Printed Photovoltaics: Market Opportunities for the Materials and PV Industry

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Executive Summary

E.1 Introduction

E.1.1 Evolution of Printing in the Photovoltaics Industry

Printing has always played a critical role in the manufacture of solar panels. In conventional solar panels, it is used for metallization of the front contact grid. However, in the context of the emerging thin-film PV (TFPV) and especially organic PV (OPV) technologies, a much wider role is envisioned for printing, most notably in the laying down of the photoactive material itself; this does not exclude its use for contacts. Printing is seen as a way of lowering costs and is also highly compatible with the goal of roll-to-roll processing and increasing throughput. Several firms are already pursuing the goal of printed PV—in the sense of printing the absorber materials—using different (often semi-proprietary) printing approaches.

The central issue that confronts all business models of printed PV firms is that, today at least, there is a tradeoff between the quality of the solar cell manufacturing process and the performance of the cell itself. The adoption of printing as a manufacturing mode brings with it (at least in theory) low capital and operational costs and the ability to create solar cells on flexible substrates (which is an enabler of future BIPV products). In general however, by turning PV material into inks one lowers the performance of the cell that is ultimately fabricated from these inks.

This central conundrum shapes the opportunities presented by printed PV now and in the future. Thus, there are those firms that have chosen to initially serve markets where cell performance is not the key issue. The most obvious of these firms are the OPV producers, notably Konarka. However, the same strategic thinking can be found at Innovalight, which has developed a solvent-based silicon nanocrystalline ink based on technology developed at the University of Texas. Recognizing the low performance of early products, some of the OPV and dye sensitive cell (DSC) firms are chasing after off-grid products such as solar umbrellas and battery chargers. The problem with this approach is that even under an optimistic scenario, these off-grid markets don't amount to much if all you are selling is photoactive films.

This means in order to be successful, printed PV firms must either find ways to improve performance of the solar products that come off their printers or move up the value chain. As far as improving product performance, there is probably more potential with inorganic PV approaches than with OPV (and maybe DSC) approaches. This is because of the special encapsulation requirements for organic materials. It seems likely that better performance can be achieved quicker with inorganic materials. Thus, Innovalight is aiming at the grid-connected market with products that will first hit the market in 2009. With regard to moving up the value chain, one might cite G24 Innovations, which sells DSC-based battery charger systems.

Improving performance of final products also means improving or changing printing technologies. Again there are some strategic decisions to be made here. Several firms—for example, Nanosolar—have chosen quasi-proprietary approaches to their printing strategy in order to improve performance and to some extent protect themselves from competition. Others—notably Semprius—have strayed from what one intuitively thinks of as printing by using its transfer printing technology primarily to put higher performance semiconductor devices on flexible substrates. Innovalight used an off-the-shelf industrial printer at this early stage in its evolution. But what is not clear is whether it will be entirely able to stick to this open strategy as it moves up the performance curve.

If it turns out that reasonable quality PV can be created using fairly conventional technology then there are clearly opportunities for printing firms, too. So far, most of the printing firms that have become involved with printing PV are already deep into printed electronics. Thus, Leonhard Kurz, a well-known German printing firm, is developing a high-speed press to enable low-cost, high-volume printing of Konarka's OPV-based material. Toppan Forms also entered into a joint agreement with Konarka in 2007 to help accelerate the development and commercialization of Konarka's Power Plastic material for consumer and electronic applications, using Toppan Forms' well-developed roll-to-roll (R2R) processes.

However, before printed PV can really take off, numerous problems have to be solved. Many of these are the teething problems that are typical even in graphics printing—something that we believe is not said enough. That is, many of the problems that are today associated with printed PV—or more generally printed electronics—are exactly the same kind of issues that pop up all the time at traditional printers. For example, Miasolé originally attempted to print silver directly onto the solar film in the manner widely used for conventional PV, but reportedly this didn't work well and shorted out the cell. This is exactly the type of irritating problem that conventional printers face every day.

