

Materials Markets for CIGS Photovoltaics

February 2009

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Executive Summary

This report focuses on the markets for the materials used in the manufacture of copper indium gallium diselenide (CIGS) photovoltaic (PV) cells—an up and coming thin-film PV technology—rather than on the devices themselves. While NanoMarkets has several other reports focused on the PV industry, and the TFPV industry in particular, both materials and manufacturing centered, this is NanoMarkets' first report that solely focuses on the materials markets for CIGS PV specifically.

Page | 1

Of course, the markets for the materials depend on the individual companies involved and thus on their manufacturing processes and materials used in these processes. Similarly, the materials markets depend directly on the growth of the CIGS PV industry in general, and this report does get into these analyses where they are required to get a handle on the materials markets. But our objective in this report is to present an analysis of the materials developments and opportunities in the CIGS PV industry and to forecast the materials markets for the next eight years.

E.1 CIGS in Today's Economic Environment

CIGS PV is coming to be known as the rising star of the TFPV world. More than ten companies were already commercially producing megawatt volumes of CIGS PV modules by the end of 2008. CIGS PV has achieved the highest efficiency of any thin-film PV technology; as of the writing of this report NREL was preparing to release certification for a 20.0 percent efficient champion cell created in its lab. Although this falls below the efficiency of crystalline silicon solar cells (barely below that of multicrystalline cells at 20.3 percent efficiency), CIGS cells can be substantially cheaper because of their reduced material usage and the ability to manufacture them using low-cost processes.

The high efficiency of CIGS PV cells is due to their very high absorption rates that allow 99 percent of available light to be absorbed in the first micron of the material. As an alloy system, the bandgap of CIGS can be tailored to maximize efficiency given the expected illumination conditions. Generally, this means optimizing the bandgap to around 1.3 or 1.4 eV to match the solar spectrum. This can be done by varying the ratio of indium to gallium and/or by substituting sulfur for some or all of the selenium.

CIGS PV is third in line for wide-scale commercialization among TFPVs. Amorphous silicon PV enjoys a multi-decade history, during most of which it was the only viable thin-film technology. CdTe PV has emerged as the second commercial TFPV technology due to the rapid expansion of CIGS PV capacity by First Solar, which had over 700 MW of capacity at the end of 2008, with more slated to come online soon. CIGS PV has had a string of disappointments over the last two years or so, starting with managerial and technical difficulties at many companies and continuing with the moderating price of polysilicon and the global economic crisis commencing in 2008.

While CIGS PV has great potential in the long run, current economic conditions will stem the realization of this growth in the short term.

Among TFPV technologies, CIGS PV is likely to be affected the most by the current global financial crisis. While a-Si PV is well-established, and First Solar has recently become a powerhouse in CdTe PV, CIGS PV is still in the state of development where production has not yet ramped up to high volumes. Just as CIGS PV was getting ready to come into its own, managerial, technical, and technological problems in 2007 and 2008 delayed its growth. Now, just as those difficulties appear to be largely under control, the economic crisis has given CIGS PV another hit, making further delays more likely.

This one-two punch is not a death blow, however. As is mentioned in the main body of this report, several firms are already in high volume production, albeit not nearly as high in volume as First Solar. NanoMarkets fully expects the CIGS PV market to pick up again and grow rapidly once the economic crisis is over.

On the demand side, the economic slowdown has already contributed to a dip in the growth of worldwide energy demand and to a reduction in oil prices to far below their mid-2008 peak. Lower energy demand and prices will reduce the demand for, and the cost effectiveness of, all PV technologies. Coupled with a slowdown in construction and a reduction in discretionary spending, new installations of PV power are expected to drop significantly. In addition to these factors, in today's tough economic times, there is a lower level of concern for the environment, and the "green" political and social impetus for growth of PV technology and adoption is likely to wane as long as times stay tough.

CIGS PV is expected to be affected disproportionately among TFPVs because it doesn't yet have the production volumes and low costs required to compete in this environment. Prices are likely to be driven down by oversupply in the CdTe and a-Si PV markets, and possibly even a glut of TFPV modules. It will be extremely difficult for CIGS PV manufacturers to profitably ramp up to higher volumes. Additional pressure is likely to come from falling silicon prices, reducing the cost of c-Si PV. Rigid modules that compete with c-Si PV are still the major products of TFPV, and lower costs for c-Si PV have the potential to drastically cut demand and profitability for TFPV. CIGS will bear the brunt of these cuts because of its still-emerging status.

