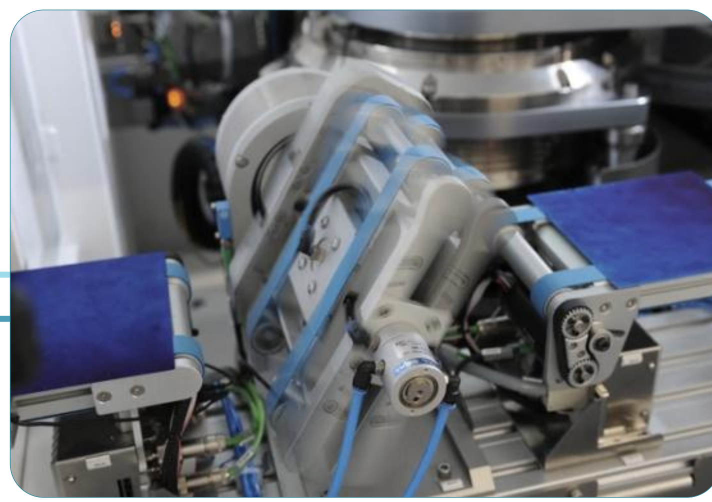
COST OR VALUE? PHOTOVOLTAIC CELL MANUFACTURERS LOOK BEYOND THE COST OF OWNERSHIP



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COST OR VALUE? PHOTOVOLTAIC CELL MANUFACTURERS LOOK BEYOND THE COST OF OWNERSHIP

Solar is the next great energy frontier. Interest in renewable energy sources has never been higher, and manufacturing process technology is advancing at a rapid pace to meet the demands of the photovoltaic market. Sunlight is free, but the technology to convert that sunlight to usable energy can be very expensive. Driving down the cost per watt of solar energy will be key to achieving grid parity in major markets, to expanding solar PV application worldwide — and to profit.

In the beginning of the solar-energy era, the cost of manufacturing a solar cell was tied directly to the capital cost of the manufacturing equipment. Price was a key element of a fairly standard process where there was not much differentiation among OEMs and the game was mostly an equipment price battle. Companies did the math to convert equipment cost to productivity, and quickly informed suppliers that the bottom line was more than the market would bear. New technologies are often very expensive — the cost of the first personal computers was as much as a mortgage payment —limiting the number of potential end customers. Just as innovation in chip manufacturing has radically reduced the size and cost of PCs to the point where most people can afford a computer or smartphone, the solar market was ripe for innovation that would reduce costs and lead the way to grid parity.

TOTAL COST OF OWNERSHIP

A new metric has emerged that is a more comprehensive way than simple Capital Expenditure (CapEx) to compare and evaluate the cost of different solutions. Total Cost of Ownership (TCO), sometimes shortened to Cost of Ownership (COO), was developed by The Gartner Group in the 1980s. It rapidly became a standard methodology providing valuable insight into the direct and indirect costs of a system over a pre-determined period of time. For high-tech companies, this period is generally five years, because that is assumed to be the amount of time that a piece of equipment will remain relevant before new technology is needed.

In addition to the capital procurement cost of tools, additional factors should be considered in calculating TCO. There are dozens of these, and a true side-by-side comparison can be very difficult to calculate. Semiconductor companies can seek guidance from SEMI, the global industry association for certain semiconductor manufacturing supply chains. Their document SEMI E35-0307, “Guide to Calculate Cost of Ownership [COO] Metrics for Semiconductor Manufacturing Equipment,” recommends quantifying many factors within three main categories:

- Fixed costs (essentially depreciation for property, plant and equipment)
- Recurring costs (mostly direct materials, consumables, maintenance and labor)
- Yield costs (essentially scrap and mean performance)

Companies may take for granted that all of these variables are known, or can be easily and closely estimated. However, this is not always the case. A realistic estimate of these variables requires inputs from process metrology and regular cost updates for direct materials and consumables. These numbers are often tied to spot market fluctuation.

