4.1: Rise of Upgraded Metallurgical Silicon

Solar cell manufacturers are learning how to implement UMG-Si quickly; combined with aggressive ramps by manufacturers, UMG-Si will represent 13% of the market in 2013.

Key Issue: Rise of Upgraded Metallurgical Silicon

In the past few years, a number of factors have combined to drive alternatives to the conventional Siemens process for making polysilicon from an experiment to a technology on the cusp of widespread viability. The catch-all "alternative silicon purification technologies" encompasses a number of different approaches which differ significantly from the dominant and energy-intensive Siemens process and its variants. These diverse approaches fall roughly into six buckets (see Figure 4.1.1) and all promise significantly reduced costs, primarily through reduction in electricity inputs, at purities that, while lower than those offered by electronics-grade silicon (EG-Si) from the Siemens process, are sufficient for making solar-grade silicon (SoG-Si) (see Figure 4.1.2 for a description of silicon purities). The dominant approaches focus on purifying or "upgrading" widely available metallurgical-grade silicon (MG-Si) or silicon metal to produce SoG-Si, giving these processes the moniker "upgraded metallurgical grade silicon" (UMG-Si). Strictly speaking, UMG-Si refers only to routes that start with MG-Si; however, for simplicity's sake, we will refer to all of these alternative approaches generally as UMG-Si, noting where the discussion is specific to one or more particular processes (see Figure 4.1.3 for a list of key producers).

A number of factors have played a critical role in bring UMG-Si to the fore now – many of which underscore the broader theme of the solar industry adopting its own value chain, unique from the semiconductor industry, which is better suited to its cost and performance needs.

- **Sustained silicon shortage forcing cellmakers to seek alternative sources of supply.** The current polysilicon shortage, which has been causing solar manufacturers headaches since 2005, arose when incumbent polysilicon producers were slow to respond to rising demand for solar applications, due to their past experiences with painful over-investment. The shortage of material is acute: In 2007, we estimate that the solar industry was forced to idle 777.1 MW of cell and module manufacturing capacity due to silicon constraints, or roughly 24% of total production capacity, with companies like Sharp, Schott, and Ersol the hardest-hit. Early responses from the solar industry focused on solutions like recycling silicon – showcased by Ersol's acquisition of Silicon Recycling Services in 2006. However, as the availability of recycled material has decreased, companies have been taking a harder look at UMG-Si.
- **Price increases enabling – and inspiring – investment in new technologies.** The polysilicon shortage has drastically increased silicon prices, providing silicon specialists with both the cash and an incentive to develop new technologies. What's more, with current polysilicon prices just under $80/kg for long-term contracts and spot prices in excess of $400/kg, a host of new producers have entered the market, drawn by the lure of obscene margins. Though there has

Fig. 4.1.1: UMG-Si Processes Fit into a Few Broad Categories

Process name	Process description
Metallurgical processes	A generalized technique that uses standard metalurgical processes such as drossing, leaching, or slagging to remove impurities from metallurgical silicon (MG-Si), typcally of 2N to 4N (99% to 99.99%) initial purity
Carbothermic reduction	Reduction of silica (SiO_2) with carbon (C). Though this is the standard production process for less pure MG-Si (up to 4N), the use of ultra-pure quartz and carbon feedstocks can yield sufficiently pure solar-grade silicon (SoG-Si).
Electron beam/plasma processes	Process by which an electron beam is directed at the silicon feedstock to vaporize phosphorous (P) impurities, while a plasma beam is oxidizes the boron (B) impurities to volatile boron monoxide (BO) by heating the silicon matrix
Chemical processes	Reduction of halo-siliane – SiX_4, where X is fluorine (F), chlorine (Cl), or bromine (Br), with a reducing agent – generally zinc (Zn) or sodium (Na) – to produce solar-grade silicon
Directional solidification	MG-Si of 4N or better purity is melted and solidified, pushing impurities to the top of the ingot where they can be cut away; requires many passes (up to six times) as a stand-alone process, so it is often used as a secondary purification step in conjunction with other routes
Blending	Secondary process by which lower purity UMG-Si, made via a metallurgical process or directional solidification, is mixed with electronics-grade silicon (9N to 11N) to provide solar-grade silicon (6N or better)

