About the Prometheus Institute

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Our Vision

Our goal is to accelerate the deployment of socially-beneficial sustainable technologies, including those of energy, water, and food, by educating industry participants, advocates, and policymakers about their advantages. We achieve our mission by collecting and disseminating reliable data, quantitative analysis, and practical information about these industries.

Today, the Institute strives to be the world’s leading source of publicly available primary data on the photovoltaic (PV) supply chain and end-markets through a series of data collection and outreach projects and the publication of the industry’s oldest newsletter, PVNews™. Currently, the Institute focuses solely on its initiatives in the solar energy industry.

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Cover photo courtesy of Renewable Energy Corporation.
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Prometheus Institute
Polysilicon: Supply, Demand, & Implications for the PV Industry
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This polysilicon supply report is the first of a series of comprehensive reports from the Prometheus Institute that delves deeply into the various links in the photovoltaic (PV) supply chain. These reports meet our mandate to provide comprehensive industry information and analyses in order to accelerate the deployment of sustainable technologies such as solar electricity. We believe that delivering good data and information about the industry’s stages of production and its prospects for growth will help industry stakeholders, users, and policy makers make the best decisions about how and where to increase the use of PV.

Given the amount of industry speculation this year about silicon supply, a comprehensive review of this vital feedstock is timely. With raw material prices rising and rumors of idle cell production capacity, silicon has become the bottleneck for the growth of the PV industry. In 2005, nearly 95% of the cells produced used silicon-based technologies, and long lead times to deploy new production plants mean bottlenecks will persist, slowing the industry’s growth rate, historically in excess of 30% per annum. Thin films, while promising, will not increase their market share fast enough to keep the PV industry from relying almost entirely on the polysilicon supply through 2010. Understanding the supply of silicon, therefore, is essential to understanding the prospects for the PV industry as a whole.

In this report, look at all of the factors that affect the availability of this feedstock for the PV industry. We survey seven major polysilicon producers and nearly 20 emerging producers (a third of them in China), and we project production capacity through 2010 under a variety of scenarios. In so doing, we determine that the current silicon supply shortage will begin to ease by 2008, and that there will be enough silicon to allow the PV industry to grow to eight GW per year by 2010.

We also look at various technological approaches to refining silicon, different methods of increasing efficiency of silicon use, and dynamics shaping the industry. What emerges is a view of a stable base of producers that is currently enjoying increased pricing power and profitability. Meanwhile, however, many new players have been attracted to silicon manufacturing. These newcomers threaten to erode the market share of established producers and perhaps even to flood the market by the end of this decade. While much new capacity is planned and outcomes are uncertain, what is certain is that polysilicon supply is in for a dynamic transformation in technology, industry structure, pricing, and margins over the next four years.

I want to thank all the staff, advisors, and company representatives who helped put this report together. Much thought and work went into creating this report, and many people provided data, insight, and suggestions for improvement. However, this report, like all the research of our Institute, remains a work in process. It is vital to us and to the mission we serve that we continue to improve the information and analysis we provide to our readers. Please help us to make this report better by sending your comments, corrections, and suggestions. They are always welcome.
In 1954, Bell Labs created the first silicon solar cell. Prior to that, solar cells were made of selenium, and not particularly productive, with a 0.5 percent sunlight-to-electricity conversion efficiency (sometimes referred to simply as “cell efficiency”). Silicon-based cells on the other hand achieved six percent conversion efficiency in the early years. Today, some companies report cell efficiencies of 20 percent or more.

While solar cell semiconductors can be made from various compounds, including silicon, cadmium telluride, copper indium diselenide, etc., the easily transferable developments in silicon technology from the electronics industry and the long history of silicon-based semiconductors make silicon by far the most popular material for solar cells. Currently, over 90 percent of the global PV production is silicon wafer-based. Until recently, solar cell manufacturers could obtain sufficient silicon feedstock supply in the form of off-spec and waste material from the electronics industry. This lower quality material was sold at half the price of high quality material. With the strong growth of the PV industry in 2003, 2004, and 2005, the demand for silicon for PV cells has exceeded the amount available through traditional supply channels and has led to industry-wide material shortages and rising silicon feedstock prices.

The PV industry has grown 40 percent per annum, on average, over the last decade. The semiconductor industry, on the other hand, has a cyclical demand pattern. In the semiconductor bust of 2001, polysilicon producers found themselves with significant overcapacity, making them until recently reluctant to increase capacity to meet aggressive growth predictions from the PV industry. In the past few months, most of the seven major polysilicon suppliers worldwide have announced new capacity expansion plans in response to the growing demand from the PV industry. In addition, numerous companies outside of these veteran producers have announced plans to produce silicon using existing and new methods of silicon production.

Polysilicon production is a capital-intensive and highly technical business that requires large amounts of electricity for melting and purification. It is not surprising then, that more than 50 percent of the polysilicon production in the world occurs in the United States which has a highly-trained labor force and relatively low energy costs. The rest of the worldwide production also occurs in technology-oriented countries, including Japan (24 percent) and Germany (18 percent). In the next few years, the industry is projected to see capacity added in countries like Norway, China, Spain, and Korea. Even as polysilicon capacity becomes more distributed throughout the world, however, the United States is expected to continue to be the top producing country through 2010.
The existing polysilicon producers traditionally catered to the electronics industry, with the majority of their product being sold for integrated circuits. We expect 2006 to mark a transition in polysilicon consumption, with the majority of the world’s polysilicon henceforth consumed by the PV industry. Most of the existing polysilicon producers are now responding to the growing PV demand by adding capacity, and a number of new companies will cater to the solar industry. Some of these companies are even developing technology to produce silicon specifically for the PV industry with appropriate purity levels and lower costs.

These new polysilicon producers fall into three groups. The first group is companies that already produce the silicon feedstock used to make polysilicon (e.g. Elkem, DC Chemical, and Degussa). The next group consists of companies that are in the solar industry and looking to become more integrated along the supply chain (e.g. GiraSolar, SolarWorld, and ARISE). The third group of companies is completely new to both silicon processing and PV manufacturing (e.g. Hoku). We believe companies that already have experience in silicon processing upstream of polysilicon production will be the most successful entrants to the market.

Table 1 illustrates the spate of new capacity expansion announcements since April, 2006. We sorted these companies into three categories: existing producers; new producers using existing technology; and new companies using new technology. Existing technology, as we will explain in more detail in Section 2, includes the Siemens process and the fluidized bed reactor (FBR) process. Siemens is the industry standard, but a few companies are involved with FBR-based production. The newer technologies being developed (which have been researched for decades but not yet brought to commercial scale production) are more focused on a solar grade, or lower quality and thus cheaper, silicon product. This is achieved by modifying and simplifying the refining process.

The advantages of building capacity based on the traditional Siemens reactors include the transparency and low risk of using a well-established and well-understood process. The Siemens process was used to produce over 90 percent of polysilicon in 2005. For producers using this established technology, there is little risk of patent infringement and it is comparatively easy to build the production facility. The newer technology of FBR has higher intellectual property concerns and technology risks, but is being deployed by a few credible producers today. Both of these technologies share the advantage that they produce silicon pure enough to be used in both PV and IC applications. However, the ability to dramatically cost-engineer these technologies and reduce the polysilicon prices for cell manufacturers is limited. A cheaper alternative would be to build capacity strictly for the PV industry, the costs of which are targeted to be half of what Siemens or FBR costs are.

The majority of new production recently announced will be undertaken by new companies using existing technology. Approximately 36,000 MT of new capacity falls into this category. The most interesting information in Table 1 is the amount of capacity under development using new technology. At the end of the day, this is where PV could ultimately reduce cost per watt, which is crucial for the industry to stimulate long-term demand.
The combination of new production by existing suppliers, new entrants, and cell producers engineering their products to use existing silicon feedstock more efficiently, will ensure that the PV industry can continue its historic trends of market growth and price reductions. This polysilicon report will explore each of these trends in detail and then look at how they will collectively affect the market through 2010.

In the next section, we explore the different silicon production technologies as well as the process of making a solar cell through ingot and wafer manufacturing.

3. We have not accounted for China’s entire 20,000 MT here because some of the companies in the article were already known to be in the construction or planning phases of polysilicon production.
2.1 Solar Grade vs. Electronic Grade

Silicon is the second most abundant element in the earth’s crust. In nature, it is found as an oxide (in the form of sand and quartz) and as a silicate (in the form of granite, clay, and mica). Silicon is sold in a range of purity levels, or grades. For silicon to be a useful semiconductor material, it must be highly purified. For solar cells, the silicon must be 99.9999 percent pure (often referred to as “six nines” or 6N pure). The silicon grade used in electronics is even more pure, typically 9N to 11N. The type of impurities also makes a difference. While carbon and oxygen are less significant, boron and phosphorus concentrations must be managed since they are important in the electrical functioning of a cell.

For silicon to reach semiconductor grade, whether for solar cells (i.e. solar grade, SoG) or integrated circuits (electronic grade, EG) it must undergo a significant amount of processing. Silicon that is purified for the semiconductor industry is referred to as polycrystalline silicon, or polysilicon (poly-Si, or poly). Silicon used in solar cells has historically come from off-spec and waste silicon, produced either during the polysilicon purification process or during ingot and wafer production.

But this is no longer the only source of polysilicon for the PV industry. As demand increases, solar companies are increasingly buying higher quality silicon. An industry rule of thumb is that 10 percent of the polysilicon sold to the semiconductor industry will eventually become available to the solar industry. However, polysilicon producers are now producing silicon specifically for PV companies. In addition, new technologies are being developed to produce silicon that caters to the needs of the PV industry.

2.2 From Silica to Metallurgical Silicon

Silicon used in the semiconductor and PV industry must go through several steps before it is a practicable feedstock. Figure 4 illustrates one route from silica mining to the solar module or integrated circuit using the Siemens purification process. This section will describe the process from mining to metallurgical silicon (referred to as metallic silicon in the figure). The next section will discuss the routes for further purification.
The first step in polysilicon production is the extraction of quartz from a silica mine. The quartz is then put into a furnace with a carbon source—a mixture of coal with coke, woodchips, or charcoal. The mixture is then heated and the silicon reduced in a process called Carbothermic Reduction. This produces liquid silicon, carbon dioxide, and silica fumes. The silica fumes are used for other industrial processes, while the liquid silicon is poured out of the furnace. The liquid is further refined, then allowed to solidify. The resulting silicon material is referred to as metallurgical silicon, or metal silicon (MG-Si). Producers then crush the MG-Si before it is sold. The purity level at this stage is 96-99 percent, with an average purity of 98.5 percent. The cost of MG-Si is relatively low, estimated to be around $0.77/lb or $1.70/kg.

