

Photovoltaic energy harvesting for intelligent textiles

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8.1 Introduction

A combination of large-scale textile manufacturing with semiconductor technology could transform the market for photovoltaic (PV) solar energy, by lightening the construction of conventional solar panels. New flexible solar cells would not necessarily challenge existing applications but would extend the collection of solar energy to situations where it is presently impractical. Indeed, e-textiles, or smart textiles, that incorporate electronic functionality into a fabric, do require a power source, and whilst it is likely to be supplemented by a storage battery, this is one demand for some form of energy harvesting from the surrounding environment. Potential energy sources include motion (e.g., piezoelectric converters) and heat (e.g., thermoelectric converters), but solar energy is the most concentrated and abundant. Before discussing these new opportunities for solar electricity, we will explain how PV cells convert light into electrical energy. The challenge of using textiles as a base for solar cells is considerable, but technical barriers are being removed, and indeed a fabric base does offer some advantages. Both the specifications for a 'solar fabric' and alternative manufacturing strategies will be described.

8.2 Background

When we wrote a previous study (Mather and Wilson, 2006) on the use of textiles in solar electricity conversion, there was a continuing concern about the worldwide dependence on oil as our prime energy source. Alternative fuels each had their promoters and detractors, from both environmental and economic considerations. This outlook has not changed, and the situation may have deteriorated further with political challenges to the assured supply of gas and oil. Therefore, some countries have revisited their shale-based reserves, which are certainly immense but raise issues about environmentally safe extraction. In addition, this fuel would add to atmospheric carbon emissions, which show little sign of being reduced in the near future.

In the absence of a proven Earth-based fusion reactor technology for electrical energy supply, we should place more emphasis on using our fusion reactor in space, which provides solar radiation in sufficient abundance to meet all our energy needs. Of course, the intermittency and variability in irradiance demand a highly technical

approach to collecting and converting it for our indirect use, with many national programs of wave, wind and solar power research. The most efficient conversion of solar radiation is delivered by PV cells, with virtually no maintenance required.

Installed PV capacity has greatly expanded since 2006, when it was 3.281 GW within the EU and 6.946 GW globally. In 2012, global capacity passed 100 GW, with over 70 GW in the EU. Germany and Italy had 31% and 16%, respectively, of global capacity in 2012, with the USA and the UK only having 7% and 2%, respectively. In 2013, the cost of PV electricity reached parity with grid electricity in Germany, Italy and Spain (European PV Industry Association, www.epia.org).

It is sometimes questioned whether renewable energy converters are indeed sustainable, or whether they just consume energy resources in their manufacture that cannot be repaid during their operational lifetime. Analyses of solar PV cells confirm that they can generate as much electrical energy as they consume in their manufacture. The payback period depends on the site and on the type of cell, but even the most energy-demanding type of cell will easily return the energy embodied in its construction within its 20-plus-year lifetime (Alsema et al., 2009; Lind et al., 2015).

8.3 PV materials and energy harvesting

8.3.1 PV cells: how they operate

The key feature in the PV effect is that light is converted directly to electricity, without an intermediate step that requires motion, heat or chemical reactions. Although exploration of light-induced changes to the electrical conductance of materials extends back into the mid-nineteenth century, conventional solar cells were not fabricated until the mid-1950s. In 1954, researchers at Bell Laboratories in the USA reported solar cells made from silicon that quite soon reached power conversion efficiencies of several percent. Over the past 60 years, the range of PV materials has extended from inorganic semiconductors to organics, and from almost flawless crystalline wafers to amorphous and nanocrystalline structures. Liquid-based cells have also been demonstrated, but their operation is sometimes accompanied by electrochemical reactions.

All these diverse PV cells absorb photons of light to generate pairs of positive and negative charges in the active medium. An electrical field is incorporated into the cell to separate these charges before they merely recombine, wastefully releasing thermal energy. Electrical contacts on the cell surface extract the electrical charges and pass them to the external load, where they may do useful work.

One of the drivers producing such a variety of cell types is the desire for greater power conversion efficiency, which has now reached 25% for the silicon cell that started today's technology, and more than 44% for a multilayer compound cell operating under concentrated sunlight. Achieving these levels of performance has necessitated the introduction of a more complicated set of features than the simple steps outlined above. These come at increased cost, thus an alternative driver is reduced cell cost, albeit with some reduction in performance. Typically, these cheaper cells use thin-film materials in place of the single-crystal wafers used for high-efficiency cells.

Unavoidable losses will always occur when energy is converted from one form to another, as shown by thermodynamic principles. In fact, the simple silicon PV cell has an upper limit of around 30% according to thermodynamics, which is not much higher than the present best value quoted above.

