Cost reduction and productivity improvement strategies for multicrystalline wafering processes

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ABSTRACT

Multicrystalline wafers are the workhorse of the PV industry, with approximately 60% of crystalline silicon solar cells made from the substrate. They offer cost advantages in the form of good conversion efficiencies, which should continue to improve as cell technology advances continue. However, wafer prices were acutely impacted by the fall in PV market demand in late 2008, which continued through most of 2009. With relatively high capital costs, continued pricing pressures and calls for greater quality and control, wafer producers are now set on a course that requires rigorous and sustainable production cost-reduction strategies to meet customer requirements. This paper focuses on strategies that can be adopted to address this need for tighter quality specifications that reduce manufacturing costs downstream and boost cell conversion efficiencies.

Introduction

Polysilicon, wafer and solar module prices all declined severely in 2009. According to a recent report from iSuppli Corp., average crystalline module prices dropped by 37.8%, solar wafer prices fell by 50%, and polysilicon prices declined by 80%.

The market research firm expects further price declines in 2010, though not at the steep levels seen last year. In 2010, iSuppli is forecasting price declines for crystalline modules of 20%, solar wafers to decline by 18.2%, and polysilicon prices falling by a further 56.3% (see Fig. 1). Many industry observers now believe that with the continued growth in polysilicon production by both major and new entrant producers, declining prices along the supply chain are now set in stone for the industry.

Of course, this is a key prerequisite for an industry chasing the elusive grid parity (and beyond), which will benefit the players in becoming increasingly competitive with other renewable energy forms.

"The erosion in pricing is bound to change the face of the solar industry," noted Henning Wicht, Senior Director and Principal Analyst for Photovoltaic Systems at iSuppli. "The freefall of PV prices represents a permanent ratcheting down of price structures that will transform the industry into a more competitive marketplace."

iSuppli expects PV manufacturers to continue to focus on cost reductions in order to keep up with the price declines and to repair compressed profit margins experienced in 2009. When the cost-down programs eventually catch up with the rate of price declines, an overall improvement in the profit picture can be expected, Wicht said.

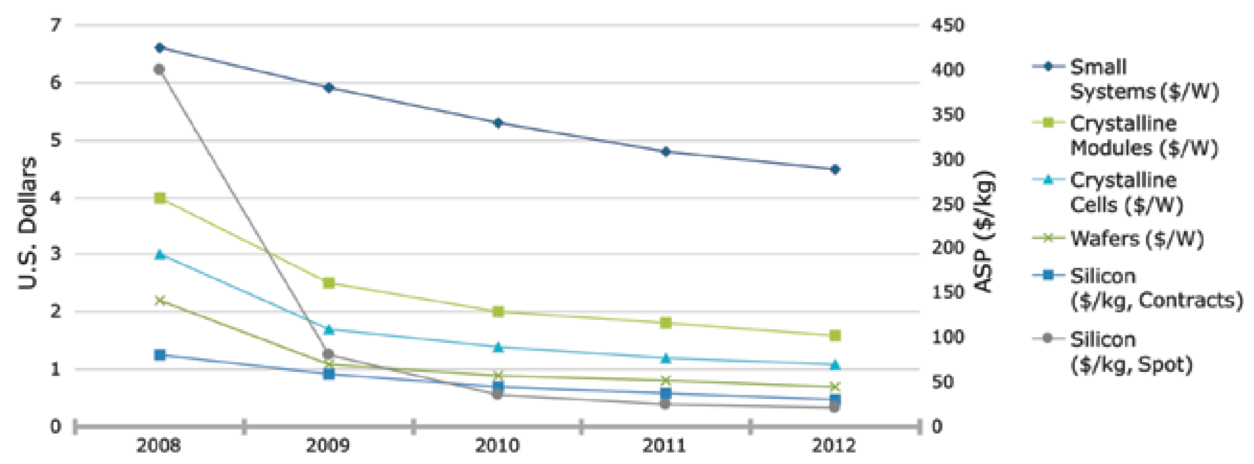
This is of particular importance to polysilicon and wafer producers, who have experienced the most aggressive price declines, yet have significantly higher capital costs compared to others downstream, such as pure-play module manufacturers.