Of the many types of printing that have been used or have been seriously considered for use in the TFPV and OPV manufacturing environments, the ones most commonly discussed are screen, inkjet and flexo. (For a comparison of these see Exhibit E-1.) There are plenty of other possibilities for manufacturing TFPV, DSC and OPV that fall within the definition of "printing." Konarka has manufactured P3HT solar cells exhibiting 3 percent efficiencies using spin coating and doctor blading. HelioVolt and Semprius use a proprietary transfer printing process in their operations.

Screen printing: Screen printing is probably a first choice for all functional printers. The equipment is fairly inexpensive and easy to use and screen printing is well established as an approach in functional printing. Screen printing is used in the manufacture of printed circuit boards (PCBs), for example, and, within the context of PV, screen printing is widely used to fabricate the contacts for conventional c-Si PV. Screen printing has been used with a variety of conductive polymers including PPV:PCBM and P3HT, a variety of metals (most notably silver), and CdTe. It might be able to be used with silicon inks and perhaps even CIGS inks. In the past, CdTe cells were produced by screen printing but this approach seems to have been entirely dropped.

Exhibit E-1
Comparison of Common Printing Processes

	Flexography	Inkjet	Screen
Technology	Complex—printed image produced on photopolymer plate by Anilox roller, where the image is physically above the non-image area. This plate is 3-9mm thick and flexible enough to adhere to printing cylinder surface	Simple—individual droplet head used, composed of many heads which drop individual drops to form patterns and by proper drop placement coherent patterns are formed on the substrate	Simple—ink is forced down through a mesh printing surface onto the substrate by movement of a squeegee on the meshes' upper surface – an image is defined by applying a stencil to the mesh
Alignment		Dynamic—easy, more flexible and self alignment process possible	Accuracy of 15 mm and stencil alignment of 3 mm per step
Patterns		Very flexible—since all-additive process and real-time patterns can be updated from PC	Ability to print variable thickness and designs
Quality	Medium print quality - closed solids require exact combination of plates, tape and ink	Low print quality	Medium quality
Reproducibility	Due to plastic elasticity and tolerances—reproducibility depends on operator skill and quality of prepress efforts	High reproducibility over large areas (up to 2m)	Difficult to reproduce very fine detail
Lateral resolution µm	5	20-50	30
Ink thickness µm	3-8	<0.5	100
Ink viscosity mPas	50-500	<20	500-50,000
Throughput m^2/sec	10	0.01	<10
Cost	\$0.5M (no servo with full UV) - \$2M (with full servo and full UV)	\$100,000 - \$500,000	Low cost allows for short production runs—not a high volume process
Typical applications	Print packaging materials	Favored for printed electronics despite spreading and coffee-stain ink effects.	Versatility facilitates use in many industries—from clothing to product labels to PCB printing.

Source: NanoMarkets, LC

There are plenty of problems with screen printing though. One of the issues with screen printing to create PV cells and other functional devices is the relatively low throughput of this kind of printing. The throughput can be improved somewhat by the use of rotary screen printing; however, this method is relatively expensive and still in its infancy compared with other high-volume processes.

That being said, screen printing seems set to play a key role in PV going forward if only to print contact materials. It will probably be the default option of many firms operating—or considering operating—in the printed PV space. As printed PV, or for that matter PV in general, becomes more important, screen printing will derive more revenues from the PV space than it does now. However, this is more of a passive development than an opportunity to pursue.

Flexo and gravure: Throughout the functional printing business, flexo and gravure are being touted as the way to scale-up volumes and this may also apply to printed PV. However, proprietary approaches seem a more attractive way to go for most PV firms. Reportedly, there is some work being undertaken on printing PV with flexo.

Initially, there were concerns that flexography would not be able to lay down a thick enough ink film to meet conductivity requirements for functional materials. However, with the improvements in conductive inks, flexo has shown itself capable of printing electronic devices with the necessary conductivity. Gravure-roll printing is an alternative printing approach to flexo for PV firms looking for high-speed processing. As with flexo, gravure is an established printing technology with a long history in graphics that is currently beginning to find its way into functional printing.