From the supply perspective, investment capital of all forms is almost certain to be only a fraction of what it had been in 2007 and 2008. What is left is likely to be applied where the return is more rapid and more certain. There is a certain newness about CIGS PV beyond that of the other TFPV's. In times of economic growth and bright outlooks, this has drawn attention and funding. With the rather gloomy current financial forecasts for 2009 and 2010, this newness turns into more of a disadvantage.

Clearly, the companies that have made it to commercial production have an advantage over those that have not. Big plans to begin large-scale manufacturing will not look so appealing in the climate of reduced demand, overcapacity, and low-priced alternatives. The ones that have already demonstrated significant levels of production volume are likely to be able to keep it up, though they are equally likely to keep volumes low until the economy improves.

Among those companies that have not yet begun high-volume manufacturing, the ones that are closer to it are more likely to begin in 2009. Building and equipping a factory is an expensive proposition when even existing factories in the industry are deliberately decreasing output.

For those companies that are not already in the midst of completing a factory, the current level and source of funding becomes even more important. The degree of persistence of funding of firms is expected to have a large impact on the likelihood of those firms to make it to production and to stay in existence. Companies that run purely on venture capital and plan on obtaining more to build first factories, are likely to have a hard time getting it. Companies expecting an initial public offering to raise funds for construction and equipment are likely to be forced to delay it indefinitely. On the other hand, companies with government contracts or substantial funding from large corporations in industries expected to weather the downturn well will likely have an easier time maintaining that funding. Entities directly supported by major conglomerated corporations, such as IBM's partnership with Tokyo Ohka Kogyo, will probably fare the best among this group.

E.2 Development of CIGS PV Materials and Manufacturing Technologies

Despite the downturn in the economy there are still opportunities for CIGS PV materials suppliers. In particular, these opportunities will grow more rapidly following the recession-deflation that NanoMarkets expects over the next year to 18 months. One area of particular interest lies in the stabilization of the manufacturing technology used to produce CIGS PV.

Some companies in or near production are using flexible substrates with roll-to-roll manufacturing processes. Some are developing non-vacuum deposition methods based on nanoparticles or electrode position. Others believe the cost of vacuum deposition can be significantly reduced in high volume, and are proceeding down that route. In addition to their high efficiency and potential for low-cost manufacturing, CIGS modules don't degrade from sunlight or heat alone; moisture is also required and effective encapsulation prevents the degradation. CIGS therefore promises respectable efficiencies at relatively low cost.

Deposition Methods: For non-vacuum deposition of CIGS, 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. While this is promising as a low-cost deposition method, its successful implementation is not certain. 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 ramp significantly 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.

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. SoloPower also appears to be preparing to ramp up to commercial production using electrodeposition. In this method, the metal precursors are applied from salt solutions and metallic anodes in an electrochemical bath, followed by addition of sulfur or selenium and a thermal processing step to crystallize the CIGS film.

Still, the highest-efficiency champion cells use CIGS precursor films formed by thermal evaporation. Sputtering provides better coverage over the large-area substrates typically used. Both of these methods still require an additional thermal step to crystallize the CIGS film. 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.

Flexible Substrates: Significant efforts are also under way for the production of CIGS solar modules on flexible substrates to allow roll-to-roll manufacturing. But changing the substrate has proven to be a non-trivial exercise. Undesirable impurities may be introduced into the absorber; sodium, which diffuses from the soda lime glass in the standard process and which improves the absorber layer film quality by increasing its charge carrier density, is not automatically present with flexible substrates; the allowed processing temperatures may not be sufficient for high film quality, and additional films may become necessary, such as an insulating layer to allow monolithic interconnection on conductive substrates. Despite the challenges, Global Solar, Odersun, and Solarion have commercially produced CIGS PV modules on flexible substrates in 2008, and more companies are eager to do so in 2009.