Challenges also exist for wafer producers. With the strong wafer demand creating a very tight supply environment, further capital expenditures will be necessary to meet customer demand. Traditionally in periods of strong demand, equipment lead times extend to over nine months as key production equipment such as furnaces and wire saws are slowly churned out. These tools are large in size and/or complex in construction making them inherently difficult to manufacture in high quantities at the short lead times.

The role of polysilicon

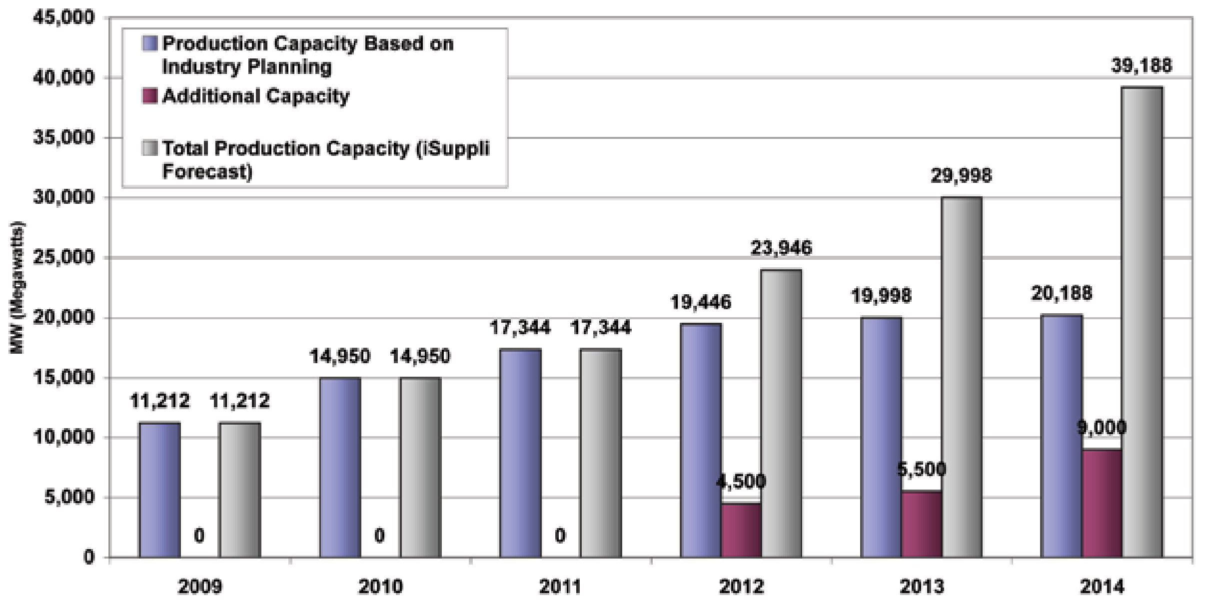
Disconnects between points in the supply chain as seen recently in polysilicon shortages are in danger of transferring to the wafering sector. This results in greater pressure to boost productivity while new capacity is planned and eventually implemented.

As can be seen in Fig. 2, iSuppli has surveyed wafer production expansion



Courtesy of iSuppli Corp.

Figure 1. Average selling price forecast 2008-2012 in US$/MW.



Courtesy of iSuppli Corp.

Figure 2. Global solar wafer production capacity plans (MW).

plans of producers that show only a gradual expansion (left column) in wafer capacity based on actual planned capacity additions. The middle column shows the potential additional plans that could be undertaken but have yet to materialize. Only in 2012 and beyond will we see those plans add meaningful production capacity.

It could be argued that such a forecast only reinforces the pressures on wafer producers to optimize current capacity throughput, yield and overall productivity. New capacity additions could also benefit from new technology introductions that also reduce production costs. Those that successfully tackle these challenges will not only benefit from lower costs and improved margins, but also attract more customers downstream requiring lower prices to remain competitive. They will also gain advantage in a continuing overall price decline environment.

There should be little doubt that polysilicon and solar wafers are intrinsically linked. Wafer price declines have primarily been a result of the even greater decline in virgin polysilicon prices since mid-2008. Numerous market research reports point to continuing capacity expansions that should lead to further price declines. A recent report from Bernreuter Research estimates that global polysilicon production will reach 250,000MT in 2012, with approximately 80,000MT produced in China alone, making up about one-third of global production.

Johannes Bernreuter, founder of the research firm, told *Photovoltaics International* that polysilicon supply/demand dynamics this year would translate into spot pricing in the range of US$45 to US$50/kg.