The crystalline silicon (c-Si) solar cell technology roadmap (Figure 1) clearly indicates acceleration towards differentiation; both evolutionary and revolutionary approaches are finding traction. In both approaches, the number of process steps is increasing. Consequently, the process variability and the manufacturing uncertainty associated with the most promising cell concepts are increasing too.

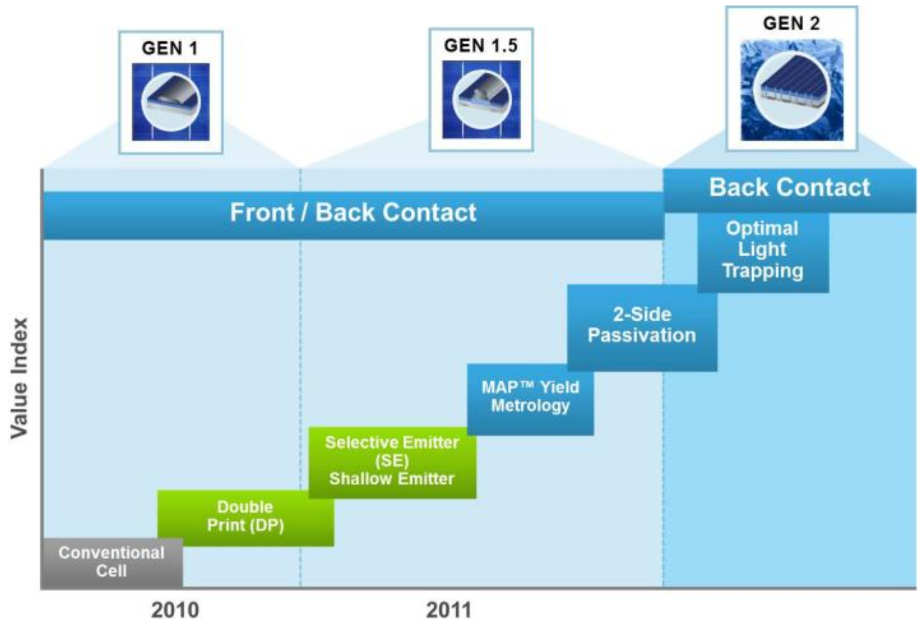

Figure 1. Crystalline-silicon roadmap (source: Applied Materials)

A DIFFERENT APPROACH

It becomes clear that a snapshot of the TCO as it currently calculated might not reflect the actual worth of an investment over its entire utilization period. A tool that can differentiate itself by its ability to adapt to changing technologies, and therefore provide greater value over time, is becoming more and more important, especially in a fast-growing and still-maturing market such as photovoltaics.

In the semiconductor industry, the capital portion of the cost of goods and services (COGS) is typically in the 30 to 50 percent range. For the c-Si solar cell manufacturing segment, it is typically between 5 and 20 percent. While this is an important cost, it is less so to c-Si manufacturers than to semiconductor manufacturers. The trend we see is that whenever a tool can flexibly and rapidly embrace differentiated process variants or additions, that tool will be preferred.

To drive down the cost per watt of solar energy, it is important to achieve high flexibility and OEE (Overall Equipment Effectiveness). Equally important is to effectively and rapidly adopt new recipes and cell structures being developed in R&D labs. This goal requires innovation from solutions, and from solution providers, that minimize the risks of adoption.

TWO EXAMPLES NOT CAPTURED IN TCO: BREAKAGE AND PRINT QUALITY

Process yield contributes significantly to OEE and influences TCO. Yield gain can be reached through better alignment for critical process steps, and real time control of out-of-spec material. The following sections use the examples of broken wafers and better print alignment to illustrate the costs and potential profit of improving yield factors.

Breakage

The ratio between the price of silicon wafers and the final solar cells is about 60%. This underscores how important material costs are for photovoltaic manufacturers. The solar market requires thinner and thinner wafers, with a roadmap down to 100 µm. Thinner wafers, however, break more easily and require more delicate and precise processing in a manufacturing line.