Fig. 4.1.2: Silicon Purities

Silicon grade	Purity	Sources	Players
Metallurgical-grade silicon	2N to 4N 99% to 99.99% pure	Carbothermic Reduction	Ferroatlantica, Invensil, Elkem, Rima Industrial, Xiamen K Metal, Globe Specialty Metals, Dow Corning
Solar-grade silicon	6N to 8N 99.9999% to 99.999999%	Siemens process, upgraded metallurgical silicon	Hemlock Semiconductor, Wacker Chemie, Timminco, Elkem, REC
Electronics-grade silicon	9N to 11N 99.9999999% to 99.999999999%	Siemens process	Hemlock Semiconductor, Wacker Chemie, MEMC, Shin-Etsu

been an explosion in the construction of new Siemens polysilicon plants, various start-up companies with radical new technologies – such as Mutosilicon and 6N Silicon – have entered the scene. In addition, incumbent metallurgical silicon players – such as Dow Corning and Globe Specialty Metals – have also been moving into SoG-Si.

- **Sky-high silicon prices force companies to seek new supplies or lose market share.** While Asian manufacturing with lower labor and fixed costs, such as Suntech Power and Yingli Green Energy, have been willing and able to pay exorbitant silicon prices in order to capture market

Fig. 4.1.3: Key Producers of UMG-Si

Company name	Country	Process type	Feedstock	Material source
6N Silicon	Canada	Metallurgical process/directional solidification	MG-Si	External
Arise Technologies	Canada	Chemical process	N/A	N/A
Chisso	Japan	Chemical process	$SiCl_4$	Internal
Dawu Silicon Photovoltaic Industry Park	China	Carbothermic reduction	SiO_2	Internal
Dow Corning	Brazil	Metallurgical process/directional solidification	MG-Si	Internal
Elkem	Norway	Metallurgical process/directional solidification	MG-Si	Internal
Globe Specialty Metals	United Stats	Carbothermic reduction	MG-Si	Internal
Guizhou New Materials	China	N/A	N/A	N/A
Henan Xuntianyu Technology	China	N/A	N/A	N/A
Honbridge	China	Metallurgical process/directional solidification	MG-Si	Internal
HyCore	Norway	Chemical process	$SiCl_4$	External
Jaco SolarSi	China	Metallurgical process	MG-Si	Internal
JFE Steel	Japan	Directional solidification/plasma process/electron beam	MG-Si	External
Jilin Fuyuan Silicon	China	N/A	N/A	N/A
Mayaterials	United States	Chemical process	Na_2SiF_6	External
Mindanao Silicon Metals	Singapore	N/A	N/A	N/A
Mutosilicon	Taiwan	Chemical process	Na_2SiF_6	External
Nan'an Sanjing Silicon Refining	China	N/A	MG-Si	Internal
Photosil	France	Metallurgical process/plasma process	MG-Si	Internal

Fig. 4.1.3: Key Producers of UMG-Si (Continued)

Company name	Country	Process type	Feedstock	Material source
RSI Silicon	United States	Carbothermic reduction	SiO_2	External
Runxiang Metallurgical Material	China	N/A	N/A	N/A
Sangxing Silicon	China	Metallurgical process/directional solidification/carbothermic reduction	MG-Si	Internal
Scheuten SolarWorld	Germany	Metallurgical process/directional solidification	MG-Si	N/A
Sinosteel	China	N/A	N/A	N/A
Solarvalue	Slovenia	Metallurgical process/directional solidification/carbothermic reduction	MG-Si	Internal
Timminco	Canada	Metallurgical process/directional solidification	MG-Si	Internal
Xiamen HCT Energy	China	Directional solidification	MG-Si	External
Yiyang Jing Xin New Energy Science and Technology	China	N/A	N/A	N/A

share, many incumbent solar manufacturers lacked that option. Firms worried about costs and idle capacity are now willing to take more technical risks and take on additional costs to implement UMG-Si their market share. Q-Cells in particular has aggressively adopted UMG-Si, securing supply from leading UMG-Si manufacturers including Elkem and Timminco, hoping to enable faster growth or even to resell the polysilicon it has already contracted at expensive market prices.

- **Producers strive to reduce costs – especially in the face of thin-film technologies.** UMG-Si has also gained traction with traditional crystalline silicon solar cell manufacturers that have not secured options in disruptive thin-film technologies. Companies such as SolarWorld, Canadian Solar, and BP Solar are counting on UMG-Si to lower their costs to compete with cheaper but less efficient thin-film technologies, especially in the high-volume utility power plant application. Recent rumors suggest that even SunPower – the poster child for premium, high-efficiency modules – is exploring deploying UMG-Si cells from Q-Cells through its project development subsidiary (formerly known as Powerlight) for utility applications. In addition, with module supply expected to go into oversupply in 2009, looming price erosions will drive cell and module manufacturers to seek low-cost polysilicon sources to keep pace.