Global MG-Si production in 2005 was 148,000 MT. Approximately half the MG-Si produced in a year is used by the aluminum industry; the other half is used in various chemical processes. MG-Si is not pure enough for use in integrated circuits or PV cells; further refining is necessary.

There are several ways in which MG-Si can be refined. We will describe these processing options below.

### 2.3 Metallurgical Silicon Processing

The majority of polysilicon used by the semiconductor and PV industry is produced via a process of chemical deposition, whereby a chlorosilane gas is deposited onto a heated rod. The first step is to react HCl with MG-Si. This forms a liquid that is distilled and then vaporized. The resulting gas is then deposited onto heated silicon rods (1100°). The earliest process, named after the company that developed the process (Siemens), uses trichlorosilane gas (TCS) as the deposition material. TCS (HSiCl₃) has many advantages, including a high deposition rate and high volatility (which makes it easier to remove two compounds that are problematic in solar cells, boron and phosphorous). One of the disadvantages of using TCS is the high electricity requirement to maintain process temperatures.

Another process further refines TCS to produce monosilane (SiH₄). This gaseous monosilane is then deposited on heated silicon rods. Monosilane is a higher purity starting material which leads to more pure polysilicon. This higher purity also makes it more expensive to produce. This process was developed by Union Carbide in the 1970’s through research funding from the US government.
Polysilicon: Supply, Demand, & Implications for the PV Industry

SECTION 2

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Polysilicon Processing

To produce solar grade silicon. The funding was then rescinded and the company’s focus shifted from PV to the semiconductor industry. The company has changed hands several times, but is now owned by Renewable Energy Corporation which has converted it back to a strictly solar grade silicon producer.

The final product of the above two processes is a rod of polysilicon that is broken up into smaller pieces; at this point the product is called “chunk polysilicon”.

A third process for polysilicon production uses a fluidized bed reactor with a final product of granular silicon.

Ethyl Corporation developed the FBR process for polysilicon production. The company used silicon fluoride instead of MG-Si, which is converted to monosilane, and then the silicon seed is dropped into the reactor while the silane and hydrogen gases pass through. The theoretical advantages of this process are lower capital and electricity costs than Siemens reactors. To date, however, only a couple of producers have established FBR capabilities, so the production economics are still unclear. Ethyl Corporation’s FBR business unit was eventually sold to Albemarle Corporation, which was in turn bought by MEMC. Renewable Energy Corporation has also announced new FBR capacity under construction. Depending on a company’s wafering process, granular polysilicon may be preferred over chunk polysilicon.

A fourth and still experimental polysilicon technology is Tokuyama’s “Vapor-to-Liquid Deposition” (VLD) process. As figure 10 shows, this process uses TCS as does Siemens, but the reactor is a tube in which liquid silicon forms. The silicon product could thereby be produced faster than through the Siemens process. The company’s focus is on making a low cost product that would be suitable for solar use. Based on results from the semi-commercial plant (200 MT), Tokuyama believes it can provide a cheaper feedstock material to the industry and is in the design phase of a large scale operation.

The polysilicon industry, regardless of the technology, requires a significant amount of capital, large amounts of electricity and a...
highly trained labor force. As a general rule, it costs $100/kg to build a polysilicon facility. For comparison purposes, a 5,000 MT plant would cost $500 million to build and could produce enough silicon for 450 MW of annual PV cell production at today’s average efficiency rates. Assumed capital recovery plus operating cost for this means that the cost of silicon is at least $0.60 to $0.75 per watt, or 15 to 18 percent of the entire cost of today’s solar modules (average of $3.50 per watt). If the industry wants to bring average costs for modules down to $2.00 per watt, a level widely thought to be economically transformative in global markets, additional cost reductions in silicon processing will be required.

In an attempt to lower silicon production costs, as well as to ensure feedstock is available to the PV industry, methods dedicated specifically to solar grade silicon have been under development. This research includes variations on existing purification processes, as well as completely novel processes. To date, minimal amounts of product have resulted from this research, though many companies have promised product over the next few years.

**Upgraded Metallurgical Silicon**

Upgrading the metallurgical silicon process could be a cost effective way to produce silicon for the PV industry.

Companies such as Dow Corning, Elkem, and others are pursuing this route of SoG silicon manufacturing. The process involves a series of refining steps and the employment of directional solidification (described in more detail in section 2.4). While this route offers the promise of lower costs than the Siemens process, product quality remains an issue. To date, only Dow Corning is commercially producing SoG from MG-Si, though the quality is not high enough for the product to be used on its own; it must be blended with purer silicon. Elkem has not brought its technology to commercial scale, though it has ambitious plans to do so by 2008.

**2.4 Silicon Ingots: Monocrystalline vs. Multicrystalline**

Wafer and cell producers receive the silicon in chunk or granular form but then need to shape it into a form that can be sliced. The shape can be an ingot, block, ribbon, or sheet. The product can also be monocrystalline (single crystal) or multicrystalline (polycrystalline). The Czochralski (CZ) and float zone methods produce monocrystalline ingots, while directional solidification/casting, ribbon, and sheet techniques produce multicrystalline structures.
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Polysilicon Processing

SECTION 2

CZ Method

Czochralski crystal growing starts with melting the silicon in a crucible. Then a rod with a silicon seed is dipped into the molten silicon and as it is drawn up, a monocrystalline silicon crystal is grown on the seed crystal. Figure 12 illustrates the concept of CZ pulling. In 2005, monocrystalline wafers made from CZ wafers accounted for 35 percent of global production. CZ pulling takes a significant amount of time and is more expensive than the other methods, but the resulting cells have some of the highest conversion efficiencies in the industry.

Float Zone

Float zone ingot formation is used for producing even more pure wafers. A float zone ingot has fewer impurities than a CZ ingot; it is particularly lower in oxygen which can decrease the efficiency of a cell. As with CZ crystal pulling, a seed crystal is exposed to molten silicon. But instead of being dipped into a crucible with a silicon melt, a heating coil passes along an ingot, effectively separating the newly crystallized monocrystalline ingot from the input silicon. Crystallization occurs between the solid and molten regions referred to as the "float zone" (figure 13).

Directional Solidification/Casting

Multicrystalline blocks are formed via casting or directional solidification. While this process takes less time than monocrystalline production, efficiencies are lower due to the variable silicon crystal sizes, dislocations, and impurities. Casting can take place in the crucible in which the silicon is melted or the silicon can be poured into a second crucible.

With directional solidification, the silicon remains in the crucible after heating. Once the silicon is melted the entire crucible is moved down, away from the heating element and the silicon solidifies as it cools. Figure 14 shows the process of casting.

Ribbon/Sheet

Two methods have been developed to reduce the amount of slicing, and thus waste, associated with the above methods. The first, String Ribbon technology, is a proprietary technology employed exclusively by Evergreen Solar. A crucible melts the silicon, and then two ribbons of silicon are pulled up out of the crucible. Once the ribbons are slightly less than two meters long, they are removed and sliced into wafers.

A second method is Edge-defined Film Fed Growth (EFG), developed and exclusively employed by SCHOTT Solar. An octagonal hollow tube is pulled up from a silicon melt. Once it reaches six meters, the tube is removed from the machine and sliced into wafers with a laser.

Crystal Growing Systems (CGS) and SCHOTT recently succeeded in improving the Edge Defined Film Fed Growth (EFG) process for wafer production. Previously, SCHOTT employed octagonal EFG process, which
produces eight-sided tubes of silicon that are then separated with a laser. The two companies developed a process for 12-sided (dodecagonal) tubes. While the increase in silicon pulled obviously has productivity benefits, the thickness of the 12-sided tubes is also reportedly more homogeneous. Both factors could offer significant cost advantages over current methods.

### 2.5 Wafering

Ingots, blocks, ribbons and sheets of silicon are sliced into wafers prior to cell manufacturing. Wafer-based PV is the predominant cell type produced: 94 percent of PV production in 2005 was based on silicon wafers. The wafering process wastes a significant amount of silicon. Wire saws are used to slice the wafers from ingots and blocks. Wafers are typically in the range of 200 – 300 µm thick. The wires destroy 220 – 230 µm of silicon as they slice though the block. Wire saw performance is improving, and new techniques are under investigation to reduce waste. Lasers are an option, though there the heat from the laser slicing through the ingot causes the outer silicon to degrade.

In 2005, it took an average of 12 grams of silicon to produce one watt of PV, including silicon lost in the wafering process. This requirement should decrease over the next few years to 9 g Si/W or less. (We perform sensitivity tests in our projections to account for greater advances in silicon use per watt. See section 6.) In order to achieve targeted improvements in grams per Watt, three methods are being pursued:

- First, sawing thinner wafers may help to reduce silicon use, though sawing losses will persist. A silicon requirement of 6 g Si/w or less is theoretically achievable, but cells this thin also increase breakage concerns for wafers in sawing and material handling.
- Second, the ribbon and sheet methods of wafering significantly reduce waste. Evergreen Solar’s wafers reportedly use 6 g Si/w today, with no material lost from wire slicing.
- Finally, efficiency improvements in cell manufacturing can reduce grams per Watt through more power from the same chip. This method has been effectively pursued by SunPower, whose 20 percent to 21.5 percent efficient cells reportedly only use 8 g/W.

Each of these will help to improve the efficiency of silicon use in PV. But to meet the dynamic growth projections of the industry and the current global demand, significant new production capacity will be required. The next section looks at the current polysilicon producers and their plans to expand capacity through 2010.
This section relied on several sources: PV handbook, Elkem’s website, http://www.wafernet.com/PresWK/h-pbl-as3_vsc_siltronic_com_pages_training_pages_Silicon_TCS-1.htm; http://www.udel.edu/igert/pvcdrom/; and personal communication with Dr. Giso Hahn of the University of Konstanz


3 EERE Solar Energies Technologies Program www1.eere.energy.gov/

4 http://minerals.usgs.gov/minerals/pubs/commodity/silicon/silicmcs06.pdf/


6 http://www.tokuyama.co.jp/eng/news/release/pdf/2004/20040908_silicon_e.pdf#search=%22tokuyama%20vapor%20to%20liquid%20deposition%22

7 Oda, Hiroyuki, Tokuyama VLD at a Glance, 3rd Solar Silicon Conference, April 2006, Munich, Germany
For the purposes of this report, we consider production capacity to be equal to the amount of polysilicon a company will produce in any given year. This number is a base estimate, however, as the amount can be increased five to ten percent depending on the desired quality of the product and improvements over time of the manufacturing process (such as de-bottlenecking). For example, a lower quality silicon destined for a solar company could be produced faster than higher quality material, which would allow for more to be produced in any given time frame. It is possible that some companies have reported theoretical capacities that are not physically achievable, but we have attempted to standardize with actual production capacities throughout this report.

