The Outlook for Crystalline Solar Photovoltaic Technology over the Next Decade

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Abstract. The solar photovoltaic (PV) industry has achieved impressive growth by producing 1,818 MW of solar cells (93.5% crystalline) in 2005, an increase of almost 45% over the previous year. However the PV industry, which has been dependent on the supply of the basic raw material (silicon) from the waste of the semiconductor industry, now faces an acute shortage of supply. The price of polysilicon has reached a peak of US$400/kg on the spot market, over ten times the long to medium term supply contract price. To overcome the shortage of silicon feedstock, a number of new solar silicon plants and processes have been announced by the PV industry. This paper discusses the implications of this shortage and the effect of new manufacturing facilities for the future of the crystalline silicon PV technology in the foreseeable future. It also discusses whether, crystalline silicon will lose its place of dominance from its current 93.5% market share, to thin film technologies, such as amorphous silicon and CIGS, or whether crystalline technology will continue to dominate after overcoming the temporary shortage of silicon supply?

Keywords: Crystalline Silicon, Solar Cells, Polysilicon, PV Technology

1. INTRODUCTION

Solar cells have many advantages that make them an attractive energy source even though the initial investment cost and the price per kilowatt hour (kWh) for solar energy are often higher than for the traditional energy sources. These include low operating costs, negligible maintenance requirements and environmental benefits. In 2004 the solar PV industry achieved a significant milestone by selling 1GW of solar cells in a year. This is not the only year where solar PV has experienced an impressive growth rate; its growth has been over 30% per annum for the past 5 years as shown in Figure 1. Its rapid growth has surprised many players in the field as this technology is still driven by government grants and incentives. But the fact is that many new funding schemes and the attractive feed-in-tariffs to the local grid in many countries around the world have played an important role in its development.

The PV industry has grown through the increasing demand for renewable energy, which is driven by a number of factors, including:

- government and political pressures to reduce carbon dioxide levels and find alternative sources of energy both domestically and internationally
- increasing government expenditure to support renewable energy programs
- improving technologies creating more efficient and cost effective products
- diminishing fossil fuel resources.

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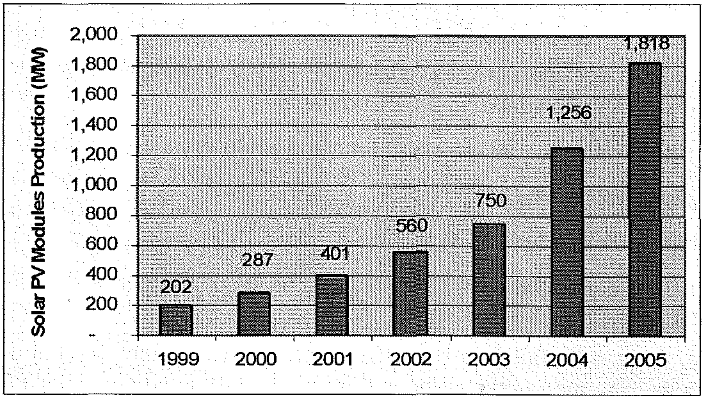

FIGURE 1. Production of Solar Cells [2].

The current installed cost of solar PV is approximately US$6 per watt but it is generally expected that the widespread adoption of PV electrical production will require an installed price of around US$2 per watt and a payback period of 6 to 7 years without any kind of government incentives [1]. However, an installed cost of $3 to $3.50 per watt will be acceptable in the short term and will permit significant market growth over the next six to seven years for the following reasons:

- The government in many countries is providing significant incentives by subsidizing the higher initial investments, and this will be continued for the foreseeable future.
- Germany, Italy, Spain, France and many other countries are developing feed-in-tariff schemes based on the real cost of power generation from solar PV.
- Electricity costs are steadily rising throughout the world and the diminishing sources of coal, gas and oil are putting pressure on to increase electricity tariffs in many countries.
- Solar power has developed its credentials to be a major source for meeting peak demand, especially in the summer months, when traditional power generation sources are under pressure.
- The payback period of 6-7 years is very reasonable, while the design life of a solar PV system is typically 30 years [1].

Even though the current cost of PV power generation ranges from 20 to 40 cents/kWh, three to ten times higher than that of coal, nuclear, gas, oil or wind, which range from 2 to 8 cents/kWh, the solar industry will continue to grow at its current pace with the total turnover of solar companies expected to increase from around $7 billion in 2004 to $30-$40 billion in 2010 and operating earnings expected to expand from $700 million to $3 billion in the same period of time [2].