Survey of UMG-Si suppliers indicates performance is "good enough," but at much lower cost

As UMG-Si has been in development for some 30 years, many industry veterans snicker at the idea of using UMG-Si at commercial scale, primarily due to concerns over scalability, consistency, and purity. In order to determine what is enabling UMG-Si adoption this time around, we surveyed five UMG-Si suppliers, as well as four key consumers of UMG-Si – that is, companies making solar cells using UMG-Si – about the cost, performance, scale, and process specifics for UMG-Si. From the survey, we learned that:

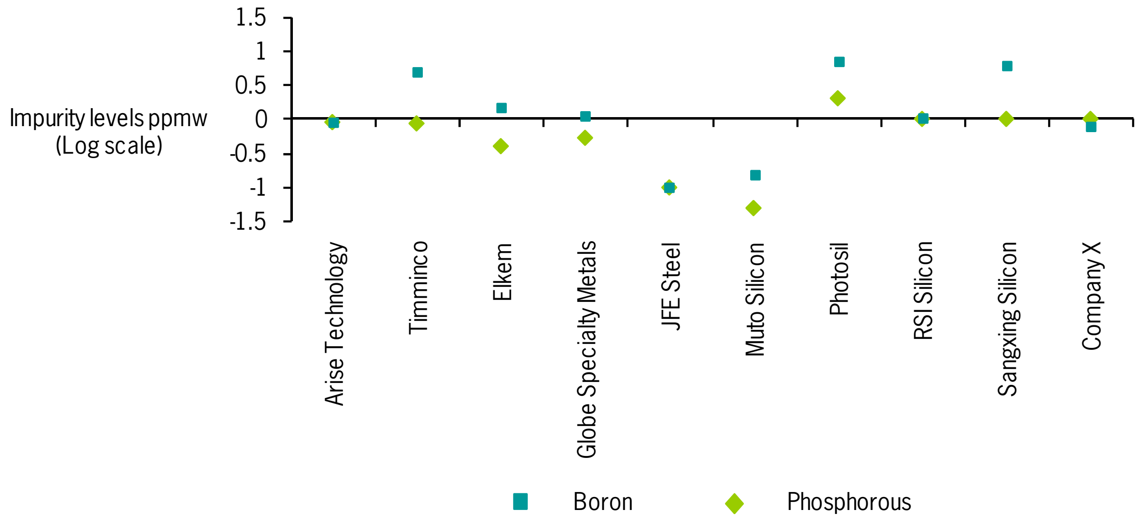
- **UMG-Si has edged past the "good enough" threshold, but is still not a drop-in replacement.** Since each UMG-Si manufacturer uses different feedstock and starting materials, as well as greatly varying processes for removing impurities, the specific attributes of UMG-Si vary significantly by supplier. Different suppliers' materials work better with different customers' production recipes – and it is impossible to predict which material will work best with which cellmaking process. As a result, it's not straightforward to simply replace Siemens polysilicon with UMG-Si – would-be users need to identify a supplier selling material that happens to mesh well with their cellmaking "recipe," or to tweak their own processes to successfully use material from another supplier.

  In general, however, the minimum purity requirement for UMG-Si for using in solar cells is 1 part per million by weight (ppmw) and 1:1 parts per million atoms (pmma) for boron and 3 ppmw or 1 ppma for phosphorus. Currently, Muto Silicon, JFE Steel, and RSI Silicon have achieved this threshold, and companies like Timminco, Elkem, and Globe are still working towards those targets (see Fig. 4.1.4). Some do far better: Mutosilicon, which uses a unique chemical process licensed from SRI International, has been able to consistently achieve boron and phosphorous purity levels almost two orders of magnitude below the typical standard for SoG-Si, although its process is still at pilot scale.

- **Improved downstream manufacturing processes have enabled viable UMG-Si modules – though efficiencies lag.** Even though some UMG-Si developers are able to meet the stringent purity requirements for solar cells in the lab, the commercially available UMG-Si still requires extensive downstream process modifications in order to yield commercially viable cells and modules. Producers report that successfully implementing UMG-Si requires additional control of the ingoting step – essentially incorporating additional purification into the directional step that's an ordinary part of the ingoting process – as well as precise tweaks to the cell manufacturing recipe. Specifically, cellmakers modify the phosphorous diffusion step, employing a "gettering" process common in semiconductor manufacturing, which adds an additional layer of phosphorous to the backside of the cell to act as a trap for metal impurities.

