13th Workshop on Crystalline Silicon Solar Cell Materials and Processes
PV Feedstock Costs—Five Year Outlook

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Abstract
At the 8th Workshop on Crystalline Silicon Solar Cell Materials in 1998, the polycrystalline silicon production capacity and forecasted semiconductor and PV demand was discussed [1]. Feedstock sources, costs and options for low-cost solar grade polysilicon were presented. It was projected that the traditional sources of secondary grade poly material would be inadequate to meet PV demand by 2002. The surprise downturn in the semiconductor market and resultant polysilicon over-capacity alleviated a shortage as suppliers produced a solar grade polysilicon to meet PV demand. This paper charts the current and forecasted supply and demand for PV feedstock over the next five years. Feedstock costs, cost projections and cost reduction opportunities are presented. Even with a conservative PV growth rate of 15% per year, polysilicon capacity will be inadequate to meet PV demand by 2004. This will increase the average cost. Suppliers and users can cooperate to reduce total feedstock and ingot growth costs by: studying product mix effects on ingot volume, crucible load and melt time; incorporating bulk packaging; and establishing continuous feed systems. Purity data for large polysilicon lots can be correlated with ingot yield and cell efficiency data to define a feedstock purity specification and improve cell efficiencies.

Polysilicon Capacity
In 1998, the polysilicon industry was responding to rapidly increasing demand from the semiconductor industry, building new plants and expanding production facilities. The electronics industry demand was projected to be 29,000 metric tons per year by 2003. Capacity was expanded to 19,000 tons, and then up to 22,000 tons in 1999. Table 1 charts the 1998 projection of polysilicon capacity and forecasted semiconductor demand (Poly Capacity 1998 Estimate and IC Demand 1998 Estimate). This anticipated demand did not develop, with only 15,900 tons shipped in 1998. The downturn in the semiconductor industry and subsequent inventory build-up greatly reduced polysilicon requirements, with slow recovery. Shipments in 2003 are projected at only16,500 tons. In response, the poly suppliers cut back on expansion plans and operated at reduced volumes to match semiconductor demand. Operating capacity over the next five years is estimated in Table 1 (Poly Capacity 2003 Estimate). Consensus of the semiconductor forecasting services is for recovery in 2003-2004 [2]. Table 1 (IC Demand 2003 Estimate) lists actual shipments for 1998-2002 and assumes an average growth in semiconductor-grade poly at 10% per year to 26,600 tons by 2008. The polysilicon suppliers will add capacity based only on semiconductor demand. Semiconductor-grade polysilicon is priced at \$40-\$60 per kg, with the higher prices allowing construction of new capacity. New facilities and newer, larger reactors will be installed or started only as needed. Solar grade silicon (SOG) will be supplied from secondary material and a limited number of reactors modified for solar grade poly production. The low margins of SOG at \$25-\$35/kg do not justify additional

capacity expansions. A new polysilicon plant, constructed on a greenfield site, has a capital cost of up to $100 per kg, not including interest charges.

Table 1. Polysilicon supply and demand, 1998 estimates and 2003 update forecast, in metric tons.

Year	Poly Capacity 1998 estimate	IC Demand 1998 estimate	Poly Capacity 2003 estimate	IC Demand 2003 estimate
1998	19,000	19,000	19,000	15,900
1999	22,950	21,000	22,000	14,400
2000	25,800	22,000	23,300	17,000
2001	28,000	25,000	23,300	13,000
2002	29,300	27,000	23,300	15,000
2003	29,300	29,000	25,400	16,500
2004			25,400	18,100
2005			25,400	20,000
2006			25,400	22,000
2007			27,300	24,200
2008			30,000	26,600

Available Solar Grade Silicon Capacity

The amount of polysilicon available to the PV industry is determined by installed capacity minus the volume required for the electronics industry. Available capacity includes scrap or secondary material not meeting electronic grade specifications and material produced directly as SOG (Solar Grade Silicon). The seven major suppliers operate ten production facilities. Two of the suppliers in three of the facilities have decided not to deliberately produce SOG, but to market only secondary material and scrap to the PV market. One facility, ASiMI, Moses Lake, WA, has been converted to a dedicated SOG supplier, Solar Grade Silicon, LLC. Other suppliers have been willing to modify a limited number of reactors to produce a lower-cost poly product as Direct SOG, some sold at or below full production cost. The polysilicon suppliers have been willing to do this to keep experienced people employed and equipment utilized during the semiconductor downturn. When semiconductor growth resumes, this material will not be available, or available at higher prices, since new capacity must be funded by higher margin electronic grade poly sales.