With demand exceeding supply for polysilicon, the prices of solar modules have started rising, reversing the previous downward trend over the past 30 years. Despite this it is estimated that in 2007 the production of solar PV will achieve another record high of 2.75 GW per annum and this sector has a realistic potential to exceed 6 GW of production in 2010.

2. SOLAR CELL TECHNOLOGY

Several types of solar cells are available with more under development. The types of solar cells currently available in the market are:

- Crystalline silicon – Mono-crystalline and Multi-crystalline (c-Si)
- Amorphous Silicon (a-Si)
- Cadmium Telluride (CdTe)
- Copper Indium Gallium Diselenide (CIGS) or Copper Indium Diselenide (CIS)

Broadly, these cells fall into two generic categories namely crystalline and thin film solar cells. The mono-crystalline and multi-crystalline silicon solar PV modules are the most widely used for numerous applications from space application to large-scale power generation projects. These crystalline solar PV modules traditionally have been considered to have greater longevity for outdoor applications than thin film solar modules and also they are more efficient.

Amorphous silicon thin film technology has been in the market since the eighties, but it is not widely used for large scale solar power generation because a-Si solar modules have low efficiencies and degrade in the working environment unlike its major competitor, crystalline silicon modules. Although considerable progress has been made in overcoming these deficiencies, amorphous silicon technology has only been able to capture a small share (>5%) of the solar cell market, mainly for consumer products.

With the current shortage of solar silicon feedstock, it is natural to seek an alternative to creating solar cells that use silicon based products. CIGS solar cells, sometimes referred to as CIS, are made from copper, indium, gallium and selenium and have been under development for some time. Most notably, they do not contain any silicon.

CIGS cells are claimed to be less expensive per watt installed, more efficient in low-angle and low-light conditions and consume less material overall. They also have the potential to be flexible in their configurations, making them attractive for building-integrated PV (BIPV) applications.

The thin-film cadmium telluride / cadmium sulphide solar cell has for several years been considered to be a promising alternative to the more widely used silicon devices. CdTe has a high absorption coefficient, so that approximately 99% of the incident light is absorbed by a layer thickness of only 1μm (compared with around 10μm for Si), cutting down the quantity of semiconductor material required. However, a concern often expressed about CdS/CdTe solar cells is the effect on health and the environment of the cadmium used.

The use of non-silicon semiconductor materials could dramatically reduce the materials cost of solar cells, with the absorber of such cells being two orders of magnitude thinner than that of silicon wafer cells. However, it appears that this is not enough to make a fundamental difference in the cost efficiency of solar panels overall: the drawback is the low yield and throughput limits of vacuum based thin-film deposition techniques, which result in higher process cost. As a result, none of the many thin-film efforts based on vacuum deposition has been able to produce products that are less expensive than crystalline silicon cells.

Some of the companies pursuing the CIGS line of development and attempting to ramp-up to full scale production in the next 6 – 18 months are:

TABLE 1. CIGS Modules Manufacturing Capacity Under Installation.

Sr.	**Vendor**	**Planned Capacity MW/Year**
1.	Aleo AG, Germany	30
2.	DayStar Technologies, USA	20
3.	Global Solar Inc, USA	60
4.	Honda Motor Company, Japan	27.5
5.	MiaSol, USA	200
6.	Nonosolar, Germany	430
7.	Shell Solar, France	20
8.	Showa Shell Sekikyu, Japan	20
9.	Würth GmbH, Germany	14.7
	Total	**822.2**

There will be another 4 to 5 companies entering the market for CIGS solar cells in 2007. If current announced plans are achieved, this technology should be able to deliver solar modules in production quantities by 2007-2008. However, it is difficult to predict, what will be the actual level of production as most of the new facilities are being created from the laboratory level experiments.

Another promising approach is thin film crystalline silicon. CSG Solar AG has started production of thin film crystalline silicon-on-glass modules from its 25 MW facility at Thalheim, Germany while Origin Energy has planned a 5 MW annual capacity facility for Sliver™ Cells in Adelaide, Australia. These cells are less than 70 μm thick, micro-machined from monocrystalline silicon. The application of these cells include building integrated photovoltaic (BIPV), semitransparent flexible modules and portable devices. Even if they are successful in producing commercial solar modules, they will still be small players in the market.

