

Organic Photovoltaic Materials Markets: 2009-2016

Chapter One

Chapter One: Introduction

1.1 Background to This Report

Until recently, almost all commercially produced solar cells relied on crystalline silicon (c-Si) technology. This technology has been able to deliver adequate conversion efficiency at acceptable costs, which make them suitable for a wide range of applications, such as providing electricity in remote locations that are not served by the electrical power grid. Crystalline silicon does not produce electricity at costs comparable with other electrical power generation sources, however, so it is not yet a competitive solution.

While the c-Si technology has a long head start over novel approaches, organic photovoltaics (OPV) and dye-sensitized solar cells (DSC) have the potential to overtake the established solar cell solutions. These new technologies hold out the promise of significantly lower material costs due to the thin film structures that can be fabricated on inexpensive substrates, as well as lower manufacturing costs because these designs can be adapted for high-speed roll-to-roll (R2R) production. New materials also open the possibility of new installations for photovoltaic devices. They can be incorporated in building materials ranging from roofing materials to transparent cells for windows that make electricity from infrared radiation.

1.1.1 Efficiency Alone Is Not Enough

In discussing any photovoltaic technology, it is tempting to be distracted by the question of device efficiency. Certainly, millions of dollars are spent each year on trying to improve the efficiency of solar cells, and this clearly is a critical factor. But it's only half the story.

A cell that is ten times as efficient as competing designs is of interest, but if it cost 1,000 times as much to make, it cannot be competitive. On the other hand, if a cell that was only one-tenth as efficient as the average cell cost only one-hundredth as much to produce, it would be an instant winner.

Now, there are certainly limits; at some point, the size of a highly-inefficient solar cell would become so large that it might become impractical for some applications, or its installation costs might increase to the point that its other cost savings are wiped out.

So while it is important to consider solar cell efficiencies in terms of how much sunlight power is converted to electricity, the ultimate question is how much will that electricity cost over the useful life of the solar cell. If the cost is low enough, then the photovoltaics can compete successfully with other forms of electrical generation, including fossil fuel.

Another important consideration about OPV and DSC module efficiencies is that they continue to perform well in low levels of light. Unlike c-Si modules that need direct sunlight to be effective, these other materials can produce significant amounts of electricity from lower level light sources, including from surfaces that do not face the sun directly, or in cloudy conditions.

1.1.2 The Solution Advantage

The appeal of OPV and DSC technologies is that they can be produced using novel deposition techniques. The materials can be dissolved in solvents to create inks that can be applied using ink jet printing, spin coating, screen printing, and other high-speed techniques. These techniques open up the potential for roll-to-roll (R2R) production; when paired with low-cost, flexible substrates, this approach can reduce production costs to as little as 25 percent that of the crystalline silicon technologies, which require traditional batch processing production. Lower material costs and lower production costs — even at lower solar cell efficiencies — can result in competitive products.

In October 2008, Konarka Technologies announced the launch of the largest commercial R2R production line for OPV in New Bedford, Massachusetts. Formerly the site of Polaroid Corporation's printing operation, the 250,000 square foot facility has the potential capacity of up to 1 gigawatt (GW) of thin-film solar modules per year.

G24 Innovations has an R2R production facility for DSC devices in Cardiff, Wales, with an annual capacity of about 20 megawatts (MW). The company has announced plans for a second line for 2009 that will increase production capacity by an additional 25 MW.

Note that another way to reduce the total cost of solar cells is to have them replace other materials, either in part or in total. One of the most dramatic examples of this approach is the creation of building-integrated PV (BIPV) materials. For example, PV components can be incorporated in materials that are already going to be used in the construction of a building. If adding solar cell functionality to siding or roofing materials only causes a small increase in the combined cost, it may end up costing considerably less than an add-on installation of solar cell modules. This could help swing the cost-benefit analysis in favor of OPV and DSC devices.

Note also that OPV and DSC modules tend to maintain their efficiency in lower light levels, which is not the case for crystalline silicon devices. This means that they can be used to generate electricity on surfaces that may not receive direct sunlight. They may also be effective at scavenging power from ambient light indoors.