In reality, losses arise from incomplete absorption of light as well as from incomplete collection of charges. PV cells have a threshold energy below which light cannot free charges from the material, which for silicon lies in the near infrared region. Fortunately, this is quite close to the optimum wavelength for collecting solar radiation. Much of the sun's radiation lies in the ultraviolet (UV) to visible part of the spectrum. In addition, each photon that is absorbed can only produce one pair of electrical charges, even if it actually is equivalent to twice the threshold energy. This leads to unavoidable losses from the short wavelength part of the spectrum.

If the material has a higher absorption threshold, further towards the visible region, then it will have lower maximum conversion efficiency. However, such a value does enable a higher voltage to be generated per cell. This voltage is related to the electrical field that is built into a PV cell by its construction, being established between two parts of the cell that have slightly different compositions. Without going into detail, we note that the maximum voltage generated by a PV cell is numerically around half the value of the threshold energy for generating charges (known as the *bandgap energy* and equivalent to the chemical binding energy of the constituent atoms), if this is given in units of electron volts. (Silicon's bandgap at ~ 1.2 eV equates to a threshold of 1033 nm in wavelength, and the maximum voltage from a silicon PV cell is ~ 0.6 V, depending on detailed construction.)

Some losses may be ameliorated by good technological design, which usually comes at a price. The surface through which the cell is illuminated may be roughened to reduce reflection loss, and the rear surface of thin-film cells may also be roughened to scatter unabsorbed light back through the cell for a second chance. This surface may also have an additional electric field to repel charges moving in the wrong direction, an actual enhancement in modern-day silicon cells. The electrical contacts are designed to block as little of the illumination as possible, without increasing electrical resistance by being too thin. This is achieved by placing the top gridded contact in narrow, but relatively deep, slots that are laser-cut into the surface.

Although the voltage from any type of PV cell is restricted and quite low, it may be increased by connecting cells in series, much as is done for electrochemical battery cells. The current is relatively high from most types of cells, depending on both illumination and cell area, with further increases by connecting many cells in parallel. Finally, it should be noted that most cells have a slightly derated performance when they are heated, as an otherwise small leakage current that can flow back through the cells will increase as the temperature rises.

8.3.2 Types of PV cells

Reference has been made above to the best established type of PV cell, namely that using crystalline silicon, and it was noted that the current best efficiency for this cell type uses several enhancements to the basic device. The most obvious restriction with

crystalline silicon, or indeed most other crystalline inorganic PV absorbing materials, is the processing temperature. They are high melting-point materials and are not readily deposited by a solution-based process, although electrochemical plating has been used with limited success for some semiconductors. Thin-film materials utilize less of the expensive semiconductor but generally have a poorer defined structure. Silicon is available in thin-film form, having been synthesized on a heated substrate from an electrical discharge in a gaseous precursor (usually silane, SiH_4), but it is actually a compound of silicon and hydrogen, known as amorphous silicon, a-Si:H. PV cells are readily available using this material and have a solar energy conversion efficiency of around 10%. By adding more hydrogen to the gas mixture and increasing the electrical discharge power, a micro- or nanocrystalline form is produced, which has better electrical performance and similar optical absorption to a-Si:H. By using very high frequency-driven discharges instead of the usual radio frequency, the deposition temperature may be reduced towards 100 °C (Rath et al., 2010). However, it is only by increasing the synthesis temperature that true polycrystalline silicon can be synthesized; otherwise, this large-grained form of crystalline silicon has a similar high-energy requirement to single-crystal silicon for its synthesis. Neither of these forms are amenable to deposition on textiles.

Compound semiconductors using III–V or II–VI elements offer a range of materials that will absorb different parts of the solar spectrum. Only CdTe, and the chalcopyrite compounds, CuInSe (CIS) and $\text{CuIn}_x\text{Ga}_{1-x}\text{Se}_2$ (CIGS), have reached commercial availability in thin-film PV modules. There has been some concern about the environmental issues of Cd, Te and some other constituent elements when modules reach their end of life and should be recycled, or if severe damage should occur that risks material entering susceptible locations, but there is no health risk during normal operation. Nonetheless, thin-film CIGS and CdTe cells have both shown efficiencies around 20%, albeit for small areas at this time. Their main drawback with regard to using a textile substrate is that a high-temperature anneal is required to form an essential interlayer within the semiconductor absorber, although the deposition of the semiconductor material itself may use low temperature routes such as sputtering or electro-deposition.