Breakage rate is part of the typical TCO calculation in the semiconductor industry, but only as a cost of the wafers themselves. However, broken wafers can incur other costs that directly affect profits. Every broken wafer is missed potential revenue from a finished cell, plus the lost production time for cleaning up the broken silicon pieces. This adds up to lost profit. Figure 2 models annual loss due to wafer breakage, taking breakage rate and equipment downtime into consideration.

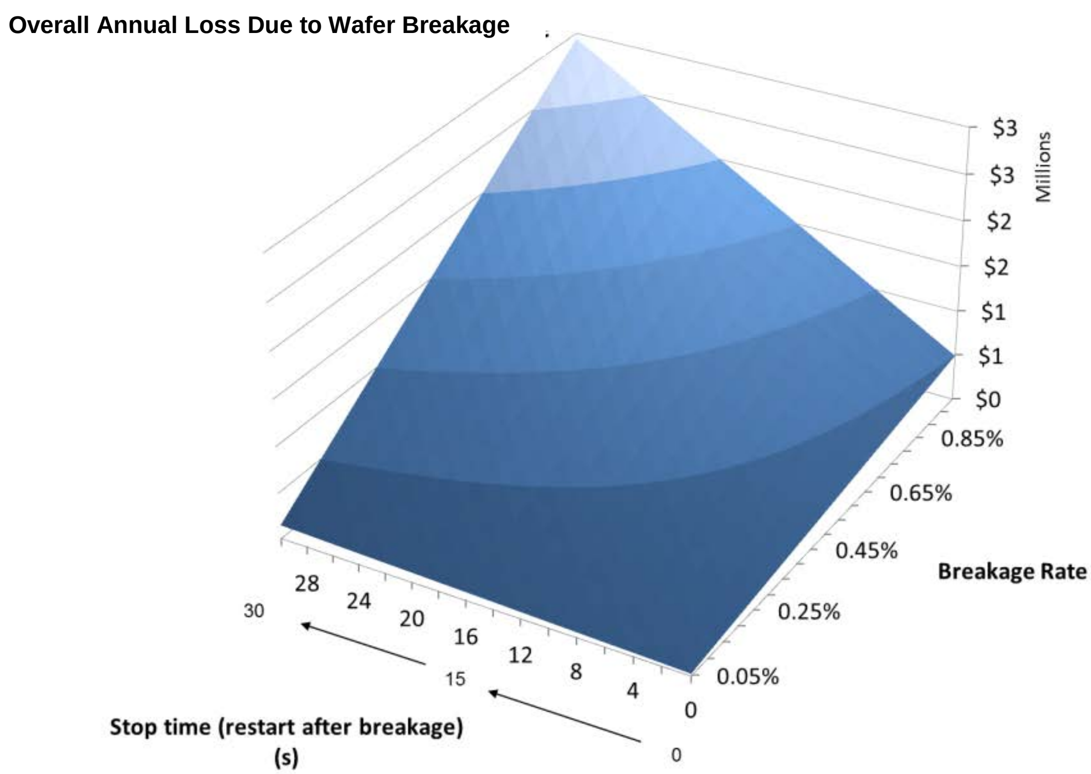

Figure 2. *This diagram shows how dramatic reduction in breakage provides a $0.5 million per year margin opportunity (assumes 24 million wafers per year at $2.10 per wafer. Source: Applied Materials).*

Table 1 provides a picture of the true costs of broken wafers. A fab that can lower its breakage rate by 0.2% can see a potential profit increase of more than $0.5 million per year.