1.1.3 Parallel Universe

Both OPV and DSC devices bear strong similarities to OLED devices, beyond just the potential for using low-cost flexible substrates and R2R production processes. Both classes of devices rely on thin-film semiconductor technology. Instead of applying an electrical current to an OLED device to make it emit light, you apply light to an OPV or DSC device to create an electrical current. (In fact, some OLED devices have been demonstrated to “run backwards” — generating electricity from light — albeit very inefficiently.)

OPV devices are somewhat similar to polymer OLED devices, relying primarily on polymer materials for the active components. DSC devices are similar to small molecule OLED devices. Both types of PV

devices use similar stacks of thin films — though generally much simpler than OLEDs — including a clear anode that is typically indium tin oxide (ITO).

The operation of the stack is similar between the PV and OLED devices, though they run in the opposite direction. In OLEDs, electrons are injected from one side of the stack, and holes injected from the other. They meet in the emissive layer where they combine. The recombination results in the emission of photons. In the PV devices, photons strike the active layer, stripping electrons from the donor material that are then taken up by the acceptor material. A negative charge builds up in the acceptor material, as the electrons accumulate.

The biggest differences between the PV devices and OLEDs are the issues of scale and complexity. Some OLEDs are intended for information display, such as full-color moving images. These require fine structures to support the colored sub-pixels. PV devices require no such detail; in fact, larger devices can simplify component assembly and installation. (This is more akin to the use of OLEDs for area lighting.)

The other difference is complexity. With the intended goal being competitive production of electricity, the bill of materials and manufacturing processing needs to be kept to a minimum, in order to wring out as much cost as possible from the devices. As a result, researchers are concerned with keeping the structure as simple as possible, while maximizing device efficiency and minimizing costs.

1.1.4 OPV Structure

The most common structure for an OPV device is a bulk heterojunction (BHJ) stack. The top of the device is a clear substrate. This can be glass, but flexible substrates such as polyethylene terephthalate (PET) and polyethylene naphthalate (PEN) are among the flexible substrates used for OPV devices. A clear anode is applied to the substrate, and this is typically the familiar ITO though other materials have been used.

The hole transport layer is often a PEDOT:PSS combination. Next, the BHJ layer is a mixture of the donor and acceptor materials. A variety of materials are used for this layer, but fullerenes based on C₆₀ are among the most common.

A protective layer is applied between the BHJ layer and the metal cathode. Typically, this will be a LiF layer with an Al cathode.

1.1.5 DSC Structure

A DSC device uses a similar structure. The substrate is coated with SnO₂ as an anode, and then a porous layer of TiO₂ with a dye-sensitizer — typically a ruthenium compound — is created. The cathode gets a thin catalytic coating of platinum or carbon, and then the space between the cathode and TiO₂ is filled with an electrolyte, which generally is an organic material that includes iodine.

1.1.6 Stacked Structure

One of the challenges of solar cell design is that the active layers have to be closely matched to the energy of the incoming photons. Given the wide spectrum that makes up sunlight, no single material can make use of all the light that strikes a solar cell. One approach to increasing efficiency is to create multiple cells, tuned to different photon energy levels, and stacking them one on top of the other.

This naturally creates a more complex structure than the idealized OPV or DSC structures, but some researchers believe that the extra fabrication and material costs can be justified by increased efficiencies.

1.1.7 Mapping the Future

Research on both OPV and DSC devices continues apace at the university, national research institute, and commercial industry levels. There are many metrics for tracking the progress of this research, but one particularly useful set of target milestones has been put forward by the U.S. Department of Energy's Solar Energy Technologies Program. In 2007, the agency developed draft reports on the National Solar Technology Roadmap, with sections for both OPV and DSC.

Here are the current status (as of 2007) and target goals for OPV from this draft report:

Parameter	Present Status (2007)	Future Goal (2020)
Champion device efficiency	5.2%	12%
Cell degradation	< 5% per 1000 h, research-scale	< 2% per 1000 h, module
Material figure-of-merit efficiency. Identification of candidate materials whose fundamental properties, such as optical absorption, band structure, and carrier mobility, allow for high theoretically attainable efficiencies.	Some material sets with improved figure-of-merit efficiencies exist.	Identification and synthesis of multiple donor-acceptor materials that meet all the fundamental requirements to achieve the Shockley-Queisser limit.