Organic semiconductors present a similarly complicated set of materials, with the additional problem that many are unstable in the presence of oxygen or water vapour, thus requiring extremely effective hermetic sealing. The best efficiency to date with ‘plastic solar cells’ is close to 10%. To encourage high optical absorption without the need for a thick cell (in which electrical charges will be only poorly transported to the contacts), a blend of two polymers is often used. For instance, poly-3-hexyl thiophene (P3HT) and phenyl- C_{61} -butyric acid methyl ester (PCBM) may be deposited onto a substrate by spin coating from a solution or by another liquid-based technique. The chemical structures of P3HT and PCBM are shown in Figure 8.1. Structuring the polymer pair into ordered shapes should enhance electrical charge collection and so improve energy conversion efficiency. This is being tackled by using a template of material, such as nanostructured TiO_2 , with an ordered structure that can be infiltrated by the polymer melt or solution. Regular pore shapes support well-defined paths through the completed cell, which will then have the desired effective electrical

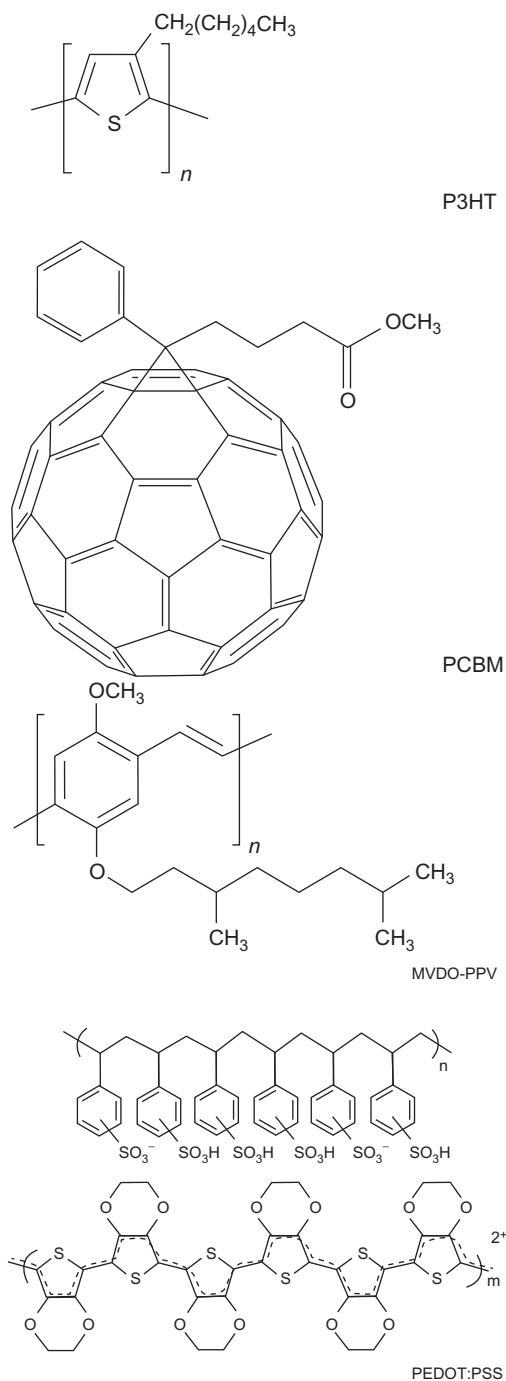


Figure 8.1 The structures of P3HT, PCBM, MVDO-PPV and PEDOT:PSS.

charge collection. This small-scale engineering may deliver the highest performance from polymer PV cells but may also require high temperatures to produce the template itself. Meanwhile, a polymer solar cell has been produced on a paper substrate below 100 °C using liquid processes, with a solar energy efficiency of 0.40% (Kim et al., 2012), demonstrating that a base of non-electronic grade material may be used, provided that a low-power output is acceptable.

Other PV cells use liquid-based processing, namely dye-sensitized solar cells (DSSCs) that are based on TiO_2 . These devices have only modest efficiencies (around 10%) but operate well in diffuse sunlight compared with most crystalline cells. They typically comprise a transparent positive electrode that is coated with a layer of porous TiO_2 , having a light-absorbing dye on its other surface. Sunlight frees electrons from the dye to pass into the underlying electrode. Electrons are replaced by an electrolyte, thus reactivating the dye, leaving a positive charge that is neutralized by another electron at the second electrode. These are therefore sandwich-structure devices, like other PV cells, but usually with a liquid or gel electrolyte inside. The earliest used dyes were prone to degrading in strong sunlight, and now better organic dyes are being tested. DSSCs are made by processes that are closer to those used in the textile industry than are required by conventional solar cells, encouraging equipment development by coating and printing companies with web and sheet experience. However, DSSCs have still required a high temperature sintering for the most effective TiO_2 structure. More recently, it has been reported by Oxford University that the dye may be replaced by an organometallic halide absorber with a perovskite structure (e.g., $\text{CH}_3\text{NH}_3\text{PbI}_3$), to give DSSCs with efficiencies of $\sim 15\%$. Further fine-tuning of the perovskite composition has yielded even higher efficiency, and both vapour- and solution-based processing are possible. Indeed, using porous Al_2O_3 deposited by spin coating from a nanoparticle colloid offers a much lower temperature process with similar cell performance to those using TiO_2 . By also replacing the liquid electrolyte with a spin-coated polymer film, efficiencies of over 12% have been achieved. Solid-state DSSCs are now contenders for flexible solar cells, provided they suffer no degradation in operation (e.g., Liu et al., 2013).