Inkjet: Inkjet printing is being widely promoted as a functional printing method in several different areas. "Jetting" is being used for the controlled deposition of solutions of functional materials in specific locations onto substrates and has found great success in the early development of the printed electronics industry. However, NanoMarkets believes that jetting is best suited for creating detailed features in printed electronics, which is not really what most PV firms are looking for. In any case, inkjet may not be fast enough for high-volume PV plants. This isn't clear yet, but we note that in general PV has proved itself to be an industry that thrives on economies of scale.

Today, jetting in the context of PV seems to be primarily associated with OPV, possibly because the early phase at which OPV finds itself is consistent with the relatively limited throughput provided by the current generation of inkjet. Konarka has used inkjet, and G24i describes its R2R process as "similar" to inkjet printing. Konarka recently used a novel solvent mixture to print its highly efficient 3-percent polymer fullerene BHJ solar cells with a commercial inkjet printer.

Inkjet is at a stage where it is undergoing considerable evolution as a functional printing technology—a direction that is being pursued by several inkjet printer and print-head firms and that might make it more suitable for PV applications. Also worth mentioning is the hybrid printing/vapor deposition process called organic vapor jet printing (OVJP), which is an inkjet process where the "solvent" is gas rather than liquid. While this technique has not been widely used, it can be used with small molecules at deposition rates up to 1,300 A/s. This could have some relevance in the OVP space. Another technique in the R&D phase is the selective laser sintering of inkjet-printed nanoparticles to fabricate passive electrical components. The major application of this technique is for large-area, cost-effective electronics fabrication on polymer substrate, and it is now being expanded to OPV.

Transfer printing and other approaches: Given the many inadequacies of the more standard forms of functional printing, it is not surprising that the printed PV community is looking at other alternatives.

Just about everything has been used, spin coating and doctor blading, for example. Most of these approaches will not likely have huge commercial impact any time soon though.

Where there does seem to be some potential is in transfer printing, since it combines the ability to achieve the very high performance achievable using the classic fabrication approaches of the display and semiconductor industries with flexible substrates. HelioVolt's FASST process seems to be the major example of this approach in the TFPV space and this is discussed in depth later in this report; HelioVolt says that FASST is "10 to 100 times faster than current processes." FASST also enables solar material to be created in custom shapes and sizes and to be created on a wide variety of construction material. Semprius has also recently turned its attention from creating transistors with its transfer printing approach to concentrator PV.

We believe that there is considerable potential in the transfer printing space, but we also note that there is something of a semantic issue here. The vision that printed PV summons up is one in which most of the PV cell is created using printing technology. By contrast, transfer printing is more of a process that bridges the high performance world of the semiconductor industry and the low-performance world of current functional printing.

There are also various experimental methods that are worth mentioning and may have some potential, although they may or may not ever make their way out of the labs. George Malliaras at Cornell University and researchers at NREL have successfully sprayed inks onto sheets of plastic providing an additional reduction in cost for OPV cells; this method was chosen because of the difficulty in controlling the film thickness with conventional printing processes. NREL used ultrasonic spray to print PEDOT to realize 3.7 percent efficiency with a spin-coated BHJ cell.

There are also a slew of new nanofabrication technologies that have mostly lurked at the fringes of the R&D world, but which will have major commercial impact someday, especially if future generations of TFPV begin to make wide use of nanomaterials or nanoengineered cell designs. As an example of the kind of direction these fabrication approaches might take, consider the work that was done at the University of Michigan, which demonstrated a top-down nanofabrication approach for fabricating an OPV cell, where the electron donor and acceptor components are interdigitated with precisely defined interface geometry.

E.2 Opportunities by PV Technologies

E.2.1 Silicon

Most of the PV industry is based on silicon technologies whether this is crystalline silicon, amorphous silicon or HIT cells. This is the way things are likely to stay for the foreseeable future. However, the silicon sector is precisely the sector of the PV industry where printing is likely to have the least impact. Crystalline silicon is inherently unprintable, unless one is talking about transfer printing, and there are no amorphous silicon inks. And while a considerable amount of screen pastes are used to create contacts in the silicon sector, this is largely a mature sector with established players.