Source: NREL, National Solar Technology Roadmap: Organic PV

The goal for efficiency jumps to more than double the best results of 2007 to 12 percent by 2020. Another significant issue for OPV devices is degradation; the goal is to reduce the 2007 best result of less than 5 percent per 1,000 hours to less than 2 percent per thousand hours by 2020.

The main part of the goals, however, focuses on improving our understanding of the OPV materials. Much of the work to this point has been by trial and error, while explanations of all the mechanisms at work within OPV devices remain incomplete. Fundamental materials research is needed to develop optimized materials.

Note that the Shockley-Queisser limit mentioned in the chart describes the theoretical maximum efficiency for a p-n junction type semiconductor solar cell. Assuming a band gap of 1.1 eV, the maximum conversion efficiency should be around 30 percent. It only applies to a single layer cell; stacked cells can exceed this theoretical limit.

From the draft roadmap report for DSC, here are the goals:

Parameter	Present Status (2007)	Future Goal (2015)
Champion device efficiency	11%	16%
Laboratory cell degradation	<5% after stress at 80°C for 1000 h in dark or after light-soaking for 100 h @ 1 sun at 60°C	<5% after stress at 85°C for 3000 h in the dark or after light-soaking for 3000 h @ 1 sun at 60°C
Module efficiency	5%–7%	10%
Outdoor module degradation	<15% in 4 yrs	<15% in 10 yrs
Identification of key degradation mechanisms	Degradation mechanisms are controversial	Primary degradation mechanisms identified

Source: NREL, National Solar Technology Roadmap: Organic PV

As with the OPV devices, device efficiency is the first goal, aiming to increase from 11 percent in 2007 to 16 percent in 2007. Module efficiency is always significantly less than the ideal results obtained in the laboratory setting, and the goal for modules is to reach 10 percent efficiency by 2020.

Degradation is a more serious problem for DSC, with the 2007 benchmark level being less than 5 percent after just 100 hours of light soaking at 60°C. The goal is to increase that to less than 5 percent after 3,000 hours at 60°C. Outdoor module degradation is to go from the 2007 benchmark of less than 15 percent in four years, to less than 15 percent degradation after 10 years. A clear understanding of the mechanisms of DSC degradation is another essential goal, which presumably will aid in finding materials that resolve the degradation problem.

1.2 Goal and Scope of This Report

In this report, we analyze and forecast the materials markets for OPV and DSC devices worldwide over the coming eight years. We review the range of materials used in these devices, from the active layer through to the electrodes, substrates, and encapsulation materials. We review some of the most current research in order to point the direction of possible new developments in these markets, but we also give extra weight to those bellwether companies that have already started commercial production.

It is impossible to separate materials from manufacturing processes, so we also call out the significance that the commercial fabrication approaches may have on material usage.

In addition to focusing on the materials and forecasting their use, we also provide in-depth review of the major players in the OPV and DSC materials markets. Again, this includes not just the active layers, but also transport and blocking layers, buffers, electrodes, substrates, and encapsulation.

The report is based on a worldwide view of the market, and we have not favored companies from any particular geographic region. We strive to cast as broad a net as possible in our efforts to research the information for this report.

1.3 Methodology and Information Sources for this Report

The information in this report is derived from extensive interviews with key representatives of the OPV, DSC, and related materials markets. We have also conducted an extensive review of the research literature, as well as publicly available white papers, trade press articles, corporate literature, and government agency reports in order to create as broad and timely a picture of the current market as possible. (Additional details on the forecast methodology are included in Chapter Three.)

1.4 Plan of This Report

Chapter Two of this report delves deeply into the materials used for OPV and DSC devices. It covers the evolution of the materials on a layer-by-layer basis, including not just the materials that are currently favored for commercial production, but also those that show merit as a result of research. This also includes materials and layers that are not routinely used in OPV or DSC devices now, but could have significant impact in the future.

Chapter Three covers applications and forecasts for OPV and DSC materials. It includes consideration of the various applications for these devices, and what impact these technologies may have worldwide. We break out the forecasts separately for OPV and DSC.

Chapter Four includes profiles of key manufacturers of OPV and DSC materials, as well as of some of the foremost research institutes involved in these fields. Again, given the comprehensive analysis of the materials markets, we cover not just the active layer materials, but also the entire stack including the substrate and encapsulation materials.