8.3.3 Advantages and requirements of flexible substrates

Despite the many attractions of conventional solar cells as vehicles for providing energy, the way in which they are constructed gives rise to a number of problems in their application. Typically, solar cells are either sandwiched between rigid glass or polycarbonate plates, or the cells are covered by sheets of glass or polycarbonate. The cells can, therefore, only be attached to flat surfaces. Glass and polycarbonate plates are also quite heavy, and glass is fragile. The structures to which the cells are attached must be robust enough to withstand their weight, and care has to be taken with their storage and transport. In addition, the cells have to be protected from atmospheric pollution and adverse weather.

Increasing attention has consequently been turned to the construction of lighter, flexible cells that can withstand unfavourable environments, whilst still maintaining the durability required. There are now extensive examples of solar cells applied to thin

flexible plastic or metal films. These films are much lighter than the glass or polycarbonate plates used in conventional solar cells. Nevertheless, their thin nature can render them liable to fracture, so considerable care still must be taken when they are attached to underlying structures.

The most widespread flexible materials in everyday use, however, are textile fabrics. Therefore, whilst the successful incorporation of solar cells onto plastic and metal films clearly signifies an important step in the expansion of solar cell technology, much greater expansion of the technology would be achieved through their incorporation into textile fabrics, especially if the cells are fully integrated into the fabrics. Textiles are materials with a very broad range of applications and markets, and they can be produced by a wide variety of fabrication processes, all of which offer enormous versatility for tailoring fabric shape and properties. The different types of woven, knitted and non-woven constructions that can nowadays be achieved seem almost infinite, and indeed there are even medical and technical uses for embroidered constructions (Ellis, 2000; Karamuk et al., 2001).

8.3.4 Strategies for constructing solar textile fabrics

Several approaches are being developed for the construction of solar textile fabrics. One of these is merely to attach to a textile product a conventional solar panel, though one that is not fragile. Such arrangements exist, for example, in some solar-powered bags and backpacks. However, it is arguable that such products do not really comprise solar textiles—they are just a combination of a textile fabric and solar panels. A similar approach is to attach an array of small individual cells, like sequins, onto a fabric. This approach has the advantage that it still involves the combination of known technologies, yet is more intimately a single-product unit. Because no special adaptation of fabric or cells is required, there is a wide range of both that can be selected. The approach suffers from the drawback that the attachment, and subsequent continued adhesion, of the cells to the fabric, as well as electrical connection between the cells, would be difficult to achieve viably on a commercial scale. The physical, mechanical and even aesthetic properties of the fabric are also likely to be compromised.

Several reports and patents have appeared on the production of PV fibres. These fibres are themselves constructed into fabrics or are incorporated as a part of a conventional fabric construction process. Much research has been conducted on organic PV fibres, and one example of the structure of these fibres is given in Figure 8.2 (Bedeloglu et al., 2010). Here, polypropylene monofilament is coated by successive thin layers of the conductive polymer, PEDOT:PSS, and of a photoactive material that is a mixture of either P3HT and PCBM or of MDMO-PPV and PCBM. The structures of PEDOT:PSS and of MDMO-PPV are also shown in Figure 8.1. The outer conductive coating consists of lithium fluoride and aluminium. A similar example is reported by Liu et al. (2007) for other types of fibres.

O'Connor et al. (2008) have constructed a PV fibre through the vacuum thermal evaporation of thin concentric organic PV films onto polyimide-coated silica fibres. Whilst the use of such fibres may seem to have little relevance to everyday textile

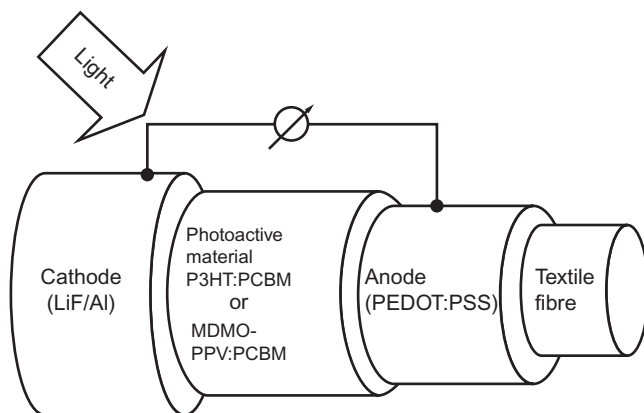


Figure 8.2 Diagrammatic representation of the structure of a PV fibre. [Bedeloglu et al. \(2010\)](#).

fabric structures, the approach may well be capable of being adapted to a variety of textile fibres.

Examples of optical fibres based on the DSSCs have also been reported ([Toivola et al., 2009](#); [Ramier et al., 2008](#)). Recently, a fibre based on a piezoelectric material such as polyvinylidene fluoride has been developed, which can convert both mechanical and light energies ([Siores et al., 2010](#)). The authors of the patent claim that the fibre is flexible and can be incorporated into textiles. The commercialisation of these PV fibres is, however, likely to be some time away.