Thus the silicon PV industry is likely to produce new opportunities for printing only at the margins. We may see some nanomaterials (such as nanosilver inks) used to improve performance of a-Si, for example. More important, a wildcard in the roadmap to advanced silicon-based thin-film PV cells is the use of silicon ink technology. So far, only one company has begun developing silicon ink-based inkjet printed PV cells, but this company has completed a 10-MW pilot plant and results should be forthcoming this year. If successful, it could shift the whole field to a new deposition strategy. One limitation of this technology is the high temperature anneal step required to cross link the silicon nanocrystals into a semiconducting film. This high temperature will likely limit its compatibility with flexible plastic substrates.

E.2.2 CIGS and CdTe

CdTe: Outside of silicon, there is also no reason to believe that printing the CdTe absorber material will make much of a commercial impact, if only because First Solar, which dominates the industry, seems to have no core use for printing. The use of screen printing in the CdTe sector, however, has been discussed in the literature and it is therefore possible that some of the newer companies in this space—and perhaps even eventually First Solar—may adopt it in some way. Screen printing is one of the methods that are being investigated to reduce costs and improve material consumption for the CdS and CdTe layers for example. However, it is not the only one. Others that are being investigated for the same reason are spray pyrolysis, electro-deposition, physical vapor deposition and MOCVD, so the use of printing is by no means assured.

While CdTe PV technology has great latitude in the number of deposition techniques that may be applied, only a few provide optimum device performance. It is far from clear whether printing fits into this description. In addition, the CdTe sector has already demonstrated that it is one where economies of scale already matter.

CIGS PV: PV has essentially been presented as "what's next" after CdTe. CIGS seems to provide all the thin-film advantages of CdTe, but with prospects for much higher conversion efficiencies. Until the major financial downturn hit the market, it seemed as if CIGS would be a major revenue generator in the very near term future. There are already a dozen or so firms producing it in modest quantities and several are using printing technologies. However, it now seems that the "CIGS revolution" is likely to be delayed for a year or two.

Nanoparticle-based inks have been developed to print the CIGS precursors onto a substrate. CIGS is crystallized from these precursors in a separate thermal step. In addition, transfer-printing technology has been developed for CIGS.

The fact that printing has already established itself as a viable manufacturing technology in these early days of CIGS (most notably at Nanosolar) bodes well for printed PV, because one can imagine a sizeable CIGS sector five-eight years from now in which printing plays a significant role. There are many materials-related issues that need to be resolved. In addition, Nanosolar, the capacity leader and most vocal proponent of printing technology for CIGS PV, has been very tight-lipped about its actual production volumes, but its 1-MW power plant project with Beck Energy appears to be somewhat behind schedule. Given Nanosolar's tremendous level of funding (over half a billion dollars), and presuming any production kinks have for the most part been worked out, the company should be able to significantly ramp up in 2009, though it will still be constrained by the economic crisis. HelioVolt, also using ink with its unique FASST process, predicts that it will begin production in 2009. ISET's ink plans are somewhat behind HelioVolt's.

All of this needs to be measured against the fact that the other non-vacuum deposition method for CIGS, electrodeposition, has had somewhat more verifiable success, with Odersun commercially producing significant volumes of CIGS PV modules in 2008 by this method. And as usual, still, the champion cells with the highest efficiency use CIGS precursor films formed by thermal evaporation. Sputtering provides better coverage over the large-area substrates typically used. Most manufacturers are currently using one of these vacuum deposition methods, and by 2016 we still expect half of CIGS PV modules to be manufactured this way. But with so much money already invested in Nanosolar's print-oriented fabrication approach to CIGS, much will depend on the long-term success of that particular company.

E.2.3 OPV and DSC

One appeal of OPV and DSC technologies is that they can be produced using novel deposition techniques, with printing being the technique that seems to get mentioned first. So, while printing is marginal to silicon- and CdTe-based PV, and of possible future interest in CIGS PV, it is central to DSC and OPV. It is, however, certainly not the only way to make OPV as Exhibit E-2 shows.

