Much of the early work on photoactive materials for photovoltaics focused on crystalline silicon, which dominates the commercial solar-energy field today. Several other materials, such as amorphous silicon (a-Si), cadmium telluride (CdTe) and copper indium gallium selenide (CIGS), are also now in various stages of commercialization, and are known as thin-film technologies. The lower manufacturing costs and higher production throughput of these materials potentially translate into lower electricity costs. Current thin-film technologies are expected to bring costs reasonably close to $1 per watt of electricity produced at peak solar power.

There is, however, another technology that has the potential to bring this cost down even further. Bulk heterojunction technology, using organic semiconductors and roll-to-roll coating and printing techniques, could become the technology that makes solar energy affordable to the general public. The technology uses abundantly available non-toxic materials, is based on a scalable production process with high productivity, and requires low investment from the manufacturer.

A bulk heterojunction is a blend of p- and n-type semiconductors, which forms molecular p–n diodes all over the bulk layer. On light absorption, photo-induced charges are produced by ultrafast charge transfer (within a few femtoseconds) between the two semiconductor types. Various material systems have been suggested for bulk heterojunction solar cells, including: organic semiconductors, inorganic and organic semiconductor nanoparticles and nanorods, metal oxides stained with dye molecules, as well as combinations of these.

Of all these technology platforms, organic photovoltaics is generating considerable interest (Box 1). As the name implies, this technology comprises carbon-based materials as donor and acceptor molecules. The most popular class of organic donor molecules are conjugated polymers, such as polythiophenes, polyfluorenes or polycarbazoles. The material choice for acceptors is much narrower — for more than ten years substituted fullerenes have given by far the best photovoltaic performance.

The feature that differentiates this technology from all of the others is its compatibility with high-speed and low-temperature roll-to-roll processing. The processes are typical of those used in the printing and coating industry in that solutions of the active materials, dissolved in organic solvents or water, are applied to a plastic sheet by means of a coating applicator.

Various printing and coating technologies have proven their compatibility with organic semiconductor processing, among them gravure printing, flexo printing, screen printing, slot die coating and, most recently, ink-jet printing. The printing solvent is evaporated when heated to moderate temperatures, producing a dried layer of the photoactive polymer. The modules are encapsulated between thin, flexible over-laminates, which protect the active layers from mechanical abrasion and the environment. Capital costs are very low, and the printing and coating processes can be done at high speed with no obvious limitation in the substrate width. The processing steps are summarized in Fig. 1.

The combination of low-temperature processing paired with high production
throughput suggests that attractive energy payback times — the time it takes to generate energy equivalent to that outlaid during fabrication — should be possible. With large-volume manufacture and reasonable efficiencies of 5% to 10%, these printed solar cells should have the potential to go significantly below $1 per watt of electricity. So far, no complete life-cycle analysis has been completed, but expectations are that the energy payback time can be as low as a few weeks.

The efficiency of organic photovoltaic technology is low when compared with silicon or compound semiconductor technologies. However, many significant modifications and improvements have been made to the polymer structures over the past few years (Fig. 2). These modifications include the incorporation of comonomers that withdraw electrons from the sea of electrons on the polymer backbone, causing a large shift in the absorption band towards the infrared. Some of these modifications result in absorption at wavelengths as long as 1,000 nm and more, enabling the cell to absorb more than 50% of the total radiation from the Sun. In addition, the structures are versatile enough, from a molecular architecture standpoint, that the entire visible spectrum can be covered as well. Modelling indicates that some of these polymers, when combined with fullerene, will exhibit cell efficiencies between 7% and 10%.

Even higher efficiency values are expected for tandem or multiple junction geometries, where solar cells of different bandgaps are stacked on top of each other and interconnected in series. Each cell absorbs at a different wavelength, reducing the amount of uncaptured radiation that is lost as heat and enabling higher efficiencies. The materials for tandem cells can come from a variety of

**Figure 2** These plots show record efficiencies achieved with organic photovoltaic technology as certified by the National Renewable Energy Lab (NREL). a, Results for a device with an active area of 1.024 cm² and an efficiency of 5.21%. b, Results for a device with an active area of 0.685 cm² and an efficiency of 5.24%.