An advantage of rendering fibres PV is that fabric made from them is inherently PV. However, the production of fibre or yarn is early in the manufacturing chain for textile fabric items, and each fabric is consequently specially constructed, rather than being ‘off the shelf.’ There is a risk of wear and tear to the PV layers on the fibres during construction of the fabric, and electrical conductivity at yarn crossovers may also be difficult to achieve, where it is required.

A widely used method of making solar textile fabric is to attach a thin film of solar plastic to the fabric. In this way, the technologies already developed for producing thin PV films can be readily utilized. Many current solar textile products use this approach. This method possesses the clear advantage that technologies already developed on a commercial scale for producing thin PV films can be exploited for producing solar textiles. Moreover, the methods of attachment of a thin film to a fabric, such as sewing, welding or laminating, are all well established commercially. However, it is critical that the film is not ruptured or otherwise damaged during the attachment process. In addition, the mechanical properties of the fabric are in danger of being compromised, through such aspects as uneven stretching and compression, as the solar fabric is flexed.

It is evident that, if it can be achieved, a method for the direct deposition of solar cells onto textile fabrics, analogous to the methods used to activate glass and thin films, would be highly desirable. This approach would be particularly attractive if

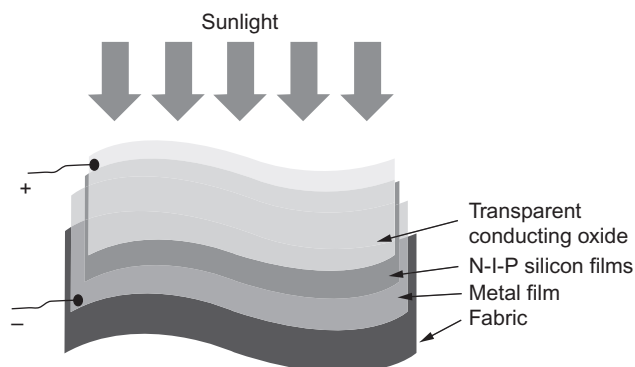


Figure 8.3 A solar textile fabric constructed by the direct deposition of silicon layers.

it could be applied to commodity fabrics. The possibilities for this approach are discussed in detail in [Section 8.4](#). A direct integration process would be more straightforward and would use a similar number of processing steps as are used for adding cells to glass or thin films. An example of a solar fabric resulting from a direct integration process using the deposition of silicon layers is shown diagrammatically in [Figure 8.3](#). However, for deposition of inorganic solar cells, a distinct challenge arises from the thermal properties of the fabric, in being able to withstand the temperatures required. The addition of organic PV compounds may offer an alternative solution (e.g., by printing), but as highlighted in [Section 8.3.2](#), many are unstable in the presence of oxygen or water vapour. If these objections are met, direct deposition of organic PV compounds may become a commercially attractive option. The direct application of DSSCs onto textile fabrics may too become a reality in the future.

Continuous production in a roll-to-roll coating machine can enable a mixture of coating techniques to be integrated into one successive process, despite the requirements for different environments for the methods. Even so, this is made more difficult by each technique having a different coating rate, requiring at least one idling chamber or a serpentine roller set, within the sequence. The most common arrangement is for a set of in-line chambers, each dedicated to one coating method and interconnected by slit valves to enable the passage of the substrate web. Nonetheless, there is at present no established production line for coating a roll of textile with the layers required for a PV array.

8.4 Requirements of textiles to be suitable substrates

For a textile to be a suitable substrate, account has to be taken of the chemical nature and physical morphology of the fibres and the method of textile fabrication. The selection of a fibre type is strongly influenced by its ability to withstand prolonged UV radiation. It is also governed by the temperatures required to deposit the thin films

comprising the solar cell and, in some approaches, the ease with which it can be made electrically conducting or PV. For many types of PV cells, such as crystalline silicon, CIGS and CdTe cells, their deposition requires too high a temperature for commodity textiles to withstand. Only fibres with high thermal stabilities, such as glass, polybenzimidazole, polyimide, polyetheretherketone and poly-(*p*-phenylene benzobisoxazole) fibres, are likely to be suitable. However, these fibres are expensive.

Mixtures of nanocrystalline and amorphous silicon cells can usefully be deposited at temperatures as low as 200 °C (Koch et al., 2001; Lind et al., 2011), and under appropriate conditions even crystalline silicon may be grown, albeit epitaxially on silicon wafers (Ji and Shen, 2004). These two factors of UV resistance and temperature of deposition, therefore, restrict the use of some types of commodity fibres for the direct deposition of silicon cells. Commercial polyolefin fibres melt below 200 °C, and cotton, wool, silk and acrylic fibres start to decompose below this temperature. Amongst polyamide fibres, nylon 6:6 fibres, which melt at 255–260 °C, can withstand deposition temperatures of 200 °C, but they need to contain light stabilizers to avoid degradation by UV radiation. *P*-aramid fibres, which are also polyamides, can for practical use withstand temperatures up to ca. 400 °C, but they would probably not be sufficiently stable against UV radiation.