Chemists at the University of California at Berkeley are working to increase the efficiency of nano-crystalline solar cells. These are made by embedding tiny rods of the material in a semi-conducting plastic layer, which is then sandwiched between two electrodes. The rods are just 200 nanometres thick, or about one thousandth of the thickness of a human hair. These rods act like wires, absorbing light to create an electric current. Although nano-rod solar cell technology is inexpensive to manufacture, its expected efficiency is only about one tenth of traditional solar cells [3].

Dye-sensitized, photoelectrochemical solar cells are another type of organic solar cell. This cell is created using layers of electron-acceptor and electron-donor organic photovoltaic materials between two electrodes. These organic photovoltaic materials release electrons when light shines on them. The electron 'donor' material conducts negatively charged particles (electrons) to the negative electrode, while the electron 'acceptor' material conducts positively charged particles (holes) to the positive electrode. The separated charges created by this effect flow through a circuit as electricity. The Titania solar cells developed by Graetzl and co-workers in Switzerland are one of the most promising designs of this type. However, the efficiency of these solar modules is still very low and they are not available commercially [4]. They are potentially suitable for large-scale applications and for building-integration.

Each incoming photon from the solar light contributes at most one energized electron to the electric current it generates. Research carried out at Los Alamos National Laboratory in New Mexico and National Renewable Energy Laboratory, Golden, USA has broken though this barrier. It is shown that by shrinking the elements of a solar cell down to a few nanometers, each captured photon can be made to generate not one, but two or even more charge carriers. If the effect can be harnessed successfully, the multiple carrier generation could one day yield a solar cell with double the present efficiency, ie approaching 50% (the current world record efficiency is 24.7% achieved at the University of New South Wales, Australia) [5].

3. MARKET SHARES OF VARIOUS TECHNOLOGIES

Crystalline silicon is the most popular material for making solar cells, representing 90.9% of the 1,256MW of PV power modules produced in 2004 and 93.5% of the 1818MW of PV power modules produced in 2005 as shown in Figure 2. Crystalline silicon solar cells are manufactured from either mono-crystalline or multi-crystalline silicon.

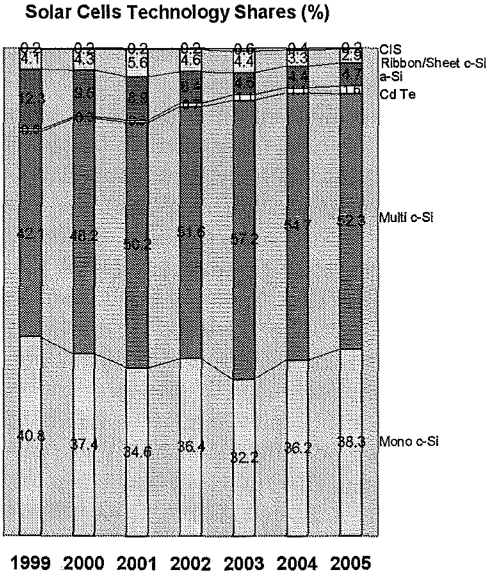

FIGURE 2. Market Share of Various PV Technologies 1999 - 2005 [2].

Although, it is commonly known that mono-crystalline silicon has a better power conversion efficiency than that of multi-crystalline silicon solar cells, industry players believe that the latter material will eventually become the mainstream material for solar cells, due to its lower cost. Mono-crystalline silicon wafers require a higher purity of polysilicon, which translates into higher costs. The cost of equipment used to produce mono-crystalline silicon solar cells is also higher than that used for multi-crystalline silicon production. From the point of profitability, solar cell makers see greater room for profits in using multi-crystalline silicon solar cells because the associated production cost savings, when compared to those of mono-crystalline silicon, can be considerable.

Therefore, as PV production output continues to grow, the cheaper multi-crystalline solar cell manufacturing technology is expected to gain greater market share.

4. FUTURE TECHNOLOGICAL TRENDS

As discussed above, crystalline technology is expected to dominate over the various thin film technologies for the foreseeable future. Figure 3 compares the expected share of crystalline silicon and non silicon technologies from 2004 to 2010. It should be noted that although there are many new industries underway to manufacture non-silicon based solar PV modules, the crystalline technology is expected to hold over 80% of the market until 2010. Secondly, the application of non-silicon technologies will remain primarily limited to BIPV and consumer products (such as solar powered watches, toys and calculators).