"Wafer producers have benefited from an overall improvement in material quality due to better availability of virgin polysilicon."

"In 2011, I expect that a significant volume in China will probably be produced at manufacturing costs below US$35/kg, and that the spot price will fall to this level – whether by the end of the year or earlier," commented Bernreuter.

Wafer prices will therefore continue to decline, but as seen in 2009, prices fell much more than manufacturing costs, leading to significant margin declines. However, wafer producers have actually benefited from the plentiful supply of polysilicon in a different way. According to Nick Sarno, the former VP of Manufacturing at LDK Solar and now currently consulting for the industry, wafer producers have benefited from an overall improvement in material quality due to better availability of virgin polysilicon and the declining dependence for some using scrap silicon to complement ingot production.

"This translates into cost reductions throughout the wafer manufacturing process," noted Sarno. "Less man hours on procurement of scrap silicon, sorting and storing has a small impact but better quality supply of virgin material produces better ingots, blocks and wafers, reducing scrap, consumables and delivering a better product all round."

Furnaces: is size the solution?

In an effort to reduce ingot costs, there has been a gradual but growing trend towards larger ingot sizes. The larger the ingot, the more blocks and consequently wafers can be produced, resulting in increased overall yield increases (see Table 1). This therefore requires larger ingot growth furnaces. Much of the current ingot production is performed using Directional Solidification System (DSS) furnaces that cast multicrystalline ingots using 450kg furnaces for volume production. Developments continue on charge sizes above 500kg and 800kg, and there are

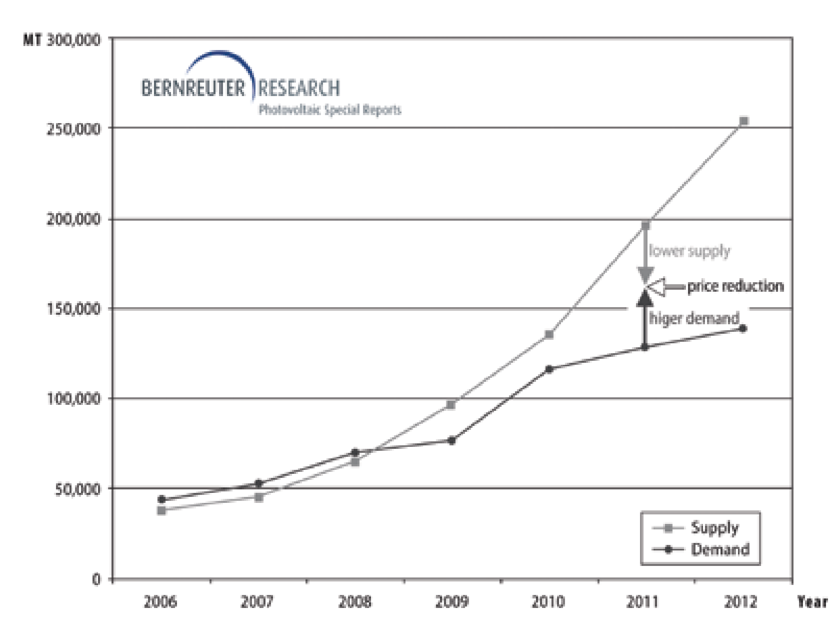


Figure 3. Bernreuter Research: polysilicon supply/demand pricing dynamics.

Figure 4. Crucibles at Ceradyne Tianjin Technical Ceramics.

Figure 5. GT Solar's DSS450HP ingot growth furnace.

Model Name		JZ-270	JZ-450	JZ-520	JZ-800
Initial Charge of Poly-silicon (kg)		270	450	520	800
Estimated Dimension of the Solidified Ingot (mm)	L & W	680	840	840	996
	Thickness	250	270	315	345
Estimated Dimension of Cropped Blocks (mm)	L & W	156	156	156	156
	Thickness	200	220	265	295
Estimated Weight of Cropped Ingot (kg)		181.4	311.8	375.7	602.2
Estimated Yield for Ingot (%)		67.2	69.3	72.3	75.3

Table 1. JYT large furnace benefit analysis.

efforts underway to increase ingot sizes to 1,000kg in the not-too-distant future.