Other Developments: The electrode materials for CIGS PV—molybdenum for the base electrode and zinc oxide for the top electrode—leave little to be desired for improvement on a cost-effective basis. Molybdenum is used exclusively for the base electrode except where a conductive metal foil serves double duty as substrate and base electrode. While some niche applications may benefit from a transparent base electrode, we do not expect molybdenum's dominance to change appreciably in the forecast period. For the top electrode, zinc oxide offers a good balance between performance and cost. Global Solar is believed to be using ITO, but for the most part the improvement ITO offers in performance is outweighed by its additional cost.

The usual junction layer materials, cadmium selenide and cadmium sulfide, suffer from two major drawbacks. They contain cadmium, making CIGS a possible target for regulatory action or public backlash, and they are not as transparent as desired. Research is underway to develop more transparent junction layer materials; zinc sulfide and zinc selenide are promising candidates. Honda Soltec is using indium sulfide to avoid regulatory restrictions in some markets.

The production of CIGS PV cells is limited by the availability of indium, which is scarce and in high demand by the display industry for ITO. This makes efficiency of indium usage a key concern, driving the development of cells with significantly reduced CIGS layer thicknesses and the use of deposition methods that are more efficient in indium use, such as electrodeposition and printing.

E.3 Opportunities for Materials Firms

The opportunities for materials firms are evident: Gear up for increases in demand for the materials that will experience the greatest growth in consumption. The largest relative growth is anticipated for the materials that are growing at the same rate as the associated CIGS PV production. Nanoparticles and inks, metal salts, junction layer materials that do not contain cadmium, encapsulation materials, polyimide films and other new substrate materials, and antireflective coatings are all expected to take increasing shares of the CIGS PV market, and hence the growth in their use for CIGS PV will outpace the overall growth of CIGS PV.

Nanoparticles and Inks: NanoSolar, HelioVolt, and ISET have big plans for expanding their printing-based commercial production of CIGS PV in the next few years. While CIGS manufacturers currently seem to prefer to produce their own nanoparticles and inks, materials companies such as American Elements and Nanoco offer nanoparticles of CIGS and its precursors, and new CIGS PV entrants may choose to outsource their nanoparticle and ink production. NanoMarkets believes that ink-based processes, while not significant in 2008, will grow to account for more than 25 percent of CIGS volume by 2016. As the pioneering companies demonstrate inks in high-volume manufacturing, we expect more companies to enter with outsourced nanoparticles and inks.

Metal Salts: Electrodeposition as a non-vacuum method of depositing CIGS precursors is expected to grow in the proportion of CIGS PV production for which it is used, at least for the next few years. While printing has had recent setbacks, electrodeposition is already successfully in use and should grow rapidly until the kinks of CIGS precursor printing are worked out. Many of the same companies that produce metallic sputtering targets and evaporation slugs also produce salts of the metals. These companies include Indium Corporation and American Elements. NanoMarkets believes that the use of electrodeposition for CIGS absorber layer precursors will increase rapidly over the next few years until the ink-based processes catch up; after that electrodeposition should hold steady at about 20 percent of CIGS volume.

Junction Layer Materials: Cadmium in photovoltaic cells is a concern due to its toxicity and environmental impact. This is mainly a matter of perception: the cadmium is handled safely, and incorporated into the cells in a way that isolates it from the external environment. While First Solar, with its high-volume manufacturing of CdTe PV modules, has gone a long way toward easing public concerns about cadmium in PV modules, there is still some risk of public backlash and regulatory restrictions. In fact, there are already regulatory restrictions in place in some markets. Besides concerns about cadmium, there are also efforts to improve the transparency of the junction layer with different materials. Current development focuses on zinc sulfide and zinc selenide, but Odorsun is using copper iodide and Honda Soltec is using indium sulfide to avoid regulatory restrictions on cadmium. NanoMarkets expects new cadmium-free junction layers to emerge and grow to over 20 percent penetration by 2016.

Encapsulation Materials: While glass is a suitable encapsulation material for rigid modules, an ideal encapsulation material for flexible modules has yet to be developed. The current state of the art is exemplified by Vitex Systems' Barix coating, which consists of multiple alternating layers of polymer and ceramic films. NanoMarkets believes that simpler solutions, even if more expensive, are likely to be implemented rapidly upon development.