3.1 PI Research Methodology

This section provides polysilicon production capacity in 2005, with projections to 2010. The Prometheus Institute for Sustainable Development, in preparing this report, obtained information from each polysilicon company concerning its current and projected production capacity at each of its facilities. We also asked several general questions that are presented in aggregated form. In almost all cases company representatives provided production data. For the few companies whose representatives were unable to comment, we used company press releases and websites to gather the needed data. The research also included surveying cell producers for their assessment of the silicon supply situation, as well as reviewing previously published reports on global silicon supply.

In April of 2006, Solar Verlag GmbH hosted the 3rd Solar Silicon Conference in Munich, Germany. Over 700 people, including silicon producers, ingot and wafer producers, cell manufacturers, and solar researchers, attended this one-day event. Industry analysts, polysilicon companies and research institutes gave presentations and took questions from the audience. We attended this event and obtained information not previously available. We also attended the Semiconductor Equipment and Materials International’s SEMI Europa event in Munich that week, where solar equipment and cell companies discussed the issues their companies were facing.

3.2 History of Polysilicon Production and Prices

Before we discuss current and future polysilicon capacity, we will briefly mention the capacity and price environment in the years leading up to the current shortage.

In 2000, polysilicon production was an estimated 24,000 MT. Around this time, demand for polysilicon from the semiconductor industry dropped, leaving the polysilicon producers with excess capacity. As figure 18 shows, very little capacity was added from 2000 to 2005.
### 3.3 2005 Polysilicon Production Capacity

In 2005, the global capacity for polysilicon production was 31,280 MT\(^1\). There are seven companies that dominate the polysilicon supply: Hemlock, Wacker, Renewable Energy Corporation, Tokuyama, MEMC, Mitsubishi, and Sumitomo Titanium Corporation. Hemlock, located in the US, is the largest of the polysilicon companies with a production capacity in 2005 of 7,700 metric tons (MT). It was followed by Wacker (5,500 MT), Renewable Energy Corporation (5,300 MT), Tokuyama (5,200 MT), MEMC (3,800 MT), Mitsubishi (2,850 MT), and Sumitomo (800 MT). There was a small amount (130 MT) supplied by two companies in China. Each of these companies is discussed in greater detail in section 3.4, except for the Chinese companies, discussed in greater detail in Section 4.1.

Polysilicon capacity has not increased significantly over the last five years due to production overcapacity that resulted from a downturn in the semiconductor demand versus the growth forecast. In 2000, polysilicon manufacturers report that there were approximately 24,000 MT of capacity worldwide.\(^2\) From 2000 and 2004, capacity expansions across all producers were very modest, on the order of 1,000 MT per year or less. Between 2004 and 2005 there was a jump in capacity of 3,000 to 4,000 MT to bring capacity above 30,000 MT.

### 3.4 Polysilicon Producer Profiles

Table 2 provides a list of the silicon producers in 2005, with 2005 actual capacity and 2010 projected capacity. The technology each company uses for polysilicon production is also listed. In the 2010 production column, we give two estimates, projected and potential capacity. In an effort to give a realistic idea of future capacity we evaluated each capacity expansion plan based on four criteria. Projects that met these criteria were considered likely to occur and thus included in the projected capacity. Potential capacity includes projects that do not meet these criteria and thus are unlikely to occur. The criteria were used were:

1. Is the company reputable in the solar or silicon space?
2. Has a technology been chosen and provided?
3. Is a funding source identified?
4. Has a timeline for project construction been provided?
In a few rare cases a project did not meet all of these criteria, but it was our opinion that the project would be completed and thus was included in the projected capacity. As table 2 shows, we believe existing producers will achieve the production capacities they announced.

The annual estimates produced throughout include not only partial year results, but ramp up periods as appropriate. We believe that additional positive news (such as marginal productivity improvements) and negative news (construction delays and reductions of new plant sizes) will likely occur, but these projections reflect our best estimates of the future capacity at this time.

### Table 2: Silicon producer capacity in 2005, projected and potential in 2010, and technology employed (* unconfirmed, assumed technology)

<table>
<thead>
<tr>
<th>Company</th>
<th>2005 Production Capacity (MT)</th>
<th>2010 Production capacity (MT) (projected/potential)</th>
<th>Technology (Siemens, FBR, VLD, MG to SoG)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hemlock</td>
<td>7,700</td>
<td>19,000/---</td>
<td>Siemens</td>
</tr>
<tr>
<td>Wacker</td>
<td>5,500</td>
<td>14,500/---</td>
<td>Siemens/FBR (trial)</td>
</tr>
<tr>
<td>REC</td>
<td>5,300</td>
<td>13,500/---</td>
<td>Siemens/FBR</td>
</tr>
<tr>
<td>Tokuyama</td>
<td>5,200</td>
<td>5,400/---</td>
<td>Siemens/VLD (trial)</td>
</tr>
<tr>
<td>MEMC</td>
<td>3,800</td>
<td>8,000/---</td>
<td>FBR/Siemens</td>
</tr>
<tr>
<td>Mitsubishi</td>
<td>2,850</td>
<td>3,150/---</td>
<td>Siemens</td>
</tr>
<tr>
<td>Sumitomo</td>
<td>800</td>
<td>1,300/---</td>
<td>Siemens</td>
</tr>
<tr>
<td>Total China</td>
<td>130</td>
<td>7,300/---</td>
<td>Siemens*</td>
</tr>
<tr>
<td>Total</td>
<td>31,280</td>
<td>72,150/---</td>
<td></td>
</tr>
</tbody>
</table>

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**Hemlock**

After producing polysilicon for several years, Dow Corning formed Hemlock Semiconductor Corporation, located in Hemlock, Michigan, as a wholly-owned subsidiary. In 1984 Hemlock became a joint venture between three companies, Dow Corning (63 percent ownership), Shin-Etsu Handotai Co., Ltd. (25 percent) and Mitsubishi Materials Corporation (12 percent). Hemlock rapidly increased production capacity, and by 1994 it became the largest polysilicon supplier in the world. Hemlock is still the largest polysilicon producer, and will likely continue to be through 2010 based on stated and likely capacity additions.

Hemlock uses Siemens reactors and trichlorosilane gas to produce chunk polysilicon at two plants. The company has expressed an interest in developing granular polysilicon depending on the market. Hemlock’s raw materials come from one of Hemlock’s parent companies, Dow Corning, which has silicon mining and processing operations in South America and the United States.
In 2005, the company reported a production of 7,700 MT. It will increase production to 10,000 MT in 2006, with an investment of $400-$500 million. By 2008 the company will have 14,500 MT of capacity and by 2009, 19,000 MT. Hemlock is expanding capacity at its Michigan facility, but is contemplating other locations for some of the additional capacity. One news report quoted a company representative as discounting Taiwan as a potential location due to political uncertainty. A location in Asia might be attractive to the company, considering the huge market potential there for solar energy and the fact that of Hemlock’s current production is exclusively in the United States. Approximately 40 percent of Hemlock’s customers in 2005 were from the PV industry.

<table>
<thead>
<tr>
<th>Year</th>
<th>Capacity (MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>7,700</td>
</tr>
<tr>
<td>2006</td>
<td>10,000</td>
</tr>
<tr>
<td>2007</td>
<td>10,000</td>
</tr>
<tr>
<td>2008</td>
<td>14,500</td>
</tr>
<tr>
<td>2009</td>
<td>19,000</td>
</tr>
<tr>
<td>2010</td>
<td>19,000</td>
</tr>
</tbody>
</table>

### Wacker

At the turn of the 20th century, Dr. Alexander Wacker founded “Dr. Alexander Wacker Gesellschaft für elektrochemische Industrie KG” in Traunstein, Germany. This consortium moved to Munich two years later and started Wacker-Chemie GmbH.

In 1916, the Burghausen facility, now the company’s largest production plant, came online. With several hundred employees, the operation produced acetaldehyde, acetone, and acetic acid. Wacker now has five business segments: semiconductors (Siltronic), silicones, polymers, fine chemicals, and polysilicon. The company has 20 production plants, 14,400 employees, and over 100 Wacker sales offices worldwide.

The polysilicon segment of Wacker experienced a 12 percent increase in sales in 2005 over 2004, slightly higher than the overall company sales growth. In 2005 polysilicon sales reached €288.1 million. The company credits the booming PV market as the main reason for its increase in polysilicon sales. Wacker also disclosed that its facility ran at full capacity in 2005. Though the company did not disclose how much polysilicon it had in inventory from the previous year, it did indicate that its stock helped the company meet some of the 2005 demand.

Wacker’s polysilicon production capacity was 5,500 MT in 2005. It will expand capacity to 6,500 MT in 2007. Wacker originally announced expanding capacity to 9,000 MT by 2009, but has since revised that estimate to 10,000 MT. A company representative attributes this extra capacity to progress the company expects to make in de-bottlenecking the production process. Wacker will add another 4,500 MT by 2010. Like Hemlock, 40 percent of Wacker’s polysilicon was sold to the solar industry.

<table>
<thead>
<tr>
<th>Year</th>
<th>Capacity (MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>5,500</td>
</tr>
<tr>
<td>2006</td>
<td>5,500</td>
</tr>
<tr>
<td>2007</td>
<td>6,500</td>
</tr>
<tr>
<td>2008</td>
<td>10,000</td>
</tr>
<tr>
<td>2009</td>
<td>10,000</td>
</tr>
<tr>
<td>2010</td>
<td>14,500</td>
</tr>
</tbody>
</table>
Polysilicon: Supply, Demand, & Implications for the PV Industry

SECTION 3

REC

Renewable Energy Corporation, with headquarters in Norway, was first incorporated as a private company in 1996 with a mission to invest in renewables. The company is now one of the few fully-integrated PV companies in the world, with full or part ownership of subsidiaries throughout the PV supply chain. The company has a polysilicon division, REC Silicon; an ingot division, REC SiTech; a wafering division, ScanWafer; a cell division, ScanCell; a module division, ScanModule; and an integrator/distributor division (for installations in developing countries), Solar Vision. REC also has a 23 percent stake in CSG Solar and a 33.3 percent stake in EverQ. In May of 2006, REC listed on the Oslo Stock Exchange.