In today's market, a key limitation is the technological capability to manufacture crucibles of ever-increasing size. Common industry practice has been to tackle this obstacle by adopting larger furnaces but using multiple crucibles at a time within the furnace for optimization and greater throughput.

"From a capital expenditure point of view this strategy is a plus," noted Sarno. "You are future-proofing investments in anticipation of the larger crucibles being available, while not having additional investments for going bigger just because of crucible size limitations."

Crucible manufacturers are attempting to address several challenges at once, answering increased demand for larger-sized crucibles – in particular 450kg products – while re-tooling for even bigger sizes in the future.

Ceradyne, a leading fused silica crucible manufacturer, is expanding manufacturing in the first half of 2010 in its existing facility, Ceradyne Tianjin Technical Ceramics (see Fig. 4), and has broken ground on a second facility, Ceradyne Tianjin Advanced Materials, which will be operational during early 2011, to meet growing demand.

A leading DSS furnace supplier is GT Solar, a company that has certainly seen the growing demand for larger systems in the last few years. During fiscal year 2009 and 2010, GT Solar sold approximately US$1 billion of capital equipment into the market to support the build-out of installed end-user capacity of approximately 8GW to 10GW.

Interestingly, the issue of larger furnace sizes was not the first point of conversation that Henry Chou, Product Marketing Manager, PV Equipment for GT Solar International wanted to mention. Rather, he noted that as the industry becomes more mature, GT Solar has brought to the table what he describes as the 'value metric.' Using simplified variables to highlight manufacturing costs, the company targets cost reductions via improved throughput of the tool coupled to higher yields and better overall ingot quality. This then translates into less wastage from the ingot to the wafer sawing steps, also lowering costs.

"Being able to get better quality wafers as a result does indeed enable cell producers to achieve higher conversion efficiencies," commented Chou. "What we look for is good kilograms produced per hour."

> "The two key metrics for cost reduction at the furnace are throughput and yield."

The two key metrics for cost reduction at the furnace are throughput and yield, according to Chou. With respect to throughput, this relates to the charge size divided by the process time.

"Interestingly, if you start to add more mass to the charge, your process time will start to increase. Based on the process time, the quality of the segregation of

Figure 6. CRS Reprocessing Services' typical slurry recycling system.

impurities and growth of the crystals changes the optimum balance. So if you grow bigger ingots it doesn't necessarily mean that you are going to get higher throughput, due to the growing cycle needing to be longer," added Chou.

He also believes that ingot sizes above 600kg could lead to other equipment changes that actually add to the cost of production. Consensus on whether charge sizes above 450kg are inevitable would seem to be premature. The company has recently been tapped for its 'DSS450' furnaces and ancillary equipment and services to the value of US$200 million. The orders come from a range of wafer producers, including Tianwei New Energy, Phoenix Photovoltaic Technology, Yingli Green Energy, JA Solar and Sino-American Silicon Products (SAS).

In early May 2010, the company launched the 'DSS450HP,' a high performance ingot growth furnace with a thermally optimized, second-generation hot zone that is said to improve throughput while delivering industry-leading crystal quality. Current users of the DSS450 and DSS240 models can migrate to the new DSS450HP with a field upgrade kit, which means that in the near term, wafer producers are regarding proven technology offerings as preferable to pushing the boundaries of even larger ingot/furnace sizes.

Slurry solutions

Slurry is at the heart of wafer manufacturing. It is used with wire saws to cut the wafers out of silicon ingots, normally comprising an abrasive mixture of silicon carbide and ethylene glycol that erodes, rather than cuts, the ingot. Generally, a conversation centring on where key costs are located across the various wafering processes will lead straight to the topic of slurry.

As the slurry is fed along a guide wire, the abrasive silicon carbide in the slurry (or 'grit') cuts through the ingots to produce the wafers. Slurry should be regularly replaced and reprocessed in order to keep the number and quality of the wafers high while maintaining acceptable unit cost.

Although slurry is vital to the process, it also represents a significant proportion of the wafer production cost; slurry costs are often second only to the cost of the polysilicon itself. Despite the relatively low price of US$3.50 per

Figure 7. In-house slurry recycling system at LDK Solar.