Polyethylene terephthalate (PET) fibres are viable substrates. PET fibres melt at 260–265 °C and exhibit better stability to UV radiation than most other commodity synthetic fibres (Moncrieff, 1975). In addition, they are commercially attractive because of their widespread use. PET fibres possess good mechanical properties, and are resistant to most types of chemical attacks. They are less resistant to strong alkalis, but a solar cell would not normally be used in a strongly alkaline environment.

Glass fibres produced from E-glass formulations (Jones, 2001) are also viable fibres, especially in fabric constructions. One obvious merit is their transparency, as with plate glass in conventional solar cells. Moreover, the price of E-glass is competitive with that of PET fibres. E-glass fibres are, however, prone to flexural rupture, and have poor resistance to environments of extreme pH. Some other types of glass, such as R-glass and S-glass, which are more stable to extreme pH, are also considerably more expensive (Jones, 2001).

The type of fabric construction is also important, in that it affects the physical and mechanical properties of the constituent fibres and its effectiveness as an electrical conductor. Whatever type of construction is used, it is important that the yarns constituting the fabric are close enough together. If the fabric is too porous, the thin layers comprising the solar cells cannot be successfully deposited onto it.

Electrical conduction is generally best achieved in woven fabrics (Abdelfattah, 2003; Bonderover et al., 2003), because they possess good dimensional stability and can be constructed to give desired flexibilities and conformations. In addition, the yarn paths are well ordered, a feature that allows the design of complex fabric-based electrical circuits (Bonderover et al., 2003). On the other hand, knitted structures are readily distorted, and the rupture of a yarn may cause laddering. These problems are exacerbated if the shape of the fabric is continually changing, as in apparel usage. Non-woven fabrics do not, as yet, generally possess the strength and dimensional stability of woven fabrics, and the construction of electrical circuits in

them is limited, because their yarn paths are highly unoriented. Embroidered structures, though, could offer opportunities for circuit design.

8.5 Strategies for rendering textiles electrically conducting

It is clear from [Figure 8.3](#) that, as with any type of solar cell, the top and bottom of a textile solar cell must be able to conduct electricity. The top layer will be a thin layer of a transparent conducting oxide, such as indium tin oxide or zinc oxide. However, unless the bottom textile fabric layer is inherently conducting, an additional conducting material is required. This material should affect the fabric's flexibility and conformability as little as possible.

One approach is to incorporate thin metal wires whilst the fabric is being constructed, and indeed, several fabrics of this type have been developed. In order not to increase the stiffness of the fabric significantly, the wires must be thin. However, they are then liable to break under the rigorous conditions of fabric construction. In addition, it is questionable whether metal wires can make good enough contact with the complete area of thin semiconducting film that will then be deposited on the fabric. An alternative approach is to produce fibres from electrically conducting polymers, such as polypyrrole, polythiophene and polyaniline. The mechanical performance of these fibres is, however, often inadequate ([Malinauskas, 2001](#)), and they possess limited flexibility ([Akbarov et al., 2005](#)). In attempts to improve mechanical performance, fibre blends with conventional polymers have been produced, with the aim of exploiting the desirable properties of both polymer components. The conductive polymer must be able to withstand the conditions for processing the conventional polymer fibre. Nevertheless, this approach has met with a degree of success ([Akbarov et al., 2005](#)). An alternative approach has been claimed, in which a solution of the conducting polymer is added to freshly extruded filaments of the conventional polymer, before the filaments have solidified ([Anon., 2001](#)).

The deposition of metals or conductive polymers offers another route, whether onto individual yarns prior to fabric construction or onto the constructed fabric. Metal coatings can be achieved, for example by vacuum deposition or sputter coating ([Sen, 2008](#)). Conductive polymer may be deposited from a suspension, or through bulk polymerisation in the presence of the textile ([Malinauskas, 2001](#)). Better control is achieved if polymerisation occurs on the actual textile fibre surfaces. A layer of monomer is first adsorbed. When exposed to a suitable oxidizing agent, the adsorbed monomer is polymerized ([Malinauskas, 2001](#)). The success of this approach is predicated on the extent of adsorption of the monomer and the resistance of the fibres to the oxidizing agent.

Whatever approach is chosen, the metallic or polymeric coating must withstand all the subsequent processes that the fibres have to undergo. Not only do these include the deposition of the solar cell, but also the conversion of fabric into product and, in the case of deposition onto yarns, the construction of the fabric. Clearly, adhesion

between coating and textile must be sufficiently strong, and like the textile, the coating must be stable at the temperatures used for depositing the solar cells.

Synthetic fibres pigmented with carbon black also possess some electrical conductivity, and there is now keen interest in the incorporation of carbon nanotubes into synthetic fibres. Although the main driver is fibre reinforcement, the fibres can also be rendered electrical conducting under the correct processing conditions. No doubt, this approach to electrical conductivity in fibres will be thoroughly pursued in the coming years.