Ultrathin, Flexible Glass and Glass-like Composites: Corning and Schott have lines of ultrathin glass that are very flexible. Corning offers thicknesses down to 0.05 mm, while Schott goes down to 0.03 mm. Neither of these companies appears to be marketing these products as substrates to the CIGS PV industry, but it is reasonable to expect some developments over the next few years. Vitex Systems offers a product called "Flexible Glass" that is essentially its Barix coating applied to a thin polymer substrate. NanoMarkets expects these materials, once demonstrated as suitable substrates, to grow rapidly, making up over 10 percent of the CIGS substrate market by 2016.

Polyimide Films: Polymer substrates for CIGS PV are anticipated to grow from under 3 percent of the CIGS PV market in 2009 to more than 14 percent of the market in 2016. NanoMarkets expects these polymer substrates to be dominated by polyimide films, which provide a good combination of strength, flexibility, heat tolerance, and cost. This growth could bring the polyimide substrate market, for CIGS PV alone, to as much as 3.5 million square meters per year by 2016. New polyimide factories have been built in recent years, increasing worldwide capacity substantially to keep up with demand for printed circuits from the mobile phone and display industries. Additional factories to keep up with demand from the CIGS PV industry are certainly feasible. NanoMarkets believes polyimide will be the fastest-growing substrate material until flexible glasses and composites are demonstrated and quickly outpace it.

Antireflective Coatings: These applied films are likely to undergo significant additional development as improvements in performance, cost, and simplicity of use are sought. Most single-layer films leave

some performance to be desired, while the best-performing multilayer solutions are costly and difficult to apply. One promising product is XeroCoat's nanoporous silicon product, which is applied as one layer but produces a nanometer-scale structure to reduce reflection. NanoMarkets believes that continued experimentation will lead to a variety of solutions. Just as for encapsulation materials, we expect simplicity in application to be worth a premium in cost for antireflective coatings.

Besides these materials that are expected to outpace the growth of CIGS PV, most of the other materials used in CIGS PV are expected to grow in their use by the CIGS PV industry at a rate similar to CIGS PV overall, which is still high. These materials include the CIGS components (especially indium, but gallium and selenium also make up a significant portion of the material costs), soda lime glass and metal foil substrates, and the molybdenum and zinc oxide used for the contacts.

Indium metal bears further discussion. Because of its scarcity and its growing consumption to make ITO for the display industry (and, to a lesser extent, CIGS for the CIGS PV industry), additional sources of indium are expected to be tapped over the next several years. The indium from these additional sources will be in lower concentration and will be more costly to extract. While the current economic situation is likely to offer a temporary reprieve, the long-term trend for indium pricing is expected to be upward. In addition to that, the long lead time for new production coupled with fluctuating demand will inevitably lead to imbalances between supply and demand, and price volatility in the short to intermediate term.

E.4 Opportunities for Production Equipment Firms

From a materials perspective, it would be advantageous for production equipment firms to take note of the equipment required to process the materials and handle the manufacturing technologies that will be used in CIGS PV. For the most part, this comes down to the equipment used to handle the substrates and the film deposition processes. NanoMarkets expects volume demand for flexible substrates, expected to comprise about one-fourth of CIGS PV volume in 2009, to grow to more than half of CIGS PV volume by 2016, and roll-to-roll equipment to handle metal foils and polymer films will need to keep up. Even more interesting, ultrathin, flexible glass and glass-like materials, although not being used for commercial CIGS production at all in 2009, are expected to grow to more than 10 percent of the CIGS PV substrate market by 2016. These new substrate materials will likely require new specialized equipment for processing.

Film deposition equipment will also need to keep up with CIGS PV volumes. This includes sputtering equipment for the CIGS metals, the molybdenum base electrode, and the zinc oxide top electrode; evaporation chambers for the CIGS metals, sulfur, and selenium; CVD furnaces for zinc oxide; baths for electroplating and CBD; and printing equipment for the nanoparticle inks used by some companies. Much of this equipment will need to be specialized for roll-to-roll processing with flexible substrates of various types.

E.5 Opportunities for Solar Panel Firms

CIGS PV modules, like other TFPV modules, are thinner and lighter than c-Si modules. Where they stand out from other TFPV modules is in their higher predicted efficiency and their stability in sunlight and at high temperatures. Their higher efficiency will reduce the area of PV modules needed per watt versus the other TFPV's, hence reducing the balance of system costs. Their greater stability will increase their life and reduce degradation and the need for premature replacement. These are selling points for CIGS PV panels.