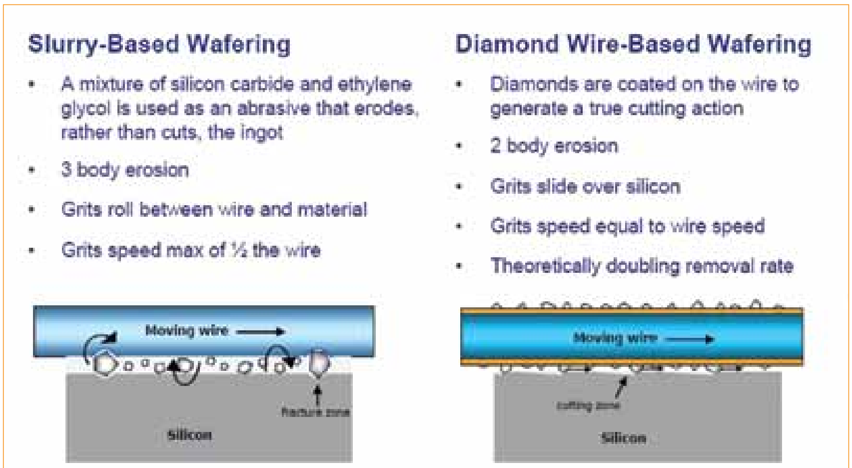


Figure 8. Meyer Berger's diamond wire comparison chart.

kilogram for new slurry, the overall cost can quickly escalate. In a scenario where 10 wire saws are being used in a process, the operating cost can be as high as US$16 million a year, not including disposal fees or labour charges.

"A do-it-yourself scenario may impact quality control and productivity."

For the vast majority of manufacturers, slurry reprocessing ranks in the top five contributors to operating cost. Optimizing this aspect of the business can have dramatic and lasting effects on wafer production costs and overall quality.

According to CRS Reprocessing Services, a leading slurry recycling firm, wafer manufacturers that are planning a slurry reprocessing program or starting from scratch in a greenfield operation can benefit from significant margin-enhancing improvements. For a wafering operation running 10 wire saws with a volume of 385 metric tons per month, slurry reprocessing can result in a saving of anwhere in the region of US$8-10 million per year, net of recycling costs, utilities, and infrastructure investment.

Figure 9. Fewer Si losses are possible through the optimal positioning of the block within the cropping saw.

"At CRS Reprocessing Services we are able recover between 80% and 90% of both the grit and the carrier," noted Bill Lawrence, founder and president. "The actual amount of recovery is a function of the wafer size, wafer thickness, saw set-up and the silicon kerf loading in the used slurry. For oil-based slurries, the recovery of the cleaning solvents used to rinse wafers and equipment is typically greater than 90%. In short, the higher the recovery rate, the more material is effectively recovered and reused, and the less that must be spent on new material."

The benefits of slurry recycling were echoed by Nick Sarno, who recalled a huge move toward recovery strategies during his time at LDK Solar. Sarno noted that LDK has a 30,000MT recycling system designed in-house (see Fig. 7), with a similar system being installed as the company ramped wafer production beyond 2GW per annum. Sarno reiterated that cost avoidance was a key aspect as recycling significantly reduces the use of new material.

Perhaps not surprisingly, CRS's Lawrence cautioned against the tendency for wafer producers attempting to design in-house systems instead of using fully supplied and managed systems from expert third parties.

"The downside is that do-it-yourself options tend to have much lower recovery rates for both grit and for the carrier. These processes typically recover only a small portion, say, 20-30%, of the carrier. In addition, a do-it-yourself scenario may impact quality control and productivity resulting from lower specifications, limited lab verification tools and increased downtime.

"To put it in perspective, an optimal reprocessing solution that increased the recovery of both grit and carrier could easily decrease the overall costs for a 10-wire-saw operation by US$275,000 to US$375,000 a month. These factors, along with the need to fund resources that are not central to the business, reduce the potential savings that are expected by taking the process in-house."

In general, there are four options when it comes to reprocessing slurry: do-it-yourself, off-site reprocessing, on-site reprocessing, or do no reprocessing at all.

Lawrence went on to point out some of the cost issues associated with off-site reprocessing, which is popular in Europe. He noted that the service fee for off-site reprocessing can be competitive, perhaps even lower than the common alternative of on-site reprocessing. There are a number of other costs, however, that factor into an off-site processing scenario that should be considered.