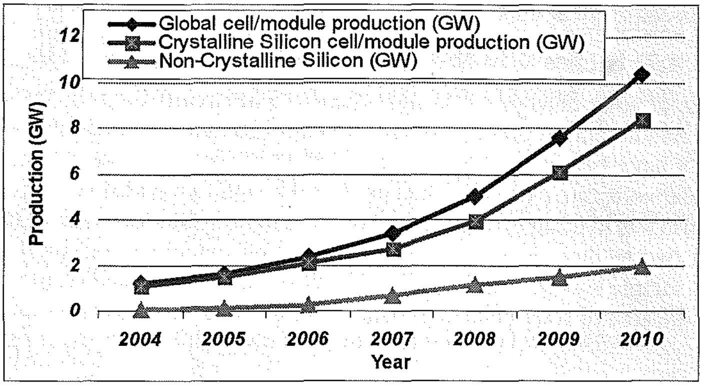

FIGURE 3. Forecast Production for Various Solar PV Technologies [2].

However, in order to maintain its share of the market, crystalline technology will need to undergo the following changes:

- Reduction in the thickness of the wafers
- Increase in the size of the wafers and solar cells
- Increase in the efficiency of solar cells
- Recovery of waste silicon in the wafer cutting processes
- Develop new technologies to use metallurgical grade silicon directly

4.1. Reduction in the Thickness of the Wafers

The thickness of the wafer is a crucial factor in reducing the consumption of expensive silicon material in the construction of solar cells. Currently 300 μm thick wafers are commonly used in the solar PV industry. There are a few solar cell manufacturers in the world, which use 180 μm thick wafers. String ribbon wafer manufacturing technology uses 30% less silicon-per-watt compared to traditional wafer manufacturing technology; however, there are also limitations to producing 150 μm thin wafers. Therefore, there is a need to reduce silicon-per-watt usage in the traditional method of wafer manufacturing. Some of the wire saw manufacturers have purity solar silicon from metallurgical grade silicon with an initial annual capacity of 1,000 tons [14].

JFE Steel Corporation has announced that it has started construction of a commercial SoG silicon plant with capacity of 100 tons/year and has also begun designing a plant to mass produce the material. JFE Steel Corporation claims that prototypes created with 100% MG-Si have achieved the same high conversion efficiency as conventional polysilicon [14].

A research team at the University of California, Berkeley, has developed a new technique to handle metal defects in low-grade silicon, an advance that could dramatically reduce the cost of silicon to be used for solar cell manufacturing [8]. Instead of taking the impurities out, they have suggested leaving them in and manipulating them in a way that reduces their detrimental impact on the solar cell efficiency. The team analyzed how metal contaminants in silicon respond to different types of processing using highly sensitive synchrotron x-ray microprobes capable of detecting metal clusters as small as 30 nanometers in diameter. The researchers found that the nano-sized defects scattered throughout the silicon limited the average distance electrons were able to travel before losing their energy. The longer the minority carrier diffusion length, the greater the energy conversion efficiency of the material. They have found that one way of managing these nano-sized metal defects is to round them up into large groups so that they are less disruptive to the electrons. Such research can lead directly to the use of MG-Si in furnaces for the ingot crystallization instead of using highly-pure and expensive polysilicon [11].

5. CONCENTRATING SOLAR CELL TECHNOLOGY

The concentrating solar cell technology is again experiencing renewed interest as the price of silicon has increased. At least seven newcomers in the market are trying to develop Fresnel lens based concentrating systems. A few manufacturers have also developed parabolic dish based technology.

In Australia, Solar Systems Pty Ltd has developed a successful concentrating system based on a combination of solar PV and solar thermal, using a hemispherical mirror collector (SEE SOLAR SYSTEMS WEB SITE http://www.solarsystems.com.au/154MWVictorianProject.html. They have recently been awarded a large Government contract to establish a 154 MW solar power project in northern Victoria.

However, the future of concentrating solar technology will remain uncertain if the supply of polysilicon improves in the coming years. The four factors in section 4 of this paper will help to further bring down the cost of manufacturing of crystalline solar cells and this may make it difficult for concentrators to compete in the market for large scale systems.