Exhibit E-2
Organic Solar Cell Manufacturing

Fabrication steps	Processes
Substrate preparation	Photolithography Printing
Active layer deposition	Vacuum evaporation/organic vapor deposition Or Spin coating/printing
Cathode deposition	Vacuum evaporation Printing
Encapsulation	Vacuum evaporation Coating

Source: IMEC, adapted by NanoMarkets

The importance of printing for OPV/DSC is demonstrated by the fact that the companies spearheading the efforts in this space, such as Konarka and Dyesol, are focusing on printing. This makes sense as most of the materials used in this type of PV can be dissolved in solvents to create inks that can be applied using inkjet printing, spin coating, screen printing, and other high-speed techniques. These techniques open up the potential for roll-to-roll 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 the OPV space, Konarka is set to be one of the first companies to put OPV technology into full-scale production using printing methods. The company claims that its process is similar to that used for printing photographic film, only different chemistry. As previously mentioned, Konarka has purchased the 250,000-square-foot plant in New Bedford, Mass. that was originally the site of Polaroid's advanced printing technology operations. It is now capable of producing up to 10 million square meters of material per year. Konarka says it continues to develop the ink formulation for the active material of its OPV Power Plastic, with the goal of achieving 5-percent efficient, factory-produced OPV cells.

G24 Innovations is the leader in applying printing to DSC. The company has a roll-to-roll production facility for DSC devices in Cardiff, Wales, with an annual capacity of about 20 MW. The company has announced plans for a second line for 2009 that will increase production capacity by an additional 25 MW. G24i claims that its process is "similar" to inkjet printing. The process used by G24i converts a lightweight roll of metal foil into a 100-pound, half-mile long sheet of DSC thin film less than 1-mm thick in less than three hours.

E.3 Implications for the Printing Equipment Industry

The growth for TFPV and OPV/DSC obviously opens up major opportunities for deposition, patterning and miscellaneous equipment of all kinds and from several industrial sectors. This includes printing equipment companies which for the most part have never paid that much attention to printed electronics until now; the inkjet segment is the exception here. More specifically, printing equipment firms serve a highly mature sector that is in serious decline at the present time, so the above news should be fairly exciting to them.

E.3.1 Selling Machinery for R2R and Flexibility

One "megatrend" that equipment firms can cash in on is the shift away from batch processing on glass substrates to a new paradigm that emphasizes flexible substrates and continuous roll-to-roll (R2R) processing. This new paradigm is much talked about, and has huge consensus support. But, as yet, it is at a relatively early stage of development. For example, Sharp, which is the largest PV manufacturer in the world, continues to use glass substrates for its a-Si output. And the first OPV products are also likely to be made on glass substrates.

Any improvements that equipment manufacturers can bring to bear in this area are likely to attract a good deal of attention from solar cell/module manufacturers. They may even be able to lure a few away from much beloved proprietary solutions, although the easiest market for them to get into will presumably be new cell/module providers that either seek a quick way to enter the PV market or whose value proposition rests more on the features and performance of products higher up the value chain rather than performance at the solar cell level, which may only have to be adequate rather than industry leading. A rollable solar charger for laptops may be an example here.

The shift to flexible substrates and R2R processing has broader implications. Other areas of thin film, organic and printable electronics are also at the beginning of their transition to flexibility and R2R. A firm that is successful with equipment in the TFPV/OPV market now may find new addressable markets opening up for itself later, such as in the display industry, for example. However, there are PV-specific reasons for preferring flexible substrates. Arguably the most important is the emergence of building-integrated PV (BIPV), which seems to require flexible substrates for products such as solar cladding and solar shingles, both of which need to reproduce the flexibility associated with the conventional (i.e., the non-solar versions) products.

E.3.2 Improving Printed PV

Printed PV presents opportunities for the equipment industry that are similar to the R2R/flexibility opportunity. Again, there is a new paradigm, one that extends beyond PV. And again, there is much talk, but relatively little real production. While printing is relatively well established as a metallization approach, its use for actually laying down photoactive layers has barely begun.