  However, efficiencies for UMG-Si-based solar cells are still consistently below those of multi-crystalline solar cells, averaging about 13.7%, compared to 15% or greater for solar cells made with EG-Si. Many cell manufacturers will not pursue the technology unless they can exceed 15% average efficiencies; but while the average efficiencies lag, leading companies like Q-Cells have already demonstrated equivalent UMG-Si efficiencies approaching 15.5% at pilot scale. As the technology to process and handle UMG-Si becomes more mature, expect to see this difference in efficiencies between UMG-Si and EG-Si tighten, and perhaps even close.

Fig. 4.1.4: Boron and Phosphorous Impurity Levels of UMG-Si from Select Producers

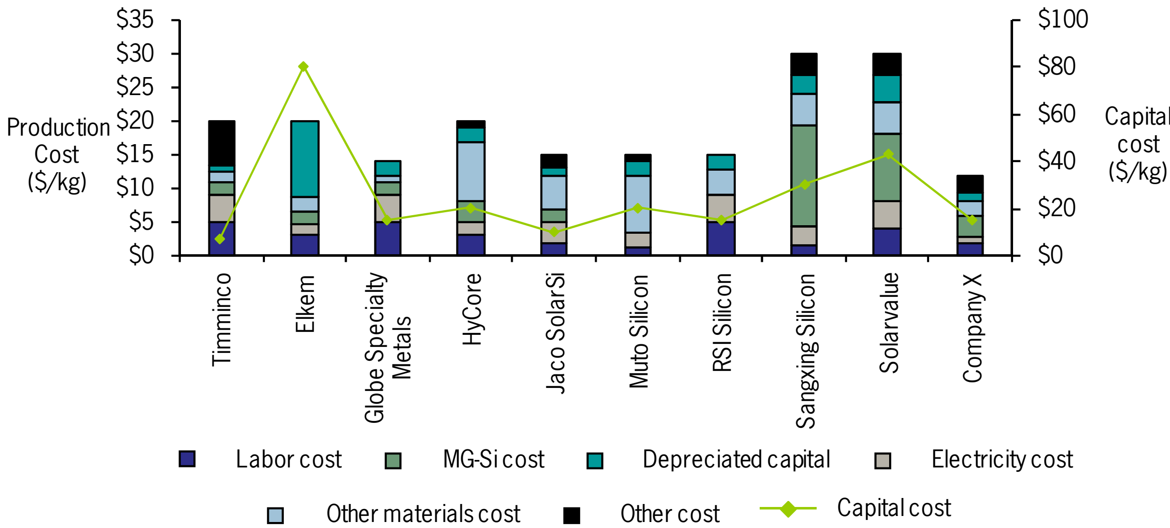


- **Prospects of lower costs than the Siemens process have enabled transition to UMG-Si.** Most of the producers surveyed cited costs in the $15/kg to $20/kg range – about $10/kg less than the Siemens process and its variants – primarily due to decreased electricity costs. Additionally, as most UMG-Si processes use conventional smelting techniques from the metallurgy industry, these companies can drastically reduce upfront capital costs by using standard equipment that does not require expensive vacuum chambers. Timminco cites capital costs of $7/kg compared to roughly $100/kg for a Siemens plant, while in unusual circumstance, Elkem cites $80/kg in capital cost(see Figure 4.1.5). As consistency and purity of UMG-Si improves with experience, however, both suppliers and customers alike agreed that this discount to EG-Si would narrow over time.

- **This decrease in manufacturing cost has enabled UMG-Si producers to pass along cost savings to the customers to entice them to shift to the material**. Lead adopters of UMG-Si are receiving significantly lower prices – $60/kg to 80/kg – than they'd have to pay for spot polysilicon, which is trading in excess of $400/kg. This discount effectively subsidizes cell producers for taking on the R&D expense necessary to implement UMG-Si into their products, and to absorb higher costs for sorting of UMG-Si, which is still relatively inconsistent. Indeed, Canadian Solar reports that it has teams of workers in China hand-sorting incoming UMG-Si materials to isolate material with desirable crystallinity, and low labor cost was likely the key driver for Q-Cells when it decided to locate its new facility, dedicated to making cells from UMG-Si, in Malaysia.