8.6 Technological specifications

The requirements for a PV material to be put on textiles are now evident: the material and processing costs must be effective when considering both economic viability and energy payback time; materials should be sufficiently abundant that they are not in short supply for large-area applications; and low-temperature processing steps are mandatory. In addition, it is obvious that all materials should have similar mechanical and thermal properties to avoid distortions under usual PV operating conditions. The energy conversion efficiency that is required depends on the usage, but values below 3% are unlikely to be economically attractive, as too large an area would be required for generating any significant current. Whatever voltage is required, it may be given by connecting a number of cells in series, preferably as an integral part of the fabrication process.

8.7 Manufacture of PV fabrics

We have referred especially to thin-film silicon cells because these have been the most widely adopted of all thin-film materials, but thin-film compound semiconductors have also been included because they have achieved higher efficiency operation. Each of these is produced by processes that are familiar to the electronics industry, but less so to the textile industry. The preferred synthetic route for thin-film silicon was briefly mentioned in [Section 8.3.2](#) as using gaseous sources for the silicon (and the essential additives needed for P–N junction formation), but dissociating these at low pressure by electrical discharge ('plasma') instead of thermally, and heating the substrate to 200 °C to control the thin-film quality. CIGS and CIS thin films are often produced by heating the solid elemental constituents in a vacuum chamber until they evaporate or sublime, and collecting the mixed vapour on a heated substrate, to control thin-film composition and quality. When semiconductor synthesis is incompatible with the intended final supporting material, the layer is grown on a different substrate, which is then removed by etching or by dissolving a thin interlayer. For thin-film solar cells, this allows a relatively high deposition temperature with a sacrificial metal foil or polyimide sheet, followed by lamination onto a lower melting-point plastic and removal of the temporary substrate by wet etching (the Helianthos method—see [Rath et al., 2010](#)).

Textile manufacturers are probably more accustomed to liquid coating, which is the process used for organic polymer cells, although cells most often use spin coating rather than spray, paint or dip coating to control the film thickness. The other materials used in DSSCs may be printed from specially formulated inks, as may some of the electrically conducting polymers. This is also closer to textile practice than those techniques requiring vacuum chambers. Nonetheless, large-scale production has been used for solar cells on a plastic web or metal strip, usually by roll-to-roll coating in chambers that provide the sources and exacting conditions for the various layers. The problem of handling plastic film in the conditions needed for plasma deposition of thin-film silicon has drawn both commercial and academic attention. A clever way of delineating the respective layers that make up a complete thin-film silicon solar cell array has been proposed by Schubert et al. at Stuttgart University. They used wire masks that were raised and lowered as a plastic substrate web was advanced between deposition process steps in an intermittent process (Schubert and Merz, 2009).

8.8 Applications: present and future

The most frequent suggestions for PV textile applications are for garments. These include clothing and fashion accessories, but it should be understood that the total area that can be illuminated on one of these items is relatively small, and so the generated electricity will be limited, even from PV cells having 20% efficiency: these would produce 200 W from a square metre of cells when exposed to the standard solar irradiance of 1 kW m^{-2} (when the sun is directly overhead). Concept jackets, bags and backpacks have been designed by a number of fashion houses and technology companies (e.g., SunLoad in Germany; Eleksen in the UK; ScotteVest in the USA; Zegna and Solarc in the EU). Most of these have employed either conventional crystalline solar cells or thin-film amorphous silicon on a metal or polymer foil, both then bonded to a fabric base, which is a costly procedure. Fashion designers Elena Scorchner and Sheila Kennedy have considered organic PV cells on textiles. Other fashion ideas have considered LED lit garments and drapes for which a power source is needed—perhaps an integrated thin-film battery with PV charging (e.g., LumeLight, Soft House design, Philips' Lumalive). More novel ideas have come from the health and sports sectors. Sensors embedded in clothing that monitor the condition of the subject, or in soft furnishings to detect intruders or fire, will require power but need only low-current sources.

Larger area PV arrays could also benefit from the textile approach to implementation. Trials have been made with PV awnings and canopies, using both rigid structures and tensile membranes. These have mostly used low efficiency a-Si:H cells ($\sim 5\text{--}7\%$) laminated onto a fabric (e.g., SKYShades, USA; ShadePlex, USA; and The Solar Cloth Company Ltd that has also tried CIGS cells). It is claimed that these amorphous silicon modules perform better over the year than do crystalline cells because they are more effective during the early and late times of the day, when sunlight arrives at a shallow angle to the module surface, which is highly reflective on glass-fronted modules.

Military interest has stimulated solar tent development for charging the batteries used by infantry to power their radios, GPS, laser rangefinders and other portable electronics (e.g., PowerFilm Solar, Inc., USA, also uses a-Si:H cells at present).