Chief among these are freight costs – both trucking and shipping, which can vary depending on the amount of slurry and transportation distance. In some cases, the expense can be considerable. Rates range from US$0.03 per kilogram within a country to up to US$0.40 per kilogram around the world. For a customer processing 800MT per month, this could total over US$200,000 per month. Off-site reprocessing also requires that a manufacturer have large amounts of slurry 'in play.'

Many of these issues have long pervaded in parallel industries such as semiconductor manufacturing, where most of the required recycling is done on site, bringing with it other benefits.

From a quality control standpoint, on-site reprocessing brings full transparency to the manufacturer, who gains the advantage of immediate and verifiable slurry. Since the slurry does not leave the facility, it is reprocessed in a closed loop that eliminates the risk of outside contaminants entering the production stream. On-site testing, conducted by experts who can easily and quickly adjust levels to achieve consistent and optimized slurry, helps ensure wafer yields are high with minimal waste.

Once again, the issue of quality is a key factor that should not be overlooked in the pursuit of straightforward cost analysis. Optimized yield and high quality products are often greater cost saving pursuits.

Chemical contribution

Of course, slurry is not the only chemical used in wafer processing. Cleaning and texturizing steps use HF acids in baths. Simply shopping around for lower cost bulk chemicals may prove effective in the short term, but once again, using the right chemistries for yield and wafer quality considerations could prove to be a greater contribution to cost reduction and optimization strategies.

Frank Haunert, Product Manager at BASF, commented that 'solar-grade' bulk chemicals such as HF acids that are not specific to semiconductor purity levels have been developed, which means that they can therefore be offered at lower prices, while maintaining the quality and consistency requirements that optimize processes. With respect to BASF's 'Seluris' range of etching and texturizing chemicals, Haunert noted that they enable saw damage to be rectified and the wafer surfaces to be structured from 'drop-in' solutions, reducing quality inconsistencies and delivering a more homogenous wafer result.

> "A key bonus of diamond wires is that slurries are not required, therefore dispensing with the expensive material altogether."

With respect to slurry, Haunert noted they are developing slurries that have tackled issues such as wire pairing: "The typical wire saw can experience surface tensions that mean the wires cannot get through the slurry solution and start coming together creating one thin and one thicker wafer. This has a negative impact of yield and overall productivity."

Diamond wire solution

The new kid on the block for sawing bricks and wafers is diamond wire technology (DWT). A key bonus of diamond wires is that slurries are not required, therefore dispensing with the expensive material altogether. This of course means that there are no recycling costs nor any of the other costs associated with the use of slurry. DWT is also claimed to provide 2.5-3x the throughput compared to conventional wire/slurry combinations and is said to offer improved cutting accuracy, reducing kerf loss and providing stable processing partly due to its simplicity relative to slurry-based processing. Although still in its infancy from an adoption perspective, the technology has some potentially compelling aspects.

"We believe we can drive down the wafering costs by 10 to 15% initially with diamond wire technology and further improvements later," commented Peter Pauli, CEO of Meyer Burger Technology AG. "The important part of that is yield improvement. The industry as a whole only has an 80 to 90% total yield. If we only deliver a 5% yield gain this would be a dramatic improvement for the industry."

However, concerns have been raised over the use of DWT, not only because of the inherent cost of diamond wire, but due to the physical difference of the resulting wafers compared to conventional wire/slurry-produced wafers.

Nick Sarno cautioned that diamond wire leaves score marks on the surface of the wafer, making the wafers look physically different from non-DWT produced wafers. This has returned some negative feedback from customers, reporting that they are 'a little afraid of using' this type of wafer.

Meyer Burger's CEO was well versed on this issue: "The sub-surface damage is actually less than with slurry," Pauli pointed out. "The surface may look a little bit different, but changing to another technology takes time. We don't expect a dramatic uptake of the technology right now."

"Changing to another technology takes time" – the same can be said about changing perceptions regarding DWT. To that end, the company has made great strides in developing and importantly demonstrating the cost and yield benefits of DWT. Meyer Berger has invested positively in the complete system technology and infrastructure that would enable the industry to migrate to DWT at the high volume commercial level. Pauli noted that the actual diamond wire was only one aspect of the complete package needed to make adoption successful.

"The key is that DWT changes wafering, internally and dramatically," he added. "It gives us the opportunity to change and improve the whole line – simplifying and reducing steps and equipment needed in the value chain. With overall complexity of the wafering process reduced, we have the ability to improve the overall yield and bring the industry into the industrialization phase. This, to me, is the future."