- **UMG-Si scale-up is quick, but maintaining quality is tricky.** Fast scale-up time is one of the major advantages of UMG-Si processes, which can allow plants to be planned, built, and ramped in as little as one year, compared two years to three years required for a Siemens-process

Fig. 4.1.5: Breakdown of Production and Capital Cost of Select UMG-Si Producers



Note: All production costs are estimated except for Muto Silicon and Sangxing Silicon. Capital cost are as stated.

polysilicon plant. However, while these processes can be scaled quickly, it's not clear yet whether producers can do so and maintain quality. For instance, though Timminco reported that quality has increased as it has scaled, a process flaw recently contaminated a large batch of UMG-Si and cause the company to shut its process down – severely hurting its share price.

UMG-Si Variants Will Grow to $460 Million or 13% of the Silicon Market in 2013

We built models describing all known UMG-Si players and potential new entrants as a part of the polysilicon component of the overall solar market model described in Section 2 of this report. We also created best-case and worst-case scenarios, in addition to our most likely case projections, for UMG-Si, illustrating the range of potential outcomes as the technology advances. We found that (see Figure 4.1.6):

- **Today, UMG-Si is in its infancy, but scale-up plans are aggressive.** In 2008, we estimate approximately 1,880 MT of UMG-Si will be produced, which represents 7.2% of the polysilicon market for solar (see Figure 4.1.7). Of the 28 UMG-SI producers that we tracked, most have announced plans to add at least 1,000 MT of capacity by 2011, which would increase UMG-Si production to 10,400 MT.

- **In 2010, UMG-Si will enable 950 MW of production, just as the solar market tips into oversupply of polysilicon.** Early but varied success in UMG-Si adoption will nevertheless contribute to polysilicon oversupply in 2010, but the traction that it has gained will enable it to hold on even as silicon prices drop. Even if prices decline below $30/kg, the lower cost structure for UMG-Si means that producers can still be profitable. In 2010, UMG-Si will grow to a 6,380 MT market – 7.9% of the total market – enabling 950 MW of production.

Fig. 4.1.6: UMG-Si Production, Three Scenarios and Projected Revenue, 2006 to 2013

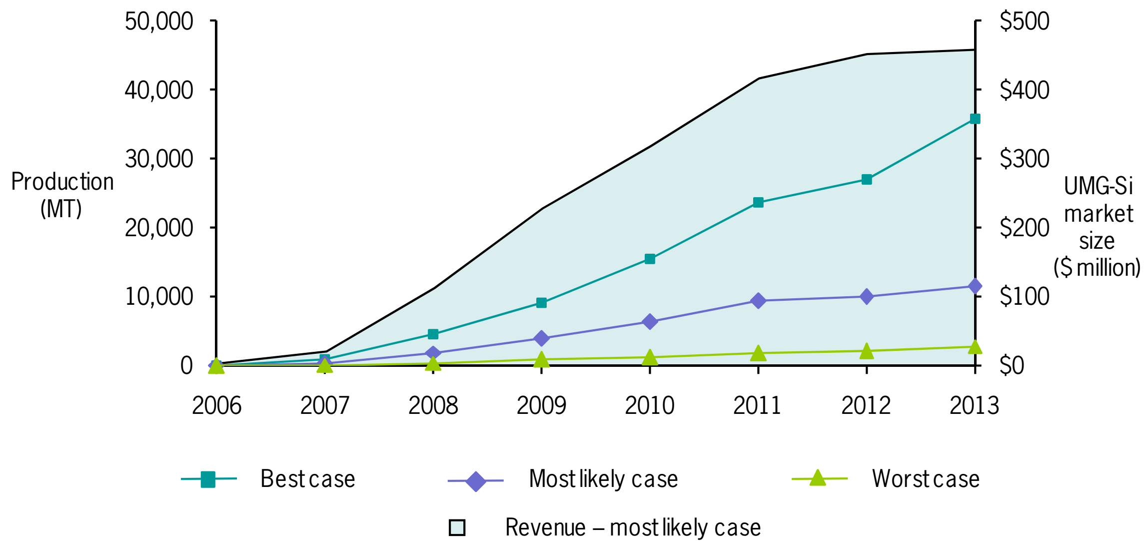
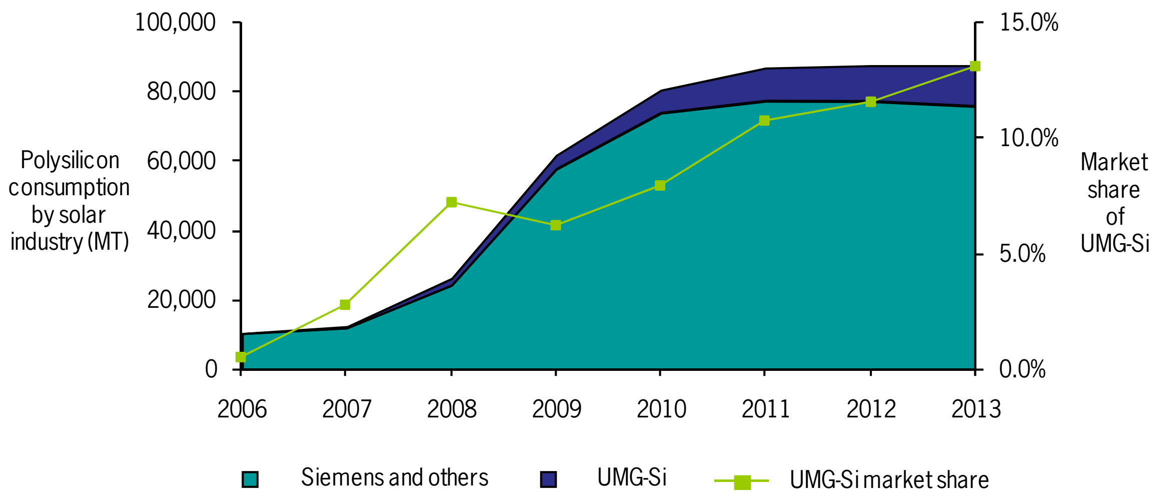