Union Carbide Corp started a polysilicon business in Moses Lake, WA in 1984. Initial production was 1,000 MT/yr, expanded to 1,400 MT of capacity in 1987. This was followed by another expansion to 2,100 MT in 1996. Komatsu bought the facility in 1990, changing the name to Advanced Silicon Materials Inc (ASiMi). In 2002, REC and ASiMi entered into a joint venture, converting the company to the first silicon producer dedicated to the solar industry and changing its name to Solar Grade Silicon LLC. REC assumed full ownership of SGS in 2005. SGS uses the Siemens process and TCS to produce polysilicon, which the company reports to be 99.999999 percent (8N) pure.

In 2005, REC purchased a polysilicon plant in Butte, MT, formerly owned by Advanced Silicon Materials Inc. This facility uses monosilane gas to produce polysilicon in a Siemens reactor.

REC has been running a fluidized bed reactor which it is now ready to bring to commercial scale. On May 23, 2006, the company approved a plan to invest $600 million for the construction of a 6,500 MT FBR plant on the Moses Lake site. REC signed a contract with the Fluor Corporation to build the new plant in June and celebrated groundbreaking of the project in mid-August.

REC produced 5,300 MT in 2005, 2,500 MT of which was solar grade. The 6,500 MT FBR plant will be online in 2008, and fully operational in 2009. With this additional capacity and de-bottlenecking at existing facilities, REC will have over 13,000 MT of capacity by 2010. The company believes that it supplies 20-25 percent of polysilicon used by the PV industry.

<table>
<thead>
<tr>
<th>REC</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (MT)</td>
<td>5,300</td>
<td>5,800</td>
<td>5,800</td>
<td>10,250</td>
<td>13,500</td>
<td>13,500</td>
</tr>
</tbody>
</table>

REC supplies Evergreen and EverQ with polysilicon. REC's vision is “to become the most cost-efficient solar energy company in the world, with a presence throughout the value chain.” The company has a target to reduce costs (per watt of module produced) by 50 percent by 2010.
SECTION 3

Polysilicon Production Capacity —Historical Production and Major Players

Tokuyama

Tokuyama was started in 1918 under the name Nihon Soda Co. Ltd., which was changed to Tokuyama Soda Co., Ltd in 1939. The focus of the company was soda ash until 1938, when it moved into the cement business.

Over the years, the company has expanded operations into three business segments (chemicals, building materials, and specialty products) that serve various industries. Tokuyama has offices and factories throughout Japan, as well as offices in the United States (California), Germany (Düsseldorf), Singapore, etc. In its 2005 annual report, Tokuyama identified the silicon component of their business as having the most potential for growth and profitability in the future.

In September 2004, Tokuyama announced its plans to expand production of polycrystalline silicon. Citing the growth in solar energy, in addition to the rebounding semiconductor industry, as the reasons for dwindling inventory, the company increased capacity from 4,800 MT to 5,200 MT at its Higashi plant. They also have plans for a 200 MT verification plant for vapor-to-liquid deposition (VLD). VLD technology allows for faster production and produces a product more appropriate for PV applications (quality is inferior for semiconductor applications).

Construction of the new VLD plant was initiated in February 2005. The Tokuyama Factory is expected to start shipping polycrystalline silicon in 2006. The New Energy and Industrial Technology Development Organization (NEDO) in Japan offered funding for the verification plant. If successful, a commercial plant should be operational by 2008. The company believes VLD could put it in position to become the world’s second largest supplier of polycrystalline silicon. However, when contacted, the company declined to provide estimates for production capacity aside from existing and pilot-scale capacity. Evidently the company is still trying to perfect the VLD process, and will need to make significant progress before it can bring VLD to commercial-scale.

MEMC

MEMC (Monsanto Electronic Materials Company) was founded in 1959 in St. Peters, Missouri as a division of Monsanto Chemical Company. The focus of the company was to produce silicon wafers (19mm diameter) for the transistor and rectifier industries. Today, the target markets for the company’s silicon wafers are the electronics and PV industries.

The German company Hüls, AG (a VEBA AG subsidiary) assumed ownership of MEMC in 1989, and then consolidated the company with an Italian company, Dynamit Nobel Silicon Holdings. The consolidated company was renamed MEMC Electronics Materials, Incorporated.
MEMC produces polysilicon feedstock usable in PV cells at two factories, one in Pasadena, Texas and the other in Merano, Italy. MEMC is the only company producing granular polysilicon at industrial scale, though both Renewable Energy Corporation (REC) and Wacker have pilot plants producing this form of purified silicon. Some cell companies prefer granular polysilicon, including Evergreen Solar for its String Ribbon technology. This puts MEMC at a competitive advantage for this product, for now. MEMC also produces chunk polysilicon.

Annual polysilicon production capacity at MEMC was 3,800 MT in 2005, or 12 percent of the global total. The Merano plant’s capacity was 1,100 MT in 2005, while the Pasadena plant’s capacity was 2,700 MT. This is expected to remain flat for 2006. In 2007, however, the capacity at the Merano Italy plant will grow to 1,600 MT for a company-wide total of 4,300 MT annual production capacity. By 2008, MEMC plans to almost double its annual production capacity to 8,000 MT between the two existing plants. The company may also build a third plant; the proposed location has not yet been announced.

### MEMC

<table>
<thead>
<tr>
<th>Year</th>
<th>Capacity (MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>3,800</td>
</tr>
<tr>
<td>2006</td>
<td>3,800</td>
</tr>
<tr>
<td>2007</td>
<td>4,300</td>
</tr>
<tr>
<td>2008</td>
<td>8,000</td>
</tr>
<tr>
<td>2009</td>
<td>8,000</td>
</tr>
<tr>
<td>2010</td>
<td>8,000</td>
</tr>
</tbody>
</table>

### Mitsubishi

Mitsubishi Materials Corporation holds 100 percent ownership of two polysilicon companies, Mitsubishi Polycrystalline Silicon America Corporation and Mitsubishi Materials Polycrystalline Silicon Co. Mitsubishi Polycrystalline Silicon America Corporation is located in Mobile, Alabama, with a capacity of 1,250 MT. Construction is underway to build an additional 300 MT at this site, the only expansion the company has publicly announced. Mitsubishi Materials Polycrystalline Silicon Co., located in Yokkaichi, Japan, has a capacity of 1,600 MT, with no publicly-known plans for expansion.

<table>
<thead>
<tr>
<th>Year</th>
<th>Capacity (MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>2,850</td>
</tr>
<tr>
<td>2006</td>
<td>2,850</td>
</tr>
<tr>
<td>2007</td>
<td>3,150</td>
</tr>
<tr>
<td>2008</td>
<td>3,150</td>
</tr>
<tr>
<td>2009</td>
<td>3,150</td>
</tr>
<tr>
<td>2010</td>
<td>3,150</td>
</tr>
</tbody>
</table>

### Sumitomo

Sumitomo Titanium Corporation, located in Japan, is an affiliated company of Sumitomo Metal Industries and Kobe Steel. It caters to the electronics industry, producing only EG polysilicon. In 2005, its production capacity was 800 MT. It will have 900 MT of capacity in 2006. In early 2006, it announced that would expand capacity by another 400 MT to respond to demand from the electronics industry.

<table>
<thead>
<tr>
<th>Year</th>
<th>Capacity (MT)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2005</td>
<td>800</td>
</tr>
<tr>
<td>2006</td>
<td>900</td>
</tr>
<tr>
<td>2007</td>
<td>1,100</td>
</tr>
<tr>
<td>2008</td>
<td>1,300</td>
</tr>
<tr>
<td>2009</td>
<td>1,300</td>
</tr>
<tr>
<td>2010</td>
<td>1,300</td>
</tr>
</tbody>
</table>
3.5 Polysilicon Recyclers – IC Castoffs

Several thousand metric tons of reclaimed silicon were recycled in 2005. While some cell companies have in-house recycling divisions, there are a few companies that specialize in this type of silicon processing. A rule of thumb is that 10 percent of the silicon sent to the semiconductor industry eventually makes its way to the PV industry. This number will likely increase in the next few years as the gap between silicon supply and demand increases, and as companies improve their recycling abilities. Here we provide a sample of silicon recyclers.

Silicon Recycling Services

Silicon Recycling Services (SRS) recycles off-spec and waste silicon. SRS has facilities in Camarillo, CA and Beijing, China. In 2005, SRS provided 700 MT of silicon on the spot market, 99 percent of which was sold to the PV industry. In addition, the company was contracted to recycle several hundred metric tons worth of silicon for companies that used the silicon in-house. In early 2006, ErSol AG, a German cell producer, purchased SRS for an undisclosed amount.

ReneSola

ReneSola started recycling polysilicon in July 2005 in Zhejiang province, but has already made quite a mark on the solar industry. ReneSola recycles scrap silicon and broken wafers primarily from the semiconductor industry, but also from the PV industry. It has 54 monocrystalline furnaces, each of which produces 0.5 MT of silicon ingots per month. ReneSola’s wafer capacity is 48 MW (as of August 2006), which it hopes to expand to 80 MW by the end of 2006 and 125 MW in 2007. The company uses the labor of 600 employees to hand-sort the scrap material for recycling. The company estimates that over 2,000 metric tons sold to PV companies was recycled material. The company believes there is even more available to recycle annually (on the order of 5,000 MT), in addition to scraps from past production. ReneSola has signed wafer supply contracts with Jiangsu Linyang Solarfun Co. and Motech. It has also signed feedstock supply contracts with Holy Technology Corporation and Komex Inc, for the delivery of scrap silicon.