For the most part, printing equipment firms have yet to focus on this area and most of the effort in printing PV has either come from the cell/module makers (e.g., Nanosolar, Innovalight) or from printing companies (e.g., Leonhard Kurz and Toppan Forms). But this would seem to be a major opportunity for printing equipment firms down the road, especially given the current depressed state of many of the graphics markets in which they currently play. Printing equipment firms that want to move into printed PV will have to prove that their equipment can be used—or easily adapted—to make high-performance TFPV or OPV. But even for the equipment firms that do not wish to get that strategically involved—and there seem to be many of those—there is probably an opportunity to exploit the high growth of the TFPV sector and to sell a few screen-printing machines.

Finally, it is worth noting the rise of transfer printing (under various names) in the TOP electronics space. Despite the name, this isn't really a printing process. Printing seems to imply solution processing in the usual sense of the word, although the point can be argued, and in transfer printing high-performance devices are created using (more or less) conventional fabrication processes and then transferred to a flexible substrate using a printing-like process. The advantage here is that one can combine high thermal processes with a plastic substrate. This approach is now being used for TFTs in the RFID and display space, as well as in the TFPV space, which we see in HelioVolt's proprietary FASST process. Perhaps there is an opportunity here for equipment firms to create a transfer printing process that would serve niche (or possibly even greater) markets in the PV business.

E.2.4 Beyond Proprietariness—"Off-the-Shelf" Equipment?

Even the most casual study seems to show that cell and module makers in the TFPV space predominately are using proprietary equipment; this does not just apply to printing. In determining the size of the addressable market for equipment makers, it is therefore vital to determine how much of the equipment used in TFPV and OPV/DSC manufacturing will continue to be built by the cell/module manufacturers themselves.

Of course, what the equipment makers would like to believe is that the PV makers themselves are only using proprietary equipment at the present time because the necessary equipment is simply not available off the shelf. As a way of making that point, it would be easy to point to the CIGS sector, where cell/module firms clearly had no options but to roll their own. However, it would be equally easy to counter with the fact that many firms offering a-Si TFPV are also using proprietary approaches even though thin-film silicon equipment is widely available as the result of a-Si's important role in the display industry. This suggests that the TFPV firms may actually enjoy some significant competitive advantages as the result of building their own equipment.

The most likely scenario for the future is a movement away from proprietariness, albeit a *slow* one. Clearly, there will be some firms whose competitive advantage lie in areas other than manufacturing and therefore would be happy to buy off-the-shelf equipment. There is already an avant garde to whom this comment could apply. These would include firms such as Innovalight and Konarka, both of which claim solar materials that can be easily printed/coated using standard equipment. But such firms are few and far between at the present time.

The other group of potential customers that is likely to favor "off-the-shelf" equipment suppliers are firms entering the PV market for the first time, with no time to develop their own equipment and processes. Several firms—of which Applied Materials is apparently the most powerful—offer the TFPV "newbie" the opportunity to swiftly set up in the TFPV business via the construction of turnkey plants. This is, however, not printing equipment that we are talking about here and we should note also that during the recent PV boom, the ease of entry that off-the-shelf manufacturing equipment provided led to the establishment of PV cell/panel firms that simply did not have the necessary skills or economies of scale for success. The result has been a lot of small a-Si firms quitting the market.

In the long run, there is likely an opportunity for solar cell/module firms that have a proprietary printing process and currently build their own machinery, but now want to expand their business. Such firms could license their process technology and sell machines in a similar way to companies like Applied Materials for which equipment manufacturing and marketing is a core business.

As this type of strategy becomes more strongly embedded in the business culture of the PV industry, it is likely to produce its own special economies of scale that some proprietary approaches will find hard to match. In particular, the availability of "standard" PV printing processes substantially reduces capital costs, while the customized approach inherent in proprietary processes/equipment will increasingly make the proprietary approach seem expensive. At the same time, competition among equipment suppliers is likely to drive rapid process improvement, narrowing the gap between the performance advantages achievable with proprietary approaches.

There is a risk here for the equipment manufacturer, however. As "newbies," these new cell manufacturers that the systems integrators will be targeting are the most likely to fail, either because the PV sector turns out to be a little too hyped or because these new firms simply lack the skill sets required for success. They might learn a lesson from the telecommunications market in the 1990s, where new telephone and data communications providers were popping up on what seemed to be an almost daily basis. Eager to provide the equipment that these service providers apparently needed, telecom/datacom equipment manufacturers launched aggressive campaigns to sell such equipment on less-than-market financial terms. When the telecom/datacom market collapsed, the equipment firms lost a lot of money.