CIGS PV also offers the possibility of high efficiency in a flexible panel that no other PV technology can provide. This combination promises to raise BIPV to a new level of performance. Products such as PV roofing shingles and tough PV cladding materials will yield the highest performance by using CIGS PV.

Although these products and efficiency targets have not yet been realized commercially, solar panel firms will want to be aware of the relative cost, availability, and efficiency of CIGS PV modules, as well as the development of durable, impermeable, flexible modules suitable for the new BIPV applications.

For the CIGS PV module manufacturers themselves, the lean years ahead are likely to precipitate a weeding-out of firms. Of course, the companies will formulate their own strategies for dealing with the economic downturn. NanoMarkets believes that the major determinants of success in the next two to three years will be the persistence of funding to establish capacity, the ability to produce cells at low enough cost to be profitable, and the ability to differentiate products from other CIGS and other PV products. Once the recovery sets in, the high-volume capacity of the competing, more-established PV technologies is likely to dilute the effect of any pent-up demand on the CIGS PV market. Even if a PV boom develops, CIGS firms will still need low costs in addition to high volume capacity to compete.

E.6 Impact of Developments in CIGS on the PV Market as a Whole

The traditional, c-Si PV market is deficient in three areas: First is cost effectiveness. Silicon is expensive, and it is used in great quantities to fabricate c-Si PV cells and modules. The easing of the silicon shortage will help to alleviate this shortcoming somewhat, but the fact remains that c-Si PV uses a tremendous amount of silicon.

The second deficiency is in the physical characteristics of the panels. In contrast to TFPV panels, they are heavy and bulky due to the quantity of silicon inside and because of its brittleness. A robust, rigid window and frame structure is required to prevent bending of the silicon wafers inside. This brittleness and lack of flexibility also precludes the use of c-Si PV for applications where toughness and/or flexibility are key, such as some BIPV applications and foldable or rollable panels. The less-expensive multicrystalline variety shows its multicrystallinity as an irregular vein pattern on its surface, a possible drawback for applications where aesthetics and appearance are important, including most installations where the modules are visible as part of the architecture.

The third deficiency of c-Si PV, and the one least recognized, is its failure to maintain its high level of performance in sub-optimal (including real-world) illumination conditions. The efficiency of c-Si PV cells drops significantly as module temperature increases. The output also drops off very rapidly when not aimed directly at the sun or when illuminated with diffuse light, as on a cloudy day. TFPV modules do not suffer these effects as severely. Some TFPV advocates are pushing to revise the standard rating system for solar panels, currently focused exclusively on peak performance, to include non-peak performance as well.

After the global economic crisis is over, CIGS may be able to make significant strides in cost and efficiency. If CIGS PV achieves higher efficiencies than c-Si PV at lower cost and in high volume, NanoMarkets believes c-Si PV will lose market share in the long run. Especially if the performance rating standards are changed to include non-peak performance, CIGS PV in particular and TFPV in general will gain a new reputation, distinct from c-Si PV, as the top-tier PV technology. On the other hand, failure of high-efficiency, low-cost CIGS PV modules to materialize may leave TFPV with a perception as the perpetually inferior product, the poor man's solar power. This could lead to reductions in demand and market share for all of the TFPV technologies.

E.7 Summary of Eight-Year Forecasts

CIGS PV Production: Exhibit E-1 summarizes NanoMarkets' latest market projections for CIGS PV over the next eight years. These projections form the basis for the growth in volumes of the materials used in CIGS PV. NanoMarkets expects growth in CIGS PV to be retarded during the global recession, for the reasons set out earlier in this summary and in the main body of this report. After the recovery, CIGS should return to respectable levels of growth, but not as high as was believed before the downturn.