Although, the concentrating solar cell modules use only a small amount of PV material in their construction, the cost of the associated components will remain high. Fresnel lenses and other components used in the construction of concentrating solar modules have lower lives in comparison to concentrating solar cells and therefore, over time, such components will need replacement. The expected installed cost per watt for such systems is likely to remain over $3 per watt. The calculated manufacturing costs are $1.58 per watt for the modules – of which 59¢ goes for solar cells – and $3.03 for the complete system. This price may not be competitive with the traditional crystalline solar cell systems [12].

6. SOURCES OF RAW MATERIAL

The basic material used in the manufacturing of silicon wafers for solar cells is chemically pure polycrystalline silicon, of a quality close to solar-grade (99.99% in comparison to 99.9999% for semiconductor grade silicon) [13]. The solar industry has historically taken off-specification material that is rejected by the semiconductor industry. However, as the growth of the PV industry now exceeds that of the semiconductor industry, this scrap is in short supply and the new methods are being investigated to convert Metallurgical Grade Silicon into Solar Grade Silicon at a low cost.

The recent shortage of polysilicon in the market either from rejected materials from the semiconductor industry or from the only solar grade silicon manufacturing company (REC, USA) has restricted supply and price trends have hampered the overall growth rates of the PV industry. Leading polycrystalline vendors cannot keep up with the huge OEM demand and have reportedly sold out their entire production for the next two years.

Most of the new polysilicon manufacturing facilities are either being built for the captive use or the supply of polysilicon has been contracted out for 5 to 10 years. Although, the vendors are increasing their respective polysilicon production or building new facilities, incremental capacity will not be available in the near future.

During 2006, the following announcements were made to set up new silicon manufacturing facilities.

TABLE 2. Polysilicon Manufacturing Capacity [4].

Sr.	Vendor	Current Capacity Tons/year	Expansion Plan Tons/year
1	Hemlock Semiconductor Corp, USA	7,000	3,000
2	Tokuyama, Japan	5,700	2,500
3	Wacker-Chemie GmbH, Germany	5,000	4,500
4	MEMC, Pasadena, USA & Merano, Italy	3,800	4,200
5	Mitsubishi, Japan & USA	2,650	300
6	Renewable Energy Corporation, USA	7,100	6,000
7	Sumitomo, Japan	800	Not known
	TOTAL	**32,050**	**20,500 +**

TABLE 3. Newly Announced Polysilicon Manufacturing Capacity in 2006.

Sr.	Vendor	Capacity Tons/year
1.	Joint Solar Silicon GmbH, Germany	1,000
2.	D C Chemical, South Korea	3,000
3.	Hoku Scientific Inc, USA	1,500
4.	Isofoton, Spain	2,500
5.	Elkem Fiskaa, Norway	5,000
6.	Dow Corning, Brazil	Not known
7.	Prime Solar Pty Ltd, Germany	7,000
8.	M Setek, Japan & China	5,000
9.	Maharishi Solar Technologies, India	1,000
10.	China	1,500
11.	Norsun, France	4,000
12.	Solarvalue, Germany	5,300
	Total	**36,800 +**

Therefore, approximately 90,000 tons of polysilicon and solar grade silicon will be available from 2009-2010. Out of this estimated production of 90,000 tons, 75% - 80% will be available for the solar PV industry to manufacture at least 6 GW of solar cells and modules in 2010 while the remaining polysilicon will be used by the semiconductor industry.

Silicon Recycling Services, USA recycle the tails of ingots collecting from various ingot growing companies and its annual recycling capacity is 2,000 tones/year.

Canadian Solar Inc. operates one of the largest silicon reclaiming business in China. CSI is engaged in purchasing, processing and supplying ingots, pot scraps, tops and tails, side wall pieces, broken wafers, reclaimed wafers and broken cells.

The price of polysilicon has increased substantially in recent years as demand exceeded supply, resulting in higher quality grades and more expensive silicon being used to satisfy the demand as shown in Figure 4. The price of silicon raw material is determined by the demand of PV production, and the surplus of interchangeable raw materials. The situation will improve after 2007-2008 and the price will decrease from the present $70 to around the $40/kg level in 2009 once supply shortages have been alleviated.

