption in less than a year, again depending on location, and also have around half the lifecycle CO₂ emissions of crystalline cells.

4. Novel developments

Given these restrictions on economically improving the performance of existing photovoltaic module types, are there any new concepts to be investigated?

Whilst the fundamental rules of physics cannot be broken, new materials and technologies may offer some hope. The arrival of nanotechnology has offered new structures for better transparent conducting contacts (e.g. silver nanowires and graphene layers) and for enhanced optical absorption of thin-film cells (e.g. by plasmonic light-trapping).

The sunlight spectrum may be converted to a wavelength range that is more strongly absorbed by the cell’s semiconducting material, by using luminescent materials: for instance, these may collect UV and blue light, and emit orange light (Fig. 5). These colourful components may be incorporated into a plastic covering sheet for solar cells or else the solar cells may be attached around the edge of a thick plastic sheet which captures the incoming light, changes its colour, and guides it to the cells. This would present the user with a different coloured solar array than the ubiquitous blue or black, albeit with lower power conversion efficiency, and the option of collecting PV electricity from a window rather than a wall or opaque roof.
Multiple quantum wells, extremely thin layers, of different semiconductors are another nanotechnology option for increasing the utilisation of the solar spectrum but the fabrication method is expensive and so these cells are more suitable for optical concentration, with which they have achieved 27% efficiency.

In contrast to these largely inorganic materials, solar cells are being developed with organic molecules and polymers. The oldest type is the dye-sensitized cell (or Graetzel cell) which combines elements of nanotechnology, organic chemistry and luminescent materials in a liquid-based photochemical device having an efficiency of ~11% at present. The dye that absorbs the sunlight is coated on nanoparticles of transparent titanium dioxide (the anode) immersed in a liquid electrolyte along with a second electrode of platinum. Electrons are freed from the dye, flow into the TiO$_2$ and pass into the external load; the circuit is completed by electrons flowing through the load and back via the platinum cathode into the electrolyte and thence into the dye. The key feature is the photo-active dye, which must be protected from UV which tends to degrade it.

Polymer-based solar cells are true photovoltaic devices that use solid state materials only. They are potentially capable of large scale production using a liquid process to coat a suitable substrate. Polymer synthesis is rather a specialised science and the combinations that have been studied are not readily available. Best efficiencies to date are ~8% but their stability is still an issue, as the materials are sensitive to air and moisture.

5. Flexible solar cells

Aside from increasing the performance of photovoltaic modules there is a market interest in foldable, rollable and otherwise flexible arrays. A typical thin-film amorphous silicon product is the series of low power rollable arrays on polyester made by Iowa Thin Film Technologies, which are suitable for leisure and marine activities.

Similar technology is used by the equally established Uni-Solar modules, but with triple-junction amorphous silicon solar cells. Each of these products costs several euros per watt. Global Solar and others produce thin-film CIGS arrays for building integrated installation. Another compound semiconductor that is capable of making thin-film solar cells is cadmium telluride, CdTe. This uses high temperature synthesis and so can only be put on to metal foils or polymers such as polyimide (e.g. Kapton).

It would be appropriate for building integrated PV on flat roofs or facades because its performance does not drop off as much as silicon when heated. Although there were health worries about CdTe, fire and leaching tests have shown that these were needless. EMPA in Switzerland has produced 13.5% efficient CdTe cells on polyimide but one of the biggest manufacturers of CdTe modules on glass, First Solar, has recently scaled back production as its market share has fallen. At an earlier stage of development are the organic-based tandem cells produced by Heliatek in Germany on a polyester sheet, but with the intention of producing building-integrated arrays.

Our own research is into flexible solar cells that are added directly on to polymer textiles. Without going into technological details, the fabrication uses low temperature vacuum-based synthesis of thin-film silicon from gases, in a similar manner to that used for amorphous silicon (which is actually an alloy of hydrogen and silicon). Most compound semiconductors must use high temperature vacuum processes, which prohibits any common polymer substrate. We are able to use polyester, a polymer that is widely available in continuous sheet or woven forms but any substrate that can withstand a temperature of ~200°C would be possible. Although these cells will not have the performance of equivalent cells on glass or metal sheet, they target different applications, such as awnings and tensile architecture fabrics.
In order to demonstrate this use, we must move from a small area batch coating process to a continuous roll-to-roll process, still some way off, but much of that technology already exists in other industries.

6. Concluding remarks
I have given a brief guide to how solar cells work and what cell types are currently available, as well as a flavour of newer developments. Any PV array will require consideration of site-specific factors and I have indicated how the output energy is determined which is a necessary part of estimating financial and energy payback times. Each of these outlines is overly brief and so a few references for further reading are added below. Finally I have tried to show that developments in materials offer a solution to the somewhat stark appearance of conventional PV modules, with the prospect that architects may have greater flexibility in designing PV into their new buildings.

Bibliography


Solar market research and analysis: http://www.solarbuzz.com/