Fig. 4.1.7: Growth of UMG-Si and Share of the Solar Market for Polysilicon



- **From 2011 to 2013, UMG-Si will force weaker Siemens players from the field.** As more players understand how to adopt UMG-Si, UMG-Si will become a major commercial force in the crystalline silicon PV market. The result is that UMG-Si suppliers will increasingly drive high-cost Siemens polysilicon manufacturers, such as Chinese players Jiangsu Daquan, Sichuan Yongxiang Polysilicon, and Jiangsu Zhongneng, out of business – especially since many upstarts using the Siemens process will continue to struggle to reach purities of even 6Ns. By 2013, UMG-Si will account for 13% of the polysilicon usage in the solar industry, reaching 11,500 MT in production and $460 million in sales.

Implications

Based on our projections, expect that:

- **UMG-Si will help solar acquire its own value chain.** To date, the solar industry has relied for its most basic raw material on the leftovers from an industry with quite different cost structures and performance needs. EG-Si optimized for the semiconductor industry has fed solar producers even though the Siemens process has been tailor to produce silicon orders of magnitude more pure than needed for solar cells, with accompanying premium prices. In UMG-Si, crystalline silicon solar will find a material supply chain that's driven by the cost and performance specs that are more suited to solar applications.
- **UMG-Si adoption will drive further vertical integration at the ingot, wafer, and cell stages.** Since UMG-Si still requires very specific processing to be used successfully, it's not surprising that all of the major cell and module manufacturers developing UMG-Si products have become more vertically integrated in order to adopt the material – if they weren't already. By integrating the ingot to cell stages, these players reduce the unpredictable quality of the product from vendors, enabling a more consistent, controlled process that will allow them to tailor the UMG-Si feedstock to their capabilities. As leading players drive to market with UMG-Si enabled products, taking market share and undercutting prices from manufacturers using conventional polysilicon, expect fast-followers to follow suit – and to vertically integrate to do so, either through organic growth or aggressive M&A activity targeted at ingot and wafer producers.
- **The learning curve for UMG-Si will give significant first-mover advantages.** Since the knowledge and experience needed to use UMG-Si effectively is highly specialized, it will take at least a year for players currently getting into UMG-Si to catch up with those that have already mastered the tricks of the trade. As a result, companies that master UMG-Si can expect to enjoy a solid year of superior output and/or pricing over companies that start later. Of the cell/module makers, Q-Cells and Canadian Solar have aggressively adopted UMG-Si, with BP Solar, CaliSolar, and Photowatt not far behind and will likewise be significant players in the near term.
- **UMG-Si modules will predominantly find their way into utility-scale applications.** Due to slightly lower efficiencies today, UMG-Si will initially find use in utility-scale applications, which are less sensitive to efficiency but more sensitive to total cost per watt. The lower manufacturing cost and price with UMG-Si will enable crystalline silicon module manufacturers to compete in this space as new, lower-cost thin-film technologies from Applied Materials and Oerlikon are introduced into the market.
- **Siemens polysilicon will see continued use in monocrystalline modules for rooftop applications.** Though UMG-Si will be a disruptive force in polysilicon, it will not drive Siemens technology out the market. Siemens polysilicon will remain necessary for EG-Si for the semiconductor industry and for monocrystalline (c-Si) modules, which will continue to be the dominant solution for roof-mounted residential and commercial PV due to their higher