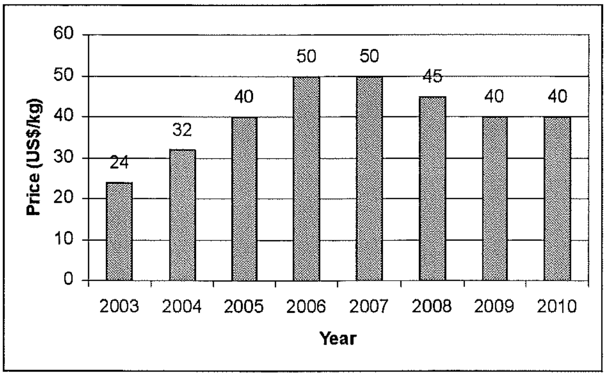

FIGURE 4. Change in the Price of Polysilicon [6].

7. CRYSTALLINE SILICON WAFER MANUFACTURING

In order to respond to the continuing strong demand for wafers, both from external customers and for their own solar cell production, REC has decided to build two new plants for multicrystalline wafers at Herøya, Norway. REC has announced in December 2006 that the company will expand its wafer production at its present Herøya production site. When up and running, total annual production will be close to 1.3 GW, making Herøya by far the largest solar production site in the world [14].

SolarWorld AG announced in December 2006 that the company will now further expand its capacity for the production of solar silicon wafers at its Freiberg location from the current 250 megawatts per annum within the next 28 months to 500 MW. Fifty per cent of this volume has already been sold up to 2018 by way of long-term supply contracts with the international solar cell industry. The other half will go into the group's internal value creation process. The solar silicon needed for the production of the 500 MW of solar wafers is secured by way of long-term delivery agreements with leading international silicon producers, the establishment of its own silicon factories and its Freiberg recycling facility [14].

Prime Solar Pty Ltd will set up a 785 MW multicrystalline wafers manufacturing facility at Thalheim, Germany. Prime Solar claims that it has received a good response mainly from the European solar cells manufacturers to its Expression of Interest for the supply of the wafers under a 10-year supply contract. Like REC and SolarWorld, Prime Solar is also setting up a polysilicon plant at Bitterfeld in Germany.

LDK Solar Hi-Tech Co Ltd is now the biggest multicrystalline wafer manufacturer in China. LDK plans to expand its capacity to 1,000 MW in 2010. The current wafer manufacturing capacity of Renesola, China is 80 MW; however it plans to expand it to 265 MW in 2007. Yingli Solar, Taiwan is expanding its 100 MW wafer manufacturing facility to 500 MW in 2007-2008 [14].

PV Crystalox Solar is the second largest European producer of silicon wafers and ingots. Operating at production sites near Oxford UK and in Erfurt Germany, the company concentrates on the dominant crystalline silicon technology, supplying both multicrystalline and single crystal products to the photovoltaic industry. Swiss Wafers AG produces 50 MW mono and multi-crystalline wafers in Switzerland. ErSol Solar Energy AG of Germany has also acquired ASi Industries GmbH in 2006 a wafer manufacturing facility at Arnstadt, Germany.

M Setek operates four mono-crystalline wafers plants in Japan and China. Further, it has announced plans to produce polysilicon for its captive use.

8. CONCLUSIONS

- During the next 10 years or so, crystalline silicon PV technology will continue to dominate as thin film technology still needs to make significant technological breakthroughs.
- The future is set for thinner wafers and higher efficiency crystalline solar cells.
- The thickness of wafers will approach 100 μm and the efficiency of solar cells will be in the 18% - 25% range.
- The reduction in wastage of silicon is imperative and the larger size of solar cells will bring the manufacturing cost down significantly.
- The thinner wafers, large size solar cells with increased efficiency, and the reduction of waste silicon will eventually bring the price of crystalline silicon solar cells below $2 per watt, well within the range of eliminating the government subsidies.
- New technological developments will permit the direct conversion of MG-Si to SoG-Si without the need to purify it to semiconductor grade..
- The price of solar grade silicon will come down within the next three to five years to its previous level of around $40 per kg as the manufacturing of polysilicon is poised to double.
- Concentrating technology will have only a small market share as it will not offer any cost-advantage over the traditional crystalline technology.
- New crystalline silicon wafer manufacturing capacity is being installed, mainly in Europe and China, to meet the expected growth in demand to 6 GW per annum of solar cells by 2010.

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