Poseidon Chemical

Poseidon Chemicals is a wafer recovery and processing company in Chennai, India. It processes wafer discarded by the semiconductor industry. Germany-based Solar-Fabrik signed a letter of intent in May 2006 to hold 80 percent of the shares of Poseidon Chemicals at a price of €3 million. The pending acquisition will turn Solar-Fabrik, a module manufacturer into an integrated solar company. This wafering capacity will be a welcome addition to Solar-Fabrik’s module production, which did not operate at full capacity in the beginning of 2006 due to insufficient cell supply. Excess wafers not used by the company will be sold to the market. The recycling capacity of Poseidon Chemicals was not available at the time this report was printed.

“Recycling of silicon will be more important in the next few years as a way of lowering material costs, and increasing usable silicon supply.”
SolarWorld

Of the cell companies that have in-house recycling capability, SolarWorld is worth mentioning due to the large scale of its operations. On June 13th SolarWorld’s subsidiary Deutsche Solar celebrated the company’s nearly completed second materials recycling facility in Freiberg, Germany. By the fourth quarter of 2006 the two plants will be capable of processing a combined total of 1,200 MT of silicon, or 40 percent of SolarWorld’s feedstock needs. Half of the material recycled comes from internal operations of the company’s wafering activities, while the other half is obtained via outside sources, including the semiconductor industry. The company also plans to provide recycling services to other companies in the fourth quarter of 2006.16

Recycling of silicon will be more important in the next few years as a way of lowering material costs, and increasing usable silicon supply. It is also important in maintaining PV’s environmentally-oriented image. In this section we presented a historical context for polysilicon production, with a detailed description of the top seven current polysilicon producers. Next, we will discuss the companies that have stated plans to enter the market in the next few years.

1 Price estimates provided by Mike Rogol
2 Hemlock and Mitsubishi presentations at Solar Silicon Conference
4 www.wacker.com "Preparing Ourselves for the Photovoltaic Boom: An Interview with Ewald Schindlbeck, President of WACKER POLYSILICON."
5 http://www.scanwafer.com/default.asp?V_ITEM_ID=488
6 Grant Country EDC, December 5, 2005.
8 REC 2004 annual report.
12 http://hugin.info/136555/R/1067341/180538.pdf
13 Prometheus Institute, PViNews, April 2006
15 http://www.solarworld.de/
Table 3 shows the new silicon producers with their production capacity goals and technology. The most striking piece of information in Table 3 when compared with Table 2 is the greater number of companies planning to employ direct MG to SoG technologies as way to reduce the cost of silicon for solar applications. We used the same criteria outlined in section 3.4 for projected and potential capacity for the companies listed in Table 3.

### 4.1 New Producers using Conventional Silicon Processing

This section describes companies that have not yet entered the polysilicon production business, but have stated plans to do so using production technologies that are well-established.

#### DC Chemical

High-efficiency cell-maker SunPower signed an agreement to provide advance payments to Korea’s DC Chemical (DCC) for the construction of a 3,000 MT polysilicon facility. This project marks DCC’s first venture into the polysilicon business. The DCC will employ Siemens technology and use TCS as the feedstock gas. In all, SunPower will pay $250 million in the multi-year agreement, though the total amount of silicon DCC will deliver has not been disclosed.

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**DC Chemical — chemical-handling expert finds strong partner with SunPower**

Prometheus Institute
Polysilicon: Supply, Demand, & Implications for the PV Industry

23
Hoku Scientific

Hoku Scientific, a fuel cell company located in Hawaii, announced in May 2006 that it will enter the solar business in an effort to diversify. The company has plans to build a 1,500 MT Siemens-based polysilicon production facility as well as a 30 MW module plant. Excess polysilicon (approximately 1,200 MT per year) will be sold to the electronics and solar industries. Hoku will invest $250 million in the project, some of which may be in the form of up-front payments from other solar companies for contracts to secure feedstock material. Hoku first indicated that the location would likely be in Singapore for several reasons, including government support of new energy technologies, its proximity to Hoku’s potential customers, and political stability. However, Hoku later announced a decision to locate the polysilicon and module facilities in the State of Idaho. The exact location in Idaho has yet to be determined; the company is still considering three locations along the Snake River. CH2M Hill Lockwood Greene will design and construct the polysilicon facility.

Isofoton, Spanish government and Endesa

A joint project between Spanish cell producer Isofoton, an Andalusian government agency (the Department of Innovation, Science and Business), and Endesa, a Spanish utility, will result in the first polysilicon plant in Spain. The 2,500 MT facility will be built in Los Barrios. This has exciting implications for the PV industry, as the plant will supply much needed solar grade silicon and is located in a region poised to be the next big market for solar installations. The utility’s involvement is particularly interesting considering the huge costs associated with the energy required to produce polysilicon.

French Consortium (Econcern, NorSun and Photon Power Technologies)

In an August press release, Econcern, a sustainable energy holding company, announced that it, along with two partners, is planning to build a polysilicon plant dedicated to the solar industry. The two other companies are NorSun, a Norwegian wafer company started by Renewable Energy Corporation founder Dr. Alf Bjorseth, and Photon Power Technologies of France. The consortium is considering Saint Auban, in the southeast of France, for the location of the 2,000 to 3,000 MT facility, which is slated to be operational in 2008.

Crystal/Russia and Former Soviet Union Companies

According to Dr. Lebedev of Swiss Wafers, Russia and countries of the Former Soviet Union have the potential to produce upwards of 14,500 MT provided the necessary investment funds are secured. He believes that it is likely that 3,000 MT of capacity will be online in this region by 2009. We found one company with firm plans to produce polysilicon over the next few years, Crystal. Located in Kyrgyzstan, Crystal did not produce polysilicon in 2005, but anticipates 60 MT in 2006. The company’s goal is 1,200 MT by 2008.
M.Setek

M.Setek, a Japanese silicon-wafer company, is adding polysilicon production to its business operations. M.Setek has not provided many details on this new area for the company, other than the below capacity projections. We have not confirmed that M.Setek will be using the Siemens process, but we assume it will.

<table>
<thead>
<tr>
<th>M.Setek</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (MT)</td>
<td></td>
<td>1,100</td>
<td>3,000</td>
<td>3,000</td>
<td>6,000</td>
<td></td>
</tr>
</tbody>
</table>

Chinese Companies

With many of the top Chinese and Taiwanese cell manufacturers having aggressive expansion plans, polysilicon production within the region is an important consideration. There are no existing polysilicon manufacturers in Taiwan. However, Taiwan’s Bureau of Energy is seeking approval from the legislature to allocate $6.2 - $9.2 million in 2007 to the advancement of domestic silicon production technologies.

In 2005, two Chinese polysilicon companies, Emei Semiconductor Material, and Luoyang Monocrystal Silicon, produced approximately 130 MT. At the end of 2005, Luoyang Zhonggui, a joint venture company in which Luoyang Monocrystal Silicon is involved, came online with a production capacity of 300 MT. Once this company was in production, Luoyang Monocrystal Silicon closed. Emei and Luoyang Zhonggui will have a combined capacity of 400 MT in 2006. In addition, three companies (Aostar, Luoyang, and Shangxin Silicon) are in the construction phase and will come online between 2007 and 2008. Three more companies (Linghai, Shizuishan, and Jinyi Silicon) are in the planning stage.

On May 23, CSG (China Southern Glass) Holding of China announced that it will invest $150 million to build a polysilicon production facility in Hubei Province. The company plans to eventually build capacity to 4,000-5,000 MT annual production. Although a construction time of 18 months was provided, the start date for the project was not disclosed. It is possible that this plant could come online by mid-2008. The process CSG will be using to produce the polysilicon is reportedly based on technology developed at a Russian research institute. CSG Holding’s core business since its inception in 1984 has been glass manufacturing. In 1992, it became one of the first Chinese companies to list on the Shenzhen Stock Exchange.
By 2010, these nine companies in China could produce over 7,000 MT of polysilicon, far short of the anticipated demand for silicon in China and Taiwan over that time period. Seven thousand metric tons may be a significant underestimate of the potential supply from China. A June 14th news article claimed that within the next three to five years, annual production in China could be over 20,000 MT. The estimate was based on "public data." The large projects mentioned in the article include a letter of intent signed between Jiangsu Sunshine, the Ningxia Dongfang Nonferrous Metal Group, and Ningxia Yinlite Electronics Group to build a 4,000 MT plant, as well as an agreement signed by Nanyang Bulk and Yinchang City (Hubei Province) for a 4,500 MT polysilicon plant. As many of these projects are still in the planning stage, whether they will actually come online is still in question. Furthermore, the quality of feedstock is also a concern.

Other rumored projects

There have been several news articles that suggest still more developments in polysilicon capacity. In a recent article in the Oregonian, state officials disclosed that the Oregon has been in talks with a Japanese company to build a polysilicon factory in the state. The $500 million project could start in 2007, with production commencing two years later. The same company may also build a module manufacturing plant, and two other solar panel companies have expressed interest in locating facilities in Oregon as well. The companies have visited manufacturing facilities that Komatsu and Sumco have left vacant.

EEtimes online reported that MEMC and Hong Kong Specialty Gases are rumored to be considering a partnership to build silane gas and polysilicon capabilities in China.

All of the companies in this section are planning to use well-understood technologies (primarily Siemens) for polysilicon production. In the next section, we turn to companies using new or not-yet-commercial silicon production methods.

### 4.2 Alternative Silicon Production

The majority of companies that have decided to pursue alternative silicon production routes are already involved in silicon processing at some level. Therefore, it is a logical step for them to build on this experience by further refining their product instead of using traditional processing techniques. Elkem, Joint Solar Silicon, ARISE, SolarValue, Global PV Specialists, JFE Steel, GiraSolar, and Dow Corning have all been investigating alternative silicon processing methods.
Emerging Polysilicon Producers and Supplemental Silicon

Elkem

The Norwegian Elkem Solar, a division of Elkem AS, is one of the most promising of the new polysilicon companies. Elkem AS produces the precursor feedstock for polysilicon production, silicon metal. The company claims to have 50 percent of the silicon metal market. Elkem Solar has been developing a new process for solar grade polysilicon production. Currently in pilot scale production, the company expects to be producing on a commercial scale by 2007. Initial capacity will be 2,500 MT, ramped up to 5,000 MT in 2008. A further 5,000 MT of capacity could be added in 2010. Like much of the new capacity coming online, initial production is already slated to go to companies that have supported the development of this project.