Conventional rigid PV arrays are heavy and difficult to fit to non-plane surfaces when integrating them into a building structure. This considerable market has driven the development of flexible cells in several companies, not all of which have managed to keep trading in recent years. Konarka Technologies, Inc. was a recent loss: they had worked with both DSSCs and polymer–fullerene solar cells, with some notable demonstration installations but could not compete on cost. Nanosolar also closed operations after significant effort in a printing technology for CIGS cells. Heliatek in Germany continues to work on a roll-to-roll process for organic PV cells using small molecules, similar to organic LED technology, and has announced 12% efficiency. However, the more conventional approach using a-Si:H cells on a flexible base that is laminated to roofing membrane remains the most widely deployed technology. Uni-Solar, USA, has worked with this type of cell for many years and has a well-developed roll-to-roll process with which it is difficult to compete. There would be cost savings with a process that can coat the cells directly onto roofing membranes without the intermediate material.

8.9 Future trends

The main driver for further development of today's PV cells is reducing the cost per unit of electricity, which may be addressed by improved energy conversion efficiency or by decreased production costs. Both tactics have been attempted for thin film as well as for crystalline wafer devices, but of course only the thin-film approach may be used for cells on textiles. In this regard, organic materials have the most potential for cheaper fabrication, as they may use liquid application without expensive vacuum tools (see [Section 8.3.2](#)). If there is a reliable hermetic sealing method from those being tested now, then the operating lifetime of polymer cells should be acceptable for all but very long-term uses. Trends in fabrication of many types of cells are towards lower processing temperatures, including the most recent dye-sensitized cells using perovskite materials to achieve impressive efficiencies ([Section 8.3.2](#)). These new cells may then be applicable to textiles.

What other novel developments may disrupt the existing types of PV devices? Scientists have suggested improved structures for cells from both chemistry and physics considerations. These may offer improved performance but usually depend on complicated and possibly expensive fabrication methods. Advanced concepts aim to defeat the limitations placed on conversion efficiency without contravening the ultimate performance that is defined by thermodynamics. Using *quantum wells* to confine photo-generated charges of opposite sign in separate regions of the structure would prevent them from wastefully recombining but requires perfect control of thin-layer thicknesses, as is done for laser diodes now. The special technology cannot yet be applied to fabric substrates. Extending the spectral range to longer wavelengths is

possible in theory, by incorporating elements into compound semiconductor materials such that they have a 'divided' bandgap and hence a lower energy absorption threshold. This also requires reduction of photo-generated carrier losses via the same route and presently cannot be done for the lower cost thin-film materials.

It appears that future performance enhancements for flexible cells must rely on adjustments to the function of the substrate itself rather than improved semiconductor material. This means selectively roughening a smooth substrate, or choosing the weave pattern and filaments of a textile substrate, such that it scatters light into the photoactive layer and so enhances optical absorption in the thin semiconductor layer. Such improvements may be done on such a fine scale that quantum effects come into play, as they do for colouration of insects, and are perhaps possible for fabrics as well.

Finally, we should include electrical storage as a desirable addition to solar PV modules, whatever their type. Integrating some form of electrochemical battery into a flexible module should be possible with lithium battery technology, or even with *supercapacitors* that store energy without requiring a chemical change. Electrical storage may be essential for smart clothing, whether applied to medical or sports requirements.

8.10 Sources of further information

For accepted efficiencies of the different types of solar cells, measured according to best practice, see the 6-monthly 'Solar cell efficiency tables': version 43 was published in 2014 (M.A. Green et al., Prog. Photovolt. Res. Appl. 22 (2014) 1–9).

For a discussion of renewable energy technology and practicalities, see the excellent book by D.J.C. MacKay, 'Sustainable Energy—without the hot air' (UIT Cambridge Limited, 2009).

For a detailed explanation of PV science and technology, see 'Handbook of Photovoltaic Science and Engineering', edited by A. Luque and S. Hegedus (2nd edition, Wiley, 2011).

For roll-to-roll vacuum coating onto flexible materials, see 'Vacuum Deposition onto Webs, Films, and Foils (Materials Science and Process Technology)' by C. Bishop (William Andrew, 2006).

The International Solar Energy Society (ISES) is the largest organisation in this field, with members in more than 110 countries and a history dating back to the 1950s. It includes PVs in its interests and organises conferences on a range of solar energy topics. Its website is www.ises-online.de.

Two chapters in the book 'Solar Cells—New Aspects and Solutions', edited by L.A. Kosyachenko (InTech, 2011), are devoted to PV textiles. Chapter 3 by M.K. Singh is on 'Flexible Photovoltaic Textiles for Smart Applications'. Chapter 12 by A. Bedeloglu is on 'Progress in Organic Photovoltaic Fibers Research'.

There are several specialist magazines that inform the trade and investors about developments in PVs, including Solar International and its regional versions, for example, Solar UK (online at <http://www.solar-uk.net> or in print versions).

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