Thinking thin

With the return of a plentiful supply of polysilicon, it would seem that there is less talk focused on migrating to thin wafers in order to reduce cost. Although companies like LDK Solar have continued to migrate gradually to thinner wafers, there is less emphasis on taking wafers thinner than 170 microns, due to concerns at the cell processing level regarding higher rates of wafer breakage. Although developments continue at the R&D level, production efforts remain focused on kerf loss.

Process optimization

However, conventional wire/slurry technology is not stagnant. Significant efforts are ongoing to provide the yield and cost reductions required for the industry across the complete wafering process flow.

Herbert Arnold GmbH & Co. KG is a leading manufacturer of production systems for processing mono- and multicrystalline silicon bricks that incorporate cutting, grinding and polishing.

> "Significant efforts are ongoing to provide the yield and cost reductions required for the industry across the complete wafering process flow."

Speaking with Wolfgang Schürgers, Sales Director at Herbert Arnold, it was apparent that there are significant opportunities in regard to the optimization of equipment and processes that not only shorten cycle times but also provide greater understanding of the overall processes that in return improve productivity, quality and yield. The introduction of advanced technology manufacturing systems improve process control and an integrated, process data analysis creates transparent and efficient production.

"What I can see is a lot of effort to optimize Gen5 ingots to produce 25 bricks of higher quality and improve the height of ingots by 300 to 400mm," noted Schürgers. "I don't see the trend towards the one-ton ingot. Kerf loss is still an important issue and we are able to provide a cut with the smallest kerf loss possible."

Schürgers highlighted that cropping with blade saws rather than wire saws provides accurate straight cutting and lower cost. The development of high precision (1.5mm) blades with the optimization of the thickness of the smallest of blades significantly reduces kerf loss and boosts machine uptime, increasing throughput.

With the move towards larger wafer production lines in excess of 500MW capacity, there will be a growing trend towards fully automated lines, according to Schürgers.

Herbert Arnold have calculated that automation of the entire process flow would generate at least a 10% overall productivity improvement. This is achieved by optimized 24-hour operations, reduced waiting times for tool availability and reduced machine idle time as a consequence. Importantly, highly optimized positioning of the brick and saw results in consistently improved yield.

Schürgers believes that high-volume facilities of 200MW and above that are still dependent on manual handling will have to deal with high error rates as a result of human operations, which have a considerable impact on the line's ability to be fully optimized.

Optimization of the complete line was repeated as a necessity by Greg Knight, Director of Process Engineering Turnkey Services for GT Solar.

"Equipment is one piece in operating a factory," remarked Knight. "How you utilize that facility is actually a bigger piece. We have done a lot of analysis on streamlining operations such as how we process material straight out of the furnace. There would seem to be a significant loss of revenue occurring in a lot of wafering facilities because they are making the decision to cut on the marked brick lifetime lines… while this is a useful metric, using metrology to determine what is good and bad enables only the bad material to be turned into dust."

According to Knight, better or less conventional cutting approaches can take yields to the 90% range when typically many wafer producers are operating in the sub-70% yield range.

Significant effort has been made with GT Solar's turnkey lines to enable the feedback of data from sawing to ingots. The multiple issues that can occur such as rejects and saw marks can be traced back to the specific furnace and correction procedures implemented in order to limit prolonged yield impacts. Detailed monitoring of the operations enables tighter process tolerances that reduce reactive changes and so boosts productivity and reduces cost.

> "Better or less conventional cutting approaches can take yields to the 90% range."

Chemical usage optimization was also a factor covered by BASF's Haunert. He noted that efforts are ongoing to maximize the use of a given amount of material for the highest possible number of wafers. Aspects such as bath temperatures and flow rates are fine-tuned to enhance the chemical characteristics for processes such as wafer cleaning.

Conclusion

As wafer producers recover from rapidly declining prices in 2009 and focus on a new wave of capacity expansions to meet strong demand in 2010, cost reduction continues to be a core focus. The continuing abundance of polysilicon may well continue to place margin pressure on wafer prices, despite tight supply and a short-term recovery in wafer prices. Wafer producers that are vigilant in regard to cost and process optimization strategies will not only weather economic conditions better, but will likely flourish ahead of those competitors that fail to tackle these challenges in a coherent manner.