Elkem’s contribution to the future silicon supply is important for two reasons. First, it will constitute a large percentage (~9.8 percent) of the total production capacity available by 2010. The scale of expansion is enormous, and could make Elkem the fourth largest polysilicon producer in the world, after Hemlock, Wacker, and REC. Second, the silicon will be solar grade, and thus presumably lower in cost, though questions remain about the product’s usefulness as a stand-alone silicon replacement. Some blending with traditional silicon may be required. Elkem meets all of our requirements for projected capacity, but given that it will use a new process, we have projected that it can meet its initial goal of 5,000 MT. If the company reaches this goal we will include the next 5,000 capacity expansion it plans for 2010. We took this approach with Elkem and SolarValue (see below) to avoid skewing the 2010 capacity total, in the event that the commercial scale production at either company is delayed. With any company that is employing MG refining to produce SoG, the time between confirmation of industrial production and subsequent capacity expansions is expected to be very short – especially in comparison to building capacity with Siemens reactors which takes approximately two years.

<table>
<thead>
<tr>
<th>Elkem</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (MT)</td>
<td></td>
<td></td>
<td>2,500</td>
<td>5,000</td>
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</tr>
<tr>
<td>Potential Capacity (MT)</td>
<td></td>
<td></td>
<td>2,500</td>
<td>5,000</td>
<td>5,000</td>
<td>10,000</td>
</tr>
</tbody>
</table>

Joint Solar Silicon GMBH & Co. KG (JSSI)

In July 2006, SolarWorld announced that its joint venture with chemical giant Degussa for a polysilicon production process would proceed to commercial scale production. The JV is currently operating a pilot plant, the product of which goes directly to SolarWorld’s wafer division, Deutsche Solar. The new plant, which will begin producing polysilicon in 2008, will have a production capacity of 850 MT for 10 years. SolarWorld currently procures silicon from Wacker and Hemlock.

<table>
<thead>
<tr>
<th>JSSI</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (MT)</td>
<td></td>
<td></td>
<td></td>
<td>850</td>
<td>850</td>
<td>850</td>
</tr>
</tbody>
</table>
ARISE

Until relatively recently, Canada-based ARISE Technologies concentrated its efforts on the downstream end of the supply chain. This year, ARISE announced plans to integrate upstream by adding polysilicon and cell manufacturing capabilities. The company will receive $6.5 million (CAD) from Sustainable Development Technology Canada (SDTC) for use towards development of a proprietary solar grade polysilicon production process. SDTC was created by the Government of Canada to provide support to clean technology projects. The money committed to ARISE by SDTC will be added to the $13.3 million of funding in the form of cash and donations from a consortium of partners. The SDTC funding will be spread out over three years, pending final agreement and the achievement of project benchmarks. ARISE is collaborating on this project with the University of Toronto, University of Waterloo, Topsil Semiconductor Materials A/S, and others.

A 200 MT pilot-scale facility will begin producing polysilicon in 2007. If everything goes according to plan, the company expects to have a 2000 MT plant operational by 2010.

<table>
<thead>
<tr>
<th>ARISE</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential Capacity (MT)</td>
<td></td>
<td></td>
<td>50</td>
<td>200</td>
<td>200</td>
<td>2,000</td>
</tr>
</tbody>
</table>

JFE Steel

JFE Steel, established in 2003 and headquartered in Japan, is a company within the JFE Group. In July 2006, JFE Steel announced that it started construction of a 100 MT solar grade silicon plant. With help from NEDO (New Energy and Industrial Technology Development Organization), JFE Steel launched an R&D project in 2001 to develop SoG from metallurgical grade silicon (figure 25). The company revealed that it is in the process of designing a larger facility.

SolarValue

The solar start-up company SolarValue is in the final stages of purchasing TDR Metalurgija, a metallurgical silicon company in Ruše, Slovenia. The purchase will secure feedstock for SolarValue for the production of solar grade silicon. SolarValue was started in 2005 in Germany and was listed on the Frankfurt Stock Exchange in September 2006. The company formed a subsidiary in Slovenia, SolarValue Productions d.d., that will use a four-step refining process to convert metallurgical silicon to solar grade silicon. The company hopes to produce 2,000 MT in 2007 and 5,300 MT in 2008. After fine-tuning its operations, SolarValue hopes to produce 10,000 MT per year by 2010. As with Elkem, we have not included the additional 5,000 MT of additional capacity in 2010 in an effort to remain conservative in our estimates. If the company is able to meet capacity goals on time, we will revise the current estimates.
Global PV Specialists

Global PV Specialists is a consulting firm based in California that provides turnkey factories for cell manufacturing as well as other services pertaining to the operation of the facilities. In an effort to support companies building new cell factories, Global PV Specialists will begin producing silicon specifically for its own customers. The technology it will use includes a unique approach with rice hulls as the feedstock material. The final location for the production facility has not been decided, though it will likely be built in the US.

<table>
<thead>
<tr>
<th>SolarValue</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity (MT)</td>
<td></td>
<td></td>
<td>2,200</td>
<td>5,300</td>
<td>5,300</td>
<td>5,300</td>
</tr>
<tr>
<td>Potential Capacity (MT)</td>
<td></td>
<td></td>
<td>2,000</td>
<td>5,300</td>
<td>5,300</td>
<td>10,000</td>
</tr>
</tbody>
</table>

GiraSolar

GiraSolar, located in the Netherlands, is an umbrella company for solar energy companies. It has subsidiaries, partners, and affiliates performing research and development, as well as doing business at several levels of the supply chain. GiraSolar serves as an investment and managing company for the group, allowing the companies to remain independent yet benefit from their association with the group. Scientists at GiraSolar have announced they have applied for a patent for a proprietary solar grade silicon production process. The company anticipates production costs for the material to be $10–$12/kg, less than half of current production costs of conventional silicon. The company CEO, Wieland Koornstra, indicated that the project is still in the research phase, but once the patent goes through they expect to build a pilot-scale facility. This project is still a long way from producing usable silicon; hence there are no capacity estimates at this time.

<table>
<thead>
<tr>
<th>Global PV Specialists</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
<th>2009</th>
<th>2010</th>
</tr>
</thead>
<tbody>
<tr>
<td>Potential Capacity (MT)</td>
<td></td>
<td></td>
<td>1,000</td>
<td>2,000</td>
<td>2,000</td>
<td>2,000</td>
</tr>
</tbody>
</table>

Dow Corning

With the PV industry in the midst of a silicon shortage, Dow Corning believes its new solar-grade silicon (SoG) offers a unique solution to the problem. The product, called PV 1101, derives from the purification of metallurgical silicon, and is used in a blend with purer silicon to manufacture flat plate silicon solar cells. Dow Corning is supplying a few PV companies with the product to test the new material in their own production processes. The undisclosed companies have blended PV 1101 into their silicon feedstock at ratios of 10 percent or more. Due to non-disclosure agreements, Dow Corning refused to provide details on specific blend ratios and resulting cell efficiencies, but it did disclose that no reduction in performance was reported by its customers.
Emerging Polysilicon Producers and Supplemental Silicon

Current production capacity of PV 1101 is around 1,000 MT, but the company could ramp up to large scale production quickly in response to demand. Dow Corning is producing the product exclusively at its new facility in Santos Dumont, Brazil. In the short term, only current Dow Corning customers can purchase the limited quantities of PV 1101 available. While the availability of public information on this new product is limited, it appears that this product could serve to add feedstock to the currently tight global silicon supply.

As this overview of current and future polysilicon producers shows, production is becoming more distributed throughout the world. We examine the current and projected regional breakdown of polysilicon supply in the next section.

2. www.solarbuzz.com/
4. Lebedev, Alexander, Revival of Polysilicon Production in Countries of the Former Soviet Union? 3rd Solar Silicon Conference, April 2006, Munich, Germany
5. Yang, Deren, Overview of Silicon from Chinese Manufacturers, 3rd Solar Silicon Conference, April 2006, Munich, Germany
6. Deren Yang, personal communication
8. All capacity projections except for CSG were provided by Deren Yang (see endnote #5)
5 Geography of Global Polysilicon Capacity

In 2005, the US dominated silicon production, providing over 50 percent of the product available on the market. Japan and Europe (mostly Germany) split the remaining production amount. In Figure 26 we show the geographic distribution of polysilicon production in 2005 and 2010. For 2010, we once again use the criteria outlined in section 3.4.

The US share of production is expected to fall over the next few years as production increases in Europe (particularly in Norway) and China (Table 4). The Japanese companies are not keeping pace with their US and Europe counterparts; however, this could change. The Japanese companies have been slow to respond to growing demand thus far, but may announce new expansions in the future.

The countries that have the potential to play a much larger role in polysilicon supply than they currently do are China and the FSU countries. If all of the potential capacity we report actually comes online, we expect the US and Japan to lose a significant amount of the polysilicon market. (In the third column of table 4, we assume that all potential capacity comes online, which affects the percentage of production for all regions/countries).

While the geographic distribution of polysilicon is interesting given the relatively low cost of shipping silicon, it does not necessarily dictate where future markets for PV will develop. In the next section we examine overall polysilicon production in the next five years and offer a forecast of PV production based on several variables. We also discuss the assumptions of our projections, and perform sensitivity analyses to investigate the range of possibilities for future industry growth.

Table 4: Geographic distribution of polysilicon production as a percent of total production

<table>
<thead>
<tr>
<th>Country/Region</th>
<th>2005</th>
<th>2010 (projected)</th>
<th>2010 (potential)</th>
</tr>
</thead>
<tbody>
<tr>
<td>US</td>
<td>54.2%</td>
<td>40.7%</td>
<td>27.6%</td>
</tr>
<tr>
<td>Japan</td>
<td>24.3%</td>
<td>14.8%</td>
<td>9.6%</td>
</tr>
<tr>
<td>Europe</td>
<td>21.1%</td>
<td>32.6%</td>
<td>30.2%</td>
</tr>
<tr>
<td>China</td>
<td>0.4%</td>
<td>7.5%</td>
<td>18.8%</td>
</tr>
<tr>
<td>Russia/FSU</td>
<td>N/A</td>
<td>1.2%</td>
<td>10.4%</td>
</tr>
<tr>
<td>RoW</td>
<td>N/A</td>
<td>3.1%</td>
<td>3.3%</td>
</tr>
</tbody>
</table>
The PV industry has grown an average of 40 percent per year over the last decade. In 2005, cell production grew 46 percent over 2004. We estimate that in 2005, the PV industry required roughly 19,000 MT of polysilicon, only 3,000 MT less than the semiconductor industry. In 2006, polysilicon demand from PV producers will likely be greater than demand from the electronics industry. But with no significant new capacity available this year, PV growth will be limited. In this section we present a forecast model of PV production growth to 2010.