Table 2 charts the total PV demand for feedstock in metric tons, recording the historical 25-35% growth to 2003, but assuming a conservative 15% per year rate for the next five years [3,4] (PV Demand). The values assume an improvement in conversion efficiency from 14 Mtons/MW to 12 Mtons/MW for Cz and multicrystalline technologies by 2005. The use of wire saws and advances in lapping/polishing techniques have made significant improvements in conversion efficiency from the 16-20 metric tons per megawatt in 1998. A wafer thickness of 300 microns corresponds to about 12 Mtons/MW. It is unlikely that conversion will drop to 10 Mtons/MW over the next five years, since breakage rates increase with thinner wafers. The production capacity available for SOG production (Available SOG, Capacity Minus IC Demand) includes the total scrap, secondary material, and unused capacity. While the capacity is available, not all suppliers have chosen to produce the low-margin SOG. As a shortage develops in 2004 and prices increase, this capacity may be made available for SOG production.

Some suppliers have announced plans for new capacity for SOG at lower costs. This material is expected to be available starting in 2004 and is added to the available SOG in Table 2 (Available SOG with New Capacity). Solar Grade Silicon, LLC, Moses Lake, WA announced in March 2003 start of a R&D program to develop a commercial fluid bed reactor to produce silane-based granular polysilicon at ~$20/kg. Plans are to have production of 2000 Mtons in 2006. Wacker Chemie, Burghausen, Germany, reported in 2002 development of a trichlorosilane-based fluid bed reactor for granular SOG, starting in 2003 at a capacity of 200 Mtons/yr. A pilot plant at 500 Mtons/yr at $25/kg is expected by 2006. Solar World and Degussa, Germany, announced in 2002 a JV to produce silane-based SOG, developing a polysilicon tube CVD reactor and a fluid bed reactor process for granular polysilicon. They expect to produce 800 tons by 2005. Even with this new capacity, a conservative PV growth rate, and a conservative semiconductor growth rate, a shortfall is projected for 2004.

There have been several R&D projects for purification of metallurgical grade silicon over the past twenty years and more continue to be studied [4]. It is unlikely that any of these will be in production in the next five years.

Table 2. Available SOG polysilicon in metric tons

Year	PV Demand 15% Growth	Available SOG Cap.- IC Demand	Available SOG With New Cap.
1998	2300	3250	
1999	2900	7600	
2000	3500	6300	
2001	4700	10300	
2002	6400	8300	
2003	7300	8900	
2004	8100	7300	7750
2005	9000	5400	6900
2006	10500	3400	6700
2007	12000	3100	7700
2008	13500	3400	8500

SOG Sources and Cost Projections

Table 3 lists the 5-year projected feedstock costs and volumes in metric tons of scrap (Scrap), directly produced SOG (Direct SOG), new capacity of SOG (New Capacity), total PV feedstock demand, and difference between capacity and demand (Balance) as shortfall to be purchased as higher priced semiconductor-grade poly. Scrap poly is from two sources: potscrap and rejects from semiconductor silicon crystal growth; and reject material from polysilicon production. Prior to 1995, this scrap material was sufficient volume to supply PV demand. The semiconductor silicon crystal growers would ship about 20-30% of production as tops and tails, reject crystals, and potscrap at prices ranging from $5-20/kg. As shortages developed, this material was found to be more valuable when used internally for production of test wafers. Some IC customers have approved the use of “refined poly” (formerly called remelt) for wafer production. As a result, the available scrap for PV is now about 5% of crystal production. Scrap from polysilicon production consists of small diameter rods, filament pieces, rod ends with graphite, small chips, chunks with surface powder, and other contaminated material rejected for semiconductor-grade poly. As shortages developed, some of this material was packaged as secondary-grade poly and shipped as SOG. About 7% of polysilicon production is now classified as scrap. Some of the scrap material is sold at prices about $5/kg, but requires significant reprocessing to remove quartz or graphite. Silicon re-processors buy this material in bulk, then process and sell at market price. The volume of scrap available increases with polysilicon production, but can not keep pace with PV demand. In addition, purity of this material is suspect with significant risk of lower ingot yields and cell efficiency. This year, scrap will account for 37% of demand, the remainder to be supplied from Direct SOG. By 2008, scrap will account for only 24% of demand, increasing the average feedstock costs.