efficiencies. Incumbent players with strong ties to the semiconductor industry and strong relationships with c-Si cell producers, such as Wacker Chemie, Hemlock Semiconductor, MEMC, and Tokuyama, will remain largely unaffected by UMG-Si's entrance into the polysilicon market.

- **No new certification will be required for UMG-Si modules.** UMG-Si skeptics claim that over time, exposure to sunlight will lead to increasing boron and phosphorous concentrations, resulting in lower efficiencies. However, while it's true that the initial efficiencies of crystalline silicon modules will depend on boron and phosphorous levels, results so far indicate that fears of light-induced degradation are overblown for modules that are well-packaged. As a result, TUV, UL, or other agencies are unlikely to require additional certification time for UMG-Si-based modules – a boon for UMG-Si players, as it means one less regulatory obstacle to deal with.

Recommendations

As these dynamics play out in the UMG-Si market, we recommend that:

- **Cell manufacturers should work with external vendors to adopt UMG-Si.** With looming price erosion – starting at the module level and moving back through the supply chain – and the current polysilicon supply constraints, cell and module manufacturers should aggressively explore UMG-Si, if they are not doing so already. Many are answering the call: Even companies such as Yingli Green Energy and Suntech Power, which publicly claim that UMG-Si will never work, are quietly experimenting with the new materials in-house. However, with the pressure on and lead adopters coming to market, these players will need to collaborate closely with equipment manufacturers and materials providers, and potentially explore strategic acquisitions in order to speed development. Specifically, equipment suppliers such as ALD Vacuum Technologies and Singulus Technologies's subsidiary Stangl Semiconductor – which supplies Q-Cells – are at the cutting edge for enabling UMG-Si and are close to offering turn-key recipes for UMG-Si ingot and cell production, respectively.
- **Ingot and wafer manufacturers should secure relationships down- and upstream.** As polysilicon demand shifts away from Siemens-grade polysilicon to UMG-Si, ingot and wafer manufacturers are left in a bind. Since their product recipes have to be tailored for each vendor's feedstock, they are reluctant to take on the additional expense of modifying processes to adopt UMG-Si. However, if they ignore the industry trend, they will see their addressable market shrink as UMG-Si gains a stranglehold on the mc-Si market. Ingot and wafer manufacturers should square this circle by establishing technology partnerships with cell manufacturers in order to become a primary UMG-Si wafer supplier, ensuring any investment in UMG-Si pays off, and sharing the risk with their customers. They should also move quickly to develop strong relationships with UMG-Si producers that produce high purity silicon feedstock, to minimize the pain of the transition.
- **Installers should secure options early with UMG-Si module suppliers.** While modules remain scarce through 2009, installers and project developers should forge relationships with producers of UMG-Si enabled modules. These connections will enable them to fulfill demand and grow market share while taking a slight discount on modules, which are likely to see slightly lower

average selling prices due to lower efficiencies. Furthermore, a foray into UMG-Si modules would help to round out their portfolio of offerings and bridge the gap between higher efficiency modules made with EG-Si and thin-film offerings.

- **Investors should favor companies employing UMG-Si – but be more cautious with UMG-Si producers.** Cell producers that have announced firm plans to deploy UMG-Si in products are indicating that they have successfully sampled the broad portfolio of UMG-Si options in front of them and found at least one viable solution. The technical barriers to entry in UMG-Si mean that UMG-Si adopters will enjoy a limited period of higher margins, making them attractive for investors. However, investors should be cautious when valuing UMG-Si producers as the lack of a "drop-in" solution to date means that one successful supply contract will not necessarily lead to others, limiting short-term market share and tempering growth expectations.