6.1 Polysilicon Production Capacity Projections to 2010

All companies that currently produce polysilicon are expanding capacity to varying degrees. Mitsubishi has the most modest capacity expansion plans (300 MT), whereas Hemlock anticipates nearly 12,000 MT of new capacity over the next five years.

By 2010, the total silicon supply is expected to grow to over 97,000 MT. This is our projected estimate, according to the criteria outlined in Section 3.4.

The top three companies will maintain their positions through 2010. Tokuyama, fourth in production in 2005, is also expected to increase capacity if and when it perfects its vapor-to-liquid deposition (VLD) process. Engineering setbacks appear to be keeping the company from moving forward with the few thousand metric tons of capacity it would like to build using this technology.
In making our projections, we have distinguished between companies that have solid reputations in the industry and clear production goals, and those firms that are less well-known with unclear or questionable plans. We are aware that there may be new announcements from existing producers as well as new entrants. But we also expect that not all of the announced expansion plans will be brought to completion on time or indeed at all. For example, there has been very little activity from the Japanese producers. One could speculate that expansion plans at Tokuyama and Mitsubishi are under consideration but not made public. However, a counterargument is that perhaps they are not as committed to the PV industry for future sales as, for instance, Hemlock or Wacker. Furthermore, some companies may worry that with all of the expansions by existing companies and the spate of new companies, there will be an oversupply. Therefore, our estimates represent a probable outcome of production over the next few years.

### 6.2 Changing Market Dynamics for Polysilicon Producers

In 2005, Hemlock was the largest polysilicon producer and accounted for approximately 25 percent of the global supply.

While some companies had pilot plants in operation during 2005 (i.e. Elkem, JSSI, etc), the amount produced is not provided here. Chinese companies produced a total of 130 MT, or approximately 0.4 percent of the global market for polysilicon.

Under the projections presented here for capacity expansion plans, by 2010 the seven largest companies producing silicon will lose market share to new entrants. Chinese companies are expected to grow collectively from less than one percent to 7.2 percent market share. The most dramatic change portrayed in this figure is the increase in market share for the "other" category. This category includes all non-Chinese producers that are one of the top seven producers. These companies - which in 2005 did not produce any polysilicon (aside from some pilot scale batches) - will capture a quarter of the market in 2010.
6.3 Demand Forecast Model

Assumptions

Silicon-based cells accounted for 94 percent of production in 2005 (91 percent were flat plate and three percent were ribbon/sheet). In our base case scenario we assume thin film production reaches 500 MW by 2010 (corresponding to a 36 percent growth rate). With so many new thin film capacity expansions announced in the spring and summer of 2006, this is likely a conservative estimate. However, we will give results of sensitivity analysis where we explore the possibility of greater market penetration by thin film.

Following Woditsche and Koch (2002),\(^1\) we assume a reduction in silicon usage per watt of five percent per year. In 2005, wafer-makers required 12 g Si/W. By 2010, with thinner wafers and higher conversion efficiencies, we expect silicon use to be around 9 g Si/W. This is also a conservative estimate. While high breakage rates are a concern for thinner cells, a great deal of research and development effort is currently devoted to producing thinner cells. A target of 6 g Si/W has been promoted, and may be achieved in the best applications, but is unlikely to be an average over the entire industry within the next few years.

For 2004 to 2008, the Semiconductor Industry Association predicts a seven percent increase in shipments of wafers. In 2005, demand for polysilicon from integrated circuit (IC) producers was approximately 22,000 MT, approximately 10 percent of which was assumed to have eventually made its way to the PV industry.

A list of our model assumptions is on the upper right-hand side of this page. For comparison we have included supply and demand estimates from Piper Jaffray (table 5).

| Table 5: Piper Jaffray solar industry production estimates\(^2\) |
|---|---|---|---|---|---|---|---|---|
| 2003 | 26,700 | 17,000 | 9,700 | 11,000 | 20,700 | 671 | 80 | 750 |
| 2004 | 28,800 | 19,350 | 9,450 | 11,700 | 21,150 | 1,142 | 114 | 1,256 |
| 2005 | 31,080 | 20,627 | 10,453 | 7,118 | 17,571 | 1,523 | 170 | 1,693 |
| 2006E | 35,800 | 22,277 | 13,523 | - | 13,523 | 1,610 | 258 | 1,868 |
| 2007E | 40,210 | 24,282 | 15,928 | - | 15,928 | 1,828 | 449 | 2,277 |
| 2008E | 57,220 | 26,710 | 30,510 | - | 30,510 | 3,162 | 720 | 3,882 |
| 2009E | 71,370 | 27,245 | 44,125 | - | 44,125 | 4,641 | 918 | 5,559 |
| 2010E | 77,370 | 28,062 | 49,308 | - | 49,308 | 6,035 | 1,098 | 7,133 |

MODEL ASSUMPTIONS (2005)

- Silicon Production: 31,280 MT
- Polysilicon Inventory: 3,000 MT
- Other: 7,600 MT
  (IC castoffs & recycling, pilot batches, & excess production)
- IC Demand: 22,000 MT
- PV Demand: 19,800 MT
- Thin Film Production: 107 MW
6.4 Model Results

Figure 24 shows our projection model through 2010. For reference, it also shows three different tracking lines for establishing various compound growth rates for the PV industry at 10 percent, 30 percent, and 50 percent per annum. These tracking lines help to conceptualize the market dynamics and the repercussions caused by silicon capacity constraints through 2010.

In 2005, we estimate there were approximately 3,000 MT in inventory draw-downs, and another 2,000 MT recycled from previous years' production. This leaves over 3,000 MT more demand from the PV industry than was thought to be available. There are two possible explanations for this discrepancy. First, polysilicon producers are able to produce more than they state with production capacity estimates. Lower purity silicon takes less time to manufacture, allowing for more to be produced in a given time period. With strong demand from the PV industry, it is very likely that polysilicon producers modified the production process for PV applications, i.e., produced lower quality material, and thus were able to make more material over the course of the year. Another explanation for the discrepancy is that pilot batches made their way to the market, but were not necessarily reported by companies. Lastly, we also believe it likely that cell manufacturers overstated their production, to some degree, in 2005. All of these factors helped the PV industry report a 46 percent growth in production in 2005.

In 2006 we anticipate that there will be no excess inventory draw-downs from 2005, but there will likely be more recycled material from previous years as companies scour the globe for wafers discarded from past production. Our estimate for recycled material in 2006 is 3,000 MT. In 2007 this will drop, perhaps 1,000 MT. We doubt that after 2007 any remaining silicon material will be worth the processing to make it usable. We also assume that pilot production and understated silicon production will continue at a level of more than 3,000 MT per year.

With all considerations embedded in the model, we expect 2006 to see very modest production growth of around five percent. This will pick up again to over 35 percent in 2007 as more production comes online and more recycling occurs. A spike in production in 2008 due to several plant expansions coming online will theoretically allow the industry to grow over 100 percent that year. While many PV companies are already expanding capacity in anticipation of greater feedstock supply, a jump from 35 percent to 100 percent in one year is unlikely. What is more likely is that the 2008 production will be incorporated into 2009’s available supply, allowing average growth rates between 2008 and
2010 to hover around 50 percent. By 2010, based on announced expansion plans and assumed silicon use and thin film market share, we forecast PV production to be just over eight GW.

With any model, certain assumptions must be made. Further analysis using sensitivity testing can show how things may change with a change in assumptions. In our model, the two assumptions that may be the most controversial are the potential growth of thin film production (we assume that thin films will account for only eight percent of 2010 PV production in 2010) and silicon requirements per watt (we assume that less than 9 g/W by 2010 is unlikely). For this reason we have performed sensitivity tests with modifications in these two variables. The results of these tests are discussed in the next section.

6.5 Sensitivity tests

The first conservative estimate we included in our model was the amount of silicon that cell producers need to produce a watt of electricity.

In our model, silicon use decreases from 12 g Si/W in 2005 to just over 9 g Si/W in 2010. In our second sensitivity test we project average silicon use decreasing more dramatically to 6 g Si/W. As figure 25 (page 36) shows, this allows for much greater growth in the industry than the base case. Even in 2006, if cell producer could decrease their silicon use to less than 11 g/W on average, the industry could grow nearly 15 percent. By 2010, the industry would reach just over 12 GW of production.

In our next sensitivity test we maintain our original assumption for silicon use, but modify the amount of growth in thin film production (Figure 26). For this we assume silicon-based production is based on the available silicon, and thin film reaches a level equivalent to 20 percent of the overall PV market. This results in more modest improvements in industry growth, bringing total production in 2010 to just less than 10 GW.

The third sensitivity test we performed combined the first two scenarios, the results of which are presented in Figure 27. If the industry were able to reduce silicon use to 6 g Si/W and if thin films were able to achieve 20 percent market share by 2010, the industry could see more than 50 percent growth after 2007 and over 15 GW of production by 2010.

Our base case model shows that a conservative estimate of PV production based on projected capacities is around eight GW. Production could be as high as 15 GW according to our sensitivity tests. These estimates are much higher than some other estimates; EPIA for example believes the
market for PV in 2010 will be only 5.5 GW. Michael Rogol believes the industry will be over 10 GW in 2010. An important consideration to keep in mind when projecting potential production is that it needs to be met with adequate demand. The strong markets of Japan and Germany are not expected to maintain the growth they have seen in years past, while new markets, such as Spain, Italy, and China, may take some time before they rival Germany at hundreds of MW installed per year. The US also has a huge potential; it will interesting to see the degree to which that potential is realized. So while we project significant production levels by 2010, we stress that is important to remember the role public policy has played in PV demand and will likely play in the next five years.

While it is likely that 2006 and 2007 will be difficult for the PV industry due to primary feedstock constraints, the silicon shortage is having a more profound impact than simply two years of higher prices and under-utilized cell and module capacity for some producers. In the next section we explore the long-term structural changes that the silicon shortage will create throughout the PV Industry.