Direct SOG represents the available polysilicon capacity (total capacity – semiconductor demand) for production of SOG. Most suppliers, reacting to the IC industry downturn, have decided to keep experienced operators employed and equipment running by producing a lower-cost poly as SOG. Faster deposition rates, reduced processing, reduced QA/QC, and bulk packaging have reduced the manufacturing costs. Prices are at or below full manufacturing costs to cover fixed costs and provide needed cash flow. Direct SOG will account for 63% of demand this year. By 2008, Direct SOG will account for only 10% of demand, as the available capacity is used for semiconductor-grade polysilicon. As the semiconductor demand increases, this capacity will be switched from SOG production, creating a larger shortfall. Some suppliers have decided not to participate in the Direct SOG market. For forecasting purposes, the total capacity is considered to be available, since these suppliers may decide to produce SOG at higher prices as a shortage develops. SOG pricing is quite fluid, with some available at ~$25/kg for long-term contracts. Source, shape, size, purity, and volume determine a price range from $25-35/kg. As the shortfall develops, higher prices are expected.

New SOG represents new polysilicon production capacity added to address the PV market, including silane and trichlorosilane-based fluid bed reactors for granular poly, and development of a tube reactor. This requires new capital investments and technology development funds. Some of the suppliers have implemented their plans, intending to produce a lower-cost product designed for SOG. It is ambitious to assume these new technologies will be available in large volumes by 2008, when they are projected to account for 38% of demand. Delays in developing the technology or installing production capacity will result in more of a shortfall and higher feedstock costs. The major roadblock to expansion of capacity is the high capital cost for construction of new chemical plants and CVD reactors. Investments can not be justified by the low margin of SOG at $20-$30/kg. Funding by consortiums, government/public funds or expansion premiums on feedstock prices will be necessary to fund future capacity growth.

The difference between PV demand and capacity from Scrap, Direct SOG and New SOG is listed as Balance. For this year, capacity exceeds demand by 2500 tons, assuming all of the available capacity could be used for SOG. No shortfall is forecast for this year, as suppliers have a large excess capacity and are willing to produce Direct SOG. The situation will be marginal in 2004, assuming a conservative 10% growth in semiconductor demand, a conservative 15% growth in PV demand, willingness of suppliers to produce more Direct SOG, some new SOG capacity on-line, and inventory levels. A 25% PV growth rate would cause a 500 ton shortfall in 2004. By 2005, the shortfall starts to increase rapidly, driving up average feedstock costs. The PV industry will have to compete with the IC industry for this polysilicon at semiconductor-grade prices, leading to higher feedstock costs

Table 3. Projected costs and volumes of PV feedstock in dollars per kilogram for metric tons.

Year	Scrap	Direct SOG	New SOG	Total Demand	Balance
Price	$5-$20/kg	$25-$35/kg	$20-$30/kg	Metric Tons	$40-$60kg
2003	2700	7100		7300	2500
2004	2700	5500	450	8100	500
2005	2800	3600	1500	9000	(1100)
2006	2900	1600	3300	10500	(2700)
2007	3000	1200	4600	12000	(3200)
2008	3300	1300	5100	13500	(3800)

Cost Reduction Opportunities

Table 4 lists the cost reduction opportunities for suppliers and users. The polysilicon suppliers have implemented some options to reduce costs: increasing silicon deposition rate, reducing the number of rod processing steps (filament reactors), adopting a wide range of chunk sizes (filament reactors), reducing the analytical sampling plan, and using bulk packaging. The faster deposition rate reduces electricity costs and increases throughput; however, the faster rate increases dendritic growth, powder content, and structural voids. Reducing the number of processing steps and allowing inclusion of rod sections, chunks, chips and small diameter rods reduces labor and increases yields. Reducing the number of samples for complete evaluation saves analysis and inspection costs. Bulk packaging saves packaging materials and labor costs. Minimal packaging materials and use of recyclable or returnable containers minimize packaging costs. For a current packaging system of 10 kg bags in a 60 kg carton, a 1000 kg bulk package would save 100,000 bags and 16,500 cartons when shipping 1000 Mtons. At this point, the suppliers have reduced production costs for SOG up to $12/kg, as reflected in semiconductor-grade poly pricing at $40-$60/kg, and Direct SOG at $25-$35/kg. Granular form polysilicon can be produced at cheaper costs, about $22/kg, since the fluid bed reactor is more energy efficient and has greater throughput than the filament reactor. Granular poly specification issues affecting costs are size distribution, shape, powder content, hydrogen content, and surface impurity levels.

Other specification issues with cost impacts are maximum/minimum sizes, size distribution range, and levels of impurities. Reduced processing steps and more cost-efficient packaging may increase the levels of surface metals and carbon impurities. It is important that the impurity levels affecting ingot yields or cell efficiencies be identified. The often unknown and suspect levels of impurities in scrap make this a risky source of feedstock, increasing costs beyond the attractive initial price. As large quantities of Direct and New SOG become the major feedstock sources, data exchanges between suppliers and users will yield statistically significant data for the design of a comprehensive SOG specification.