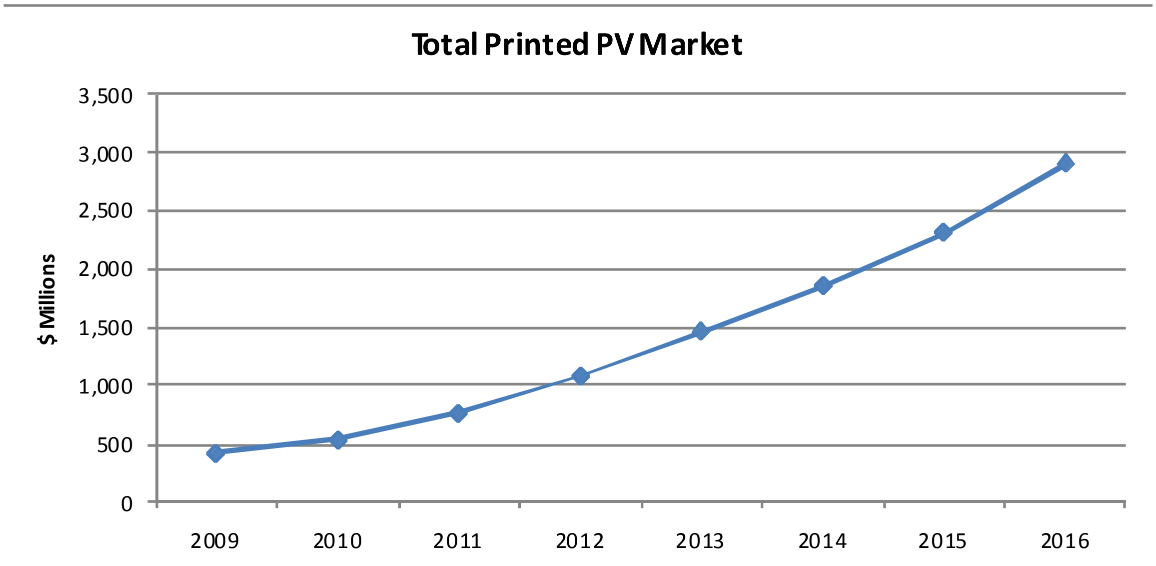
E.4 Summary of Eight-Year Market Forecasts for Printed PV

Exhibit E-3 summarizes NanoMarkets' latest forecasts for printed PV. As we discuss in the main body of this report, there are a couple of ways to approach such forecasts, neither of them especially satisfactory. Much here depends on definitions. For example, we could take "printed PV" to mean cells where at least the core absorber material was printed. This seems to capture the essence of what most people mean by printed PV. But the problem is that this approach overstates the market to the extent that it includes cells where the absorber material is printed but the electrode material is not. More importantly it excludes any reference to the printing of electrodes in conventional silicon cells, which would seem to exclude a lot of the value that is created by applying printing techniques in the PV sector.

Exhibit E-3
Printed PV Markets: Materials ($ Millions)

	2009	2010	2011	2012	2013	2014	2015	2016
Printed contacts for silicon PV								
Printed silicon cells								
Printed CdTe cells								
Printed CIGS cells								
Printed DSC cells								
Printed OPV								
TOTAL								

A second approach would be simply to count the materials that are printed; the inks and pastes and the conventional semiconductor materials used in transfer printing PV. The problem here, however, is that the forecast becomes simply a forecast of materials and fails to capture the real value created by printing in the PV industry—an approach that seems to miss the point of constructing such an approach in the first place. For this reason, we have adopted a somewhat hybrid approach here. We have calculated the value of cells where at least the core PV material is printed and then added in the large printed-electrode-for-silicon cells sector. There is an obvious methodological inconsistency in such an approach. However, it does seem to capture the value of the printed PV market in a strategically useful sense.



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