The PV industry's dependence on silicon has made it extremely vulnerable to supply shortages. Prior to 2000, the industry could survive on the small amount of feedstock not consumed by the semiconductor industry. At present, however, PV silicon demand is on the verge of surpassing IC silicon demand. In this section we provide our assessment of what the feedstock constraint means for the PV industry in terms of material prices, as well as the industry's fundamental structure.

7.1 Polysilicon Prices

PV companies have been paying increasingly higher prices over the past three years as demand has exceeded the supply available through traditional channels of the IC industry's off-spec material. Prices for EG polysilicon just a few years ago were in the $50/kg range, while PV companies were paying nearly $25/kg. In 2004 and 2005, contract prices began to rapidly increase as the demand growth became imminent and inventories were depleted. Now, long-term contract prices for PV companies mirror those semiconductor companies pay for feedstock. Today's contract prices are above $50/kg; spot market prices are $200 – $300/kg.

Of the polysilicon suppliers surveyed for this report, the majority indicated their sales were primarily via contracts with cell manufacturers; however this practice was not universal. Furthermore, some companies that primarily sold via contracts also sold on the spot market. Many of the long-term silicon contracts have fixed prices for the duration of the agreement. For this reason, as well as numerous other uncertain variables, it is difficult to predict the future price of silicon. Michael Rogol, Managing Director of Photon Consulting, believes prices will not go down until after 2008.

Profit margins for silicon producers are no doubt rising. With silicon selling at two to three times its 2003 price, there is greater incentive for more investment in the industry. As we have shown, there are now more newcomers to the business than existing players. However, even with these high prices, many of the industry veterans, (e.g. Mitsubishi, Sumitomo and Tokuyama) remain cautious—they remember all too painfully the burst of the tech bubble and the implosion of the world's demand for silicon.

With thousands of metric tons of new capacity announced in the summer of 2006, it is possible that the industry will have enough silicon to supply the projected demand, causing a stabilization or drop in prices. On the other hand, if the semiconductor industry sees an upturn in sales, or if public policies are put in place that cause the PV market to expand even more quickly, silicon demand may once again outpace supply past 2008. Furthermore, if announced capacities from new market entrants fall through, demand could exceed supply.

7.2 Changing Industry Structure

Several trends have become apparent as the industry reacts to the polysilicon shortage. First, the industry is solidifying by increasingly

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Figure 28: Average silicon prices 2003 to 2005 with projections to 2007

![Figure 28: Average silicon prices 2003 to 2005 with projections to 2007](image-url)
entering into joint ventures and long-term contracts, and by building in-house silicon processing capabilities.

**Long-term contracts and joint ventures**

Joint ventures and long-term supply contracts allow for cell producers to guarantee their feedstock supply without committing to the expensive construction of their own polysilicon production facility. REC, Q-cells, and Evergreen have entered into this type of joint venture agreement, whereby REC will provide silicon to a JV entity previously established between Evergreen and Q-cells (dubbed EverQ) and in return gain 33.3 percent ownership of EverQ.

MEMC and Motech were in discussions to sign a long-term supply agreement, but they eventually parted; MEMC signed a deal with Suntech instead, and Motech signed a supply contract with ReneSola. The MEMC/Suntech deal requires Suntech to provide MEMC with advance funding for MEMC’s wafer capacity expansion. MEMC will deliver wafers to Suntech for ten years. The Motech/ReneSola agreement will last only two, January 2007 – December 2009. ReneSola is contracted to deliver 80 MW of wafers to Motech. Incidentally, ReneSola hopes to bring its wafer production capacity up to 80 MW by the end of 2006, and Motech is expanding its cell capacity to 200 MW by the end of 2006.

Other examples of joint ventures and long-term contracts include Joint Solar Silicon, a joint venture discussed in section 4.2, and Elkem Solar, which has long-term agreements with cell manufacturers who have been involved in Elkem’s MG to SoG silicon research and development.

**Vertical integration**

It has never been more difficult for PV cell manufacturers to secure feedstock supply. The shortage has caused many to re-evaluate their business models. With the increasing scale of cell manufacturing, the shortage is causing many cell producers to explore the possibility of acquiring sufficient in-house silicon production, “vertically integrating” to ensure long-term access to vital feedstock. The costs of vertical integration will, however, remain prohibitive for most companies.

REC is a leader in vertical integration, with a presence at each level of the PV supply chain. Others are moving toward vertical integration by building polysilicon capacity for their cell production. ARISE, Hoku, and GiraSolar have plans to build polysilicon production plants specifically for their own use.

**7.3 Efficiency Gains**

The industry is also reacting to the silicon supply constraint by making strides in reducing silicon waste through increasing recycling efforts, improving the conversion efficiencies of cells, slicing thinner wafers, and devising innovative processing methods.
Recycling

Silicon recycling may be a cheaper option for smaller cell producers looking to secure silicon feedstock, although this still depends on available raw material. Furthermore, when silicon supplies are constrained and prices are high, recyclable material is also constrained and therefore more expensive. Two German companies have incorporated recycled material into their operations. SolarWorld doubled the capacity of its Solar Material Division this year and can now recycle 1,200 MT of polysilicon annually. In 2006, ErSol AG acquired Silicon Recycling Services (SRS). ErSol has not yet decided if it will offer SRS's recycled material or recycling services to outside companies. Recycling is already becoming a bigger part of PV manufacturing and will likely continue to play an important role in the years to come.

Increased efficiency of silicon use and energy conversion

Cell companies, such as ErSol Solar, Evergreen Solar, Q-Cells, and SunPower, are improving their silicon requirements per watt. One way they accomplish this is by producing thinner cells; ErSol is making great strides towards this end and hopes to release a new line of cells under 200 μm in 2006. Increasing the efficiency of the cells is another method of lowering silicon use. SunPower has achieved over 20 percent cell conversion efficiencies. Ingot processing offers another opportunity to reduce silicon waste. Solaix, located in California, has a continuous CZ process that the company claims is faster and less wasteful than the traditional method for making monocrystalline ingots.

7.4 Emergence of Alternatives: New Silicon Processing and Gains in Thin Film Production

Silicon-based cell manufacturing using chunk or granular polysilicon represents the vast majority of PV production, but alternatives are beginning to break through. Thin film's benefit of not requiring silicon has made it more attractive—evident in the numerous thin film expansion plans that have been announced recently. More companies, such as SolarValue and JFE Steel, to name a few, are also investing in MG to SoG efforts.

Potential competition from thin films

Technologies that do not use silicon are becoming more cost-effective despite their lower conversion efficiencies. In recent months announcements of increased thin-film cell production have outnumbered those touting increased silicon cell production. Several silicon-based companies are looking to diversify into thin films. This year, Shell Solar sold all of its silicon-based operations to SolarWorld to focus on thin film. Q-Cells announced that they will invest $9 million in the Swiss thin film PV
“MG silicon could offer the industry a low-cost silicon option, leading to declining cell and module costs.”

Polysilicon now available on the market is almost exclusively made using FBR or Siemens technology. The single exception is the PV1101 product from Dow, which must be blended with purer polysilicon. However, various producers are attempting to bring the MG-Si to SoG process to commercial production. It remains to be seen if companies like Elkem and SolarValue can achieve their announced, ambitious production goals while maintaining adequate purity of the feedstock and keeping the price low enough to justify the lower cell efficiencies resulting from MG-Si to SoG product. MG silicon could offer the industry a low-cost silicon option, leading to declining cell and module costs. This in turn would make PV more competitive in more markets.

7.5 Concluding Thoughts

Based on our assessment of the planned new silicon production capacity, we predict that the worst of the silicon shortage will be over by the end of 2008, and that the PV industry will have an average production growth rate between 2008 and 2010 of approximately 50 percent per year. By 2010, we forecast production to be just over eight GW.

While circumstances may cause production in 2010 to be higher or lower than eight GW, it is certain that the fundamental structure of the PV industry is changing. The polysilicon shortage has already caused companies to shift business strategies; the past three years of high prices and tight supply has led to consolidation all along the supply chain. By 2010 we expect the industry to be dominated by a smaller number of large, vertically-integrated companies.
Hilary Flynn is a senior researcher at the Prometheus Institute where she reports on the solar energy industry. She has researched wind and biomass technologies, as well as market-based policies designed to promote clean energy, such as renewable portfolio standards with REC trading and cap-and-trade programs. Hilary also has training in computer-based analysis using system dynamics modeling and geographic information systems.

She earned a BS from Rutgers University, and an MS from Washington State University under the mentorship of Dr. Andrew Ford. She has co-authored articles in *Energy Policy*, *System Dynamics Review*, *Renewable Energy World* and *Solar Today*, and has presented her research at conferences in the US and abroad.

Travis founded the Prometheus Institute in 2003 as a means to connect the vast reach and power of industrial and capital markets with the technologies necessary to sustain and develop long-term economic well-being for people around the world. Having spent time in nearly 40 countries, he has seen firsthand the state of economic development and the need to develop markets to make existing sustainable technologies more available and cost-effective.

Prior to founding the Prometheus Institute, Travis was a partner at Steel Partners II, L.P., a hedge fund based in New York City focused on the acquisition, growth, and sale of small publicly traded and privately owned businesses. In this capacity, Travis served as both a board member and active management participant in these types of businesses in industries ranging from industrial filters to fertilizer distributors. It is this practical business experience which he hopes the Prometheus Foundation can bring to the sustainable technology industry.

Travis has worked for the Federal Reserve Bank, has lectured at top Universities including Columbia University, Duke University, and New York University on finance and entrepreneurship, and is co-author of a paper in the *Journal of Applied Corporate Finance* entitled Private Equity: Sources and Uses. He is also a partner at Atlas Capital, a hedge fund based in Cambridge, MA.

Robert serves as the Institute’s Office Administrator and Graphic Designer. He attended the Defense Language Institute in Monterey, California where he studied Korean. Robert has several years of experience working in non-profit. Prior to joining the institute, he was the System Coordinator for Lesley University, where he collaborated to develop and maintain software and policies with regard to the University’s housing, registration, financial aid, and billing systems.

Kate Cell comes to the Institute with six years of experience in nonprofit media and policy outreach and fundraising, specializing in the area of helping the public and their political representatives appreciate the implications of economic research and analysis.

Kate studied writing at the University of Iowa’s Writer’s Workshop and Cognitive Psychology and English at Macalester College. She is a fellow of Economists for Peace and Security, the editor of the *EPS Quarterly*, and serves on the editorial board of the *Economics of Peace and Security Journal*, a new online peer-reviewed publication.