**Box 1 The structure of an organic photovoltaic cell**

All photovoltaic cells have several common features: they must have two electrodes and a layer of photoactive material that absorbs light (a photon) and generates current (an electron). The key to the success of organic photovoltaics is its two-component active layer, which on coating and drying forms a very unique morphology (shown schematically in Fig. B1) referred to as a bulk heterojunction. The main feature of this heterojunction morphology is the intertwining of phases of each of the components, which spontaneously occurs when the solvent is evaporated. In current designs of polymer photovoltaic cells, one of the components is a polymer that has three functions: to absorb light; to inject an electron into the second component; and to carry the resultant hole to one of the electrodes. The other component is a fullerene derivative. Its function is to accept an electron and carry it to the other electrode. The primary advantage of the bulk heterojunction is the very high surface area that is formed between the two phases, which directly affects the efficiency of charge transfer between the polymer and the fullerene phases.

External quantum efficiencies of up to 80% have already been demonstrated, though today’s power-conversion efficiency is only in the regime of 5–6%.

The current generated by the cell is related to the absorption spectrum of the polymer, which is determined by its molecular structure. The structural design of these molecules is adjusted to absorb broadly across the solar spectrum from the blue to the near infrared. As the active-layer coating is a fraction of a micrometre thick (100–200 nm), the polymers must have a very high absorptivity as well. When choosing which polymers to use as the donor and acceptor molecules, material scientists must look at the different energy states of the molecular electrons in the donor and the acceptor molecule. All charge carriers need to be transported across the bulk to the electrodes before recombination takes place. At typical carrier lifetimes of a few microseconds, charge-carrier mobilities of $10^{-3} \text{ cm}^2 \text{ V}^{-1} \text{ s}^{-1}$ or higher are required for loss-free carrier collection.

These selection criteria significantly narrow down the polymeric structures that have potential for efficient photovoltaic energy conversion. Finding suitable polymers for this application is challenging because a compromise must always be reached between the choice of bandgap (which dominates the short-circuit current) and the position of the electronic levels (which dominates the open-circuit voltage). The product of the short-circuit current and the open-circuit voltage dominates the efficiency.
Conjugated polymers, always combining a narrow-bandgap semiconductor with a wide-bandgap one. Efficiencies over 6% have already been reported for a tandem architecture based on polymer and fullerene composites (Kim, J. Y. et al. Science 317, 222–225; 2007).

Although still low compared with silicon and compound semiconductor technologies, these efficiencies represent a big step forward in polymer photovoltaic technology. Polymer systems also have many advantages over conventional photovoltaic technology. For example, organic photovoltaic modules are lightweight, have a high power-to-weight ratio (more than 100 mW g⁻¹ at 5% efficiency) and they are mechanically flexible (Fig. 3). This makes them particularly useful for portable applications, which represent the first target markets for the technology. Potential uses include battery chargers for mobile phones, laptops, radios, flashlights, toys, and almost any handheld device that uses a battery. The modules can be adhered to the outside face of a briefcase or a piece of clothing, or they can be incorporated into the housing of a device. They can also be rolled up or folded for storage in a pocket when not in use. The first products serving this market should be available later in 2008.

Potential applications are in electricity-generating awnings that can be rolled up for storage or windows in office buildings and greenhouses, where two transparent electrodes are used so that the module is semitransparent.

The biggest market for organic solar panels is large-area rooftop applications in residential and commercial buildings. This will require efficiencies between 7% and 10% and lifetimes of 7–10 years. Konarka is now running extensive lifetime investigations, and the company's cells regularly pass more than 1,000 hours under accelerated degradation. To verify the lifetime of 7–10 years, the degradation over around 3–5 years must be measured and then extrapolated. So far, Konarka has been measuring the lifetime of its cells for more than one year (extrapolated out to three years) with no degradation observed.

This shows the enormous progress that has been made over the past few years in designing environmentally stable organic materials and interfaces. Until recently it was thought that organic solar-cell lifetimes were restricted to 1–2 years, but today it is clear that the technology could reach lifetimes of 5–10 years, making it a strong contender for consumer solar-cell applications.