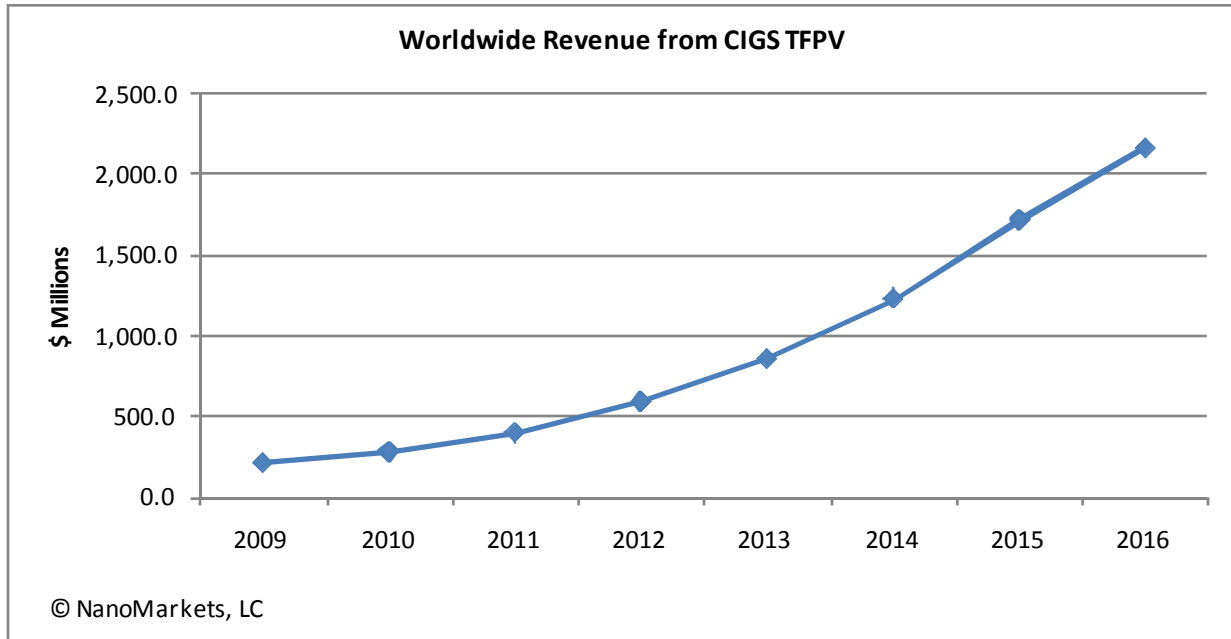
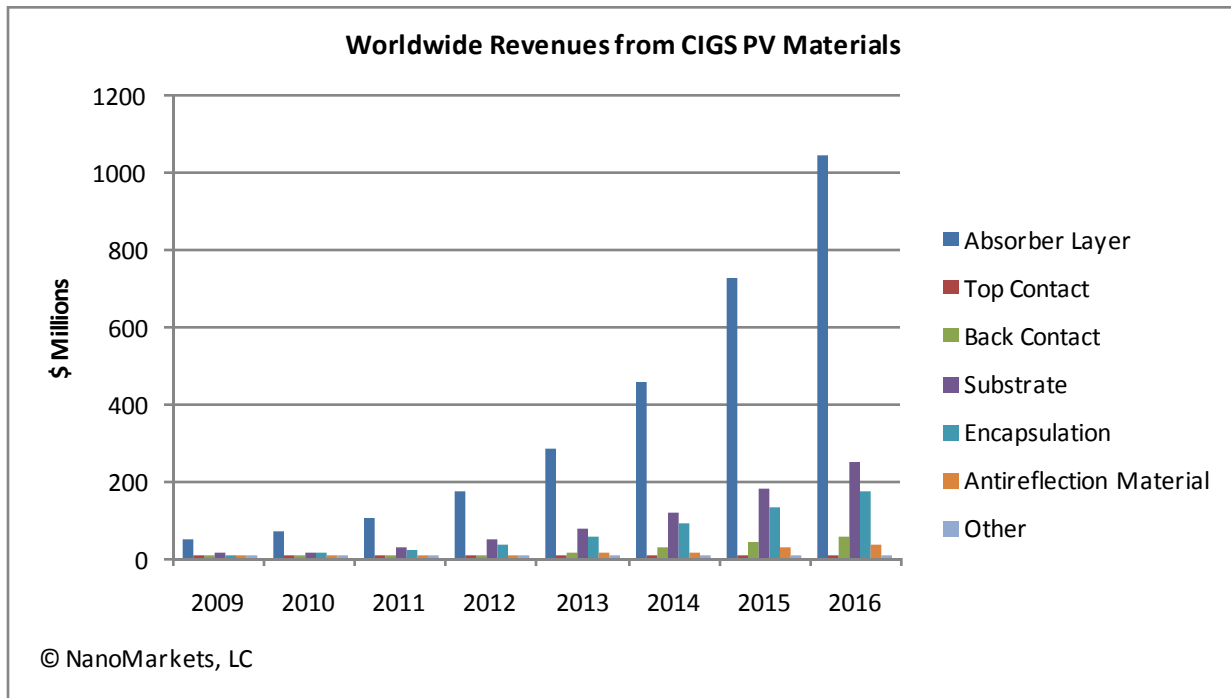
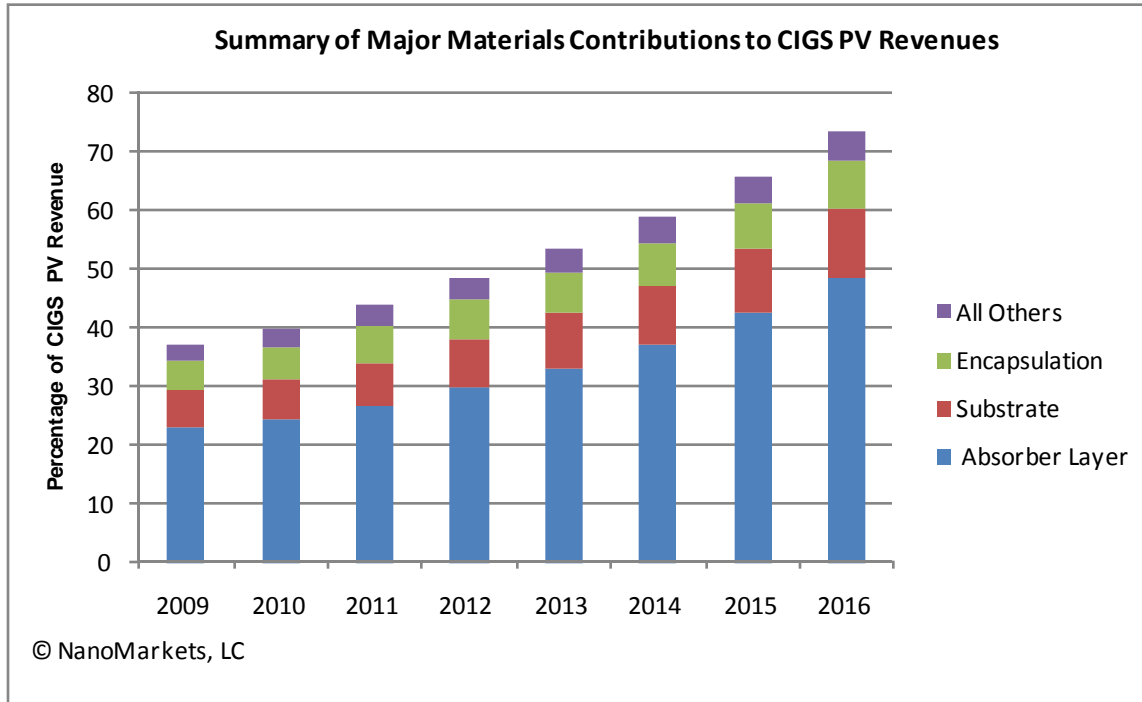


Exhibit E-2 gives NanoMarkets' forecasts for materials revenues for CIGS PV.



Materials contribution to CIGS PV revenue: Exhibit E-3 summarizes the forecasted contributions of the highest-cost materials to CIGS PV revenues over the next eight years.



NanoMarkets believes that the key long-term driver of CIGS PV production costs will be growth in the price of indium. This will be offset somewhat by wider adoption of more efficient CIGS layer deposition methods (printing and electrodeposition) and by thinning of the CIGS layer to reduce indium usage. Still, since indium consumption is dominated by the display industry, long-term pricing trends are expected to be only partially driven by CIGS PV consumption.

For additional information about this and other NanoMarkets' reports, please contact us at (804) 360-2967 or via email at sales@nanomarkets.net or visit us at www.nanomarkets.net.