The users have realized significant cost reductions from improved slicing yields. The opportunity now is for reductions in ingot growth costs by cooperative efforts with the polysilicon supplier. For Cz and multicrystal growth methods, the optimal mixture of polysilicon rods, chunks and chips/granules will improve crucible packing, thus increasing crystal weight or volume per run. Poly granules have a packing density about 1.5 g/cc, chunks about 1.66 g/cc and rods about 2 g/cc. Designing an optimal mix of rods, chunks, and chips/granules for a 24 inch diameter crucible size can increase ingot weight by 40 kg, saving $5/kg in ingot growth costs for a crucible load. Rods can be loaded faster than chunks, so load time can be reduced. Rods have a faster melt-in time than chunks or chips/granules, so electricity use is reduced and throughput increased.

Table 4. Cost reduction opportunities for suppliers and users with cost savings estimates in dollars per kilogram.

Supplier Cost Reductions		User Cost Reductions	
Item	Cost Savings Est.	Item	Cost Savings Est.
Dendritic Structure		Crucible Loading	$ 5/kg
Powder		Load Time	$ 0.2/kg
Size Distribution		Melt Time	$ 3/kg
Sample Plan		Packaging	$ 0.1/kg
Bulk Packaging		Inventory	$ 0.2/kg
Purity		1% Cell Efficiency	$ 10/kg
Total Poly Cost Reduction	~ $12/kg	Total Ingot Growth Cost Reduction	~ $ 18.50/kg

Incoming material handling charges can be reduced by the use of bulk packaging. Just-in-time delivery reduces inventory charges. As an ingot production operation grows to consume over 100 tons/year, larger bulk packages, over 1 metric ton, should be considered to further reduce packaging, inventory, and shipping costs.

By pre-packing a shipment with the optimal mix of rods, chunks, chips, and granules to the exact crucible weight, the ingot grower saves crucible loading time and labor costs. Crucible-size packages would range from 250 kg to 1000 kg, optimized for each user.

Purity has a major effect on costs if impurities reduce cell efficiency. Increasing the cell efficiency by 1% is equivalent to a $10/kg feedstock cost for the total PV module cost. It is estimated that ingot growth costs could be reduced by at least $18.50/kg ingot with initial cooperative efforts

In Cz furnaces, recharge systems allow the crucible to be reloaded with polysilicon after the first crystal pull. This extends the crucible life, with 3 to 6 pulls from one crucible. Hot zone life is increased and energy efficiency is increased since cooling to room temperature between runs is not necessary. Shell Solar [5] reported power consumption reduced by 51%, production increased 20-25%, and cell efficiency improved 5%. Recharge systems can use rods or granules. As the polysilicon supplier and ingot grower cooperate to design optimal delivery systems, further ingot growth cost reductions can be realized.

Conclusions

1. The polysilicon suppliers built excess capacity in 1998-2000 anticipating unrealized demand from the semiconductor industry.
2. Some suppliers responded to the rapidly-growing PV industry demand by producing a lower cost SOG, $25-$35/kg prices, from the excess capacity.
3. Scrap polysilicon, the historical source of feedstock, has been reduced from 20-30% of poly production to 12% as much of this material is sorted and packaged as SOG or sold for other uses.
4. The semiconductor industry is recovering, with continued growth estimated at 10% per year.
5. The suppliers need the higher margins of semiconductor-grade poly, $40-$60/kg prices, to justify any further capacity expansions.
6. The low margins of SOG do not justify capacity expansions.
7. Three suppliers have announced plans to develop new technologies for a lower-cost SOG, $20-$30/kg, to be in production over the next five years.
8. Assuming a conservative PV growth rate of 15% per year, a conservative semiconductor demand of 10% per year, continued advances in gram/watt efficiency, and plans for new SOG capacity, polysilicon production capacity will be inadequate to meet PV demand by 2004, with large shortfalls by 2005.
9. As shortages develop, prices for SOG will increase; SOG prices will approach semiconductor prices in order to fund new capacity.
10. Suppliers have reduced SOG costs ~$12/kg by increasing polysilicon deposition rates, reducing the number of processing steps, adopting a wide range of chunk sizes, reducing the analytical sampling plan, and using bulk packaging.
11. Users have opportunities to reduce ingot growth costs in cooperative programs with suppliers, including studies of product mix on ingot volume, crucible load and melt time, and implementing bulk packaging.
12. Further ingot growth cost reductions can be realized by development of continuous feed systems.
13. Purity data for large poly lots from dedicated facilities can be correlated to ingot yield and cell efficiency data to define a feedstock purity specification.
14. Increasing cell efficiency by 1% is equivalent to a $10/kg feedstock cost for the total PV module cost, so more emphasis will be placed on SOG purity and ingot quality.

References

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