Table 1. *Total annual losses due to wafer breakage for a line with a 0.3% breakage rate vs. a line with a 0.1% breakage rate (assuming the same number of wafers produced in both cases and value of wafer $2.10).*

	0.3% Breakage Rate	0.1% Breakage Rate
Wafers produced over one year without breakage (millions)	~24	~24
Breakage rate	0.3%	0.1%
Average line stop time (seconds)	15	5
Number of broken wafers	72,000	24,000
Yearly loss of production, number of wafers	864,000	96,000
Net loss due to broken wafers over one year ($)	149,300	49,770
Net loss due to lack of profit ($)	366,450	40,720
TOTAL LOSS ($)	517,750	90,490
***Yearly Benefit* ($)**		**425,260**

Print Quality

Print quality is also an important factor in overall solar cell yield. Proper print alignment is increasingly important as the industry moves toward denser interconnects and techniques such as selective emitter and double printing. Cells with improperly aligned printing must often be scrapped or placed into lower yield categories, wasting valuable production time and losing potential profit. Figure 3 and Table 2 illustrate this point. They show printing techniques for a standard single-printing process on six-inch multicrystalline wafers in six categories of sorting (excluding rejected cells). Better print quality results in a percentage of total yearly cells moving from bottom to top categories.

As these examples of breakage and print alignment show, there is quantifiable financial benefit in looking beyond the cost of equipment and understanding the value that can be gained by process and yield improvement. Scaling production is important in reducing manufacturing costs. Future cost improvements will require major changes in technology and manufacturing methods, to improve efficiency at high yield and very high factory outputs. Driving down the cost per watt even further, with the speed required to quickly expand global grid parity, calls for process control and optimization.

Table 2. *Scenarios of X% of cells moving to higher categories. Assumes solar cell ASP [$/Wp] of $0.86 for 90 MW line.*

	Baseline	1%	3%	5%
Annual cells produced	22 – 24 million			
Profit increase (over 5 years)	-	$160,000	$500,000	$800,000

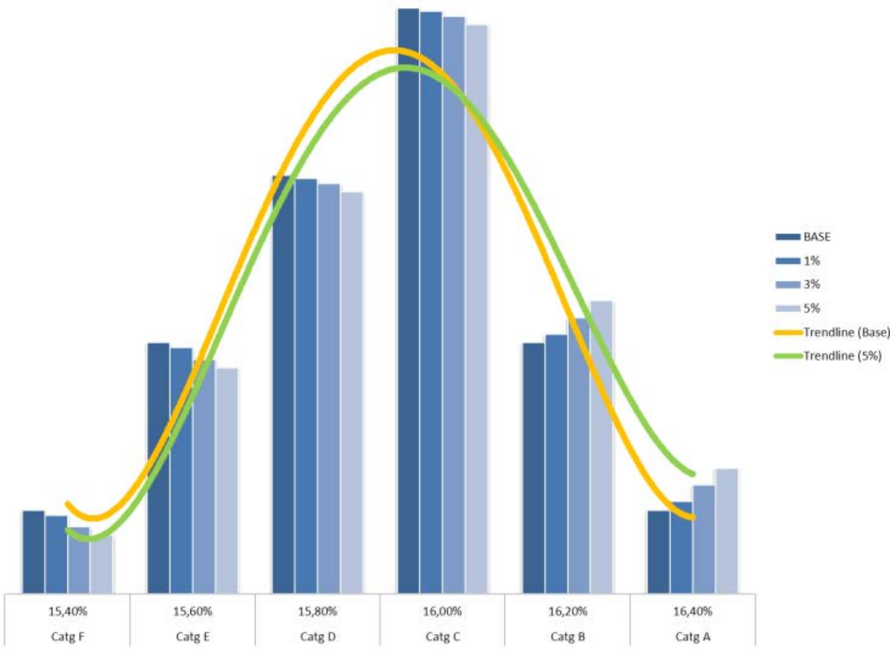

Figure 3. *Model illustrating how better print quality results in more wafers in the higher efficiency categories. (source: Applied Materials)*

THE VALUE OF PEGASO™

The new Applied Baccini® Pegaso™ platform presents a new benchmark in yield and precision, at twice the throughput of the current market leader: the Applied Baccini Soft Line. Competing systems offer high throughput, but only Pegaso provides a complete pathway to the lowest cost for cell manufacturing over the next decade. Built to meet solar cell roadmap demands for the next ten years, the Pegaso platform provides a longer depreciation time than most manufacturing equipment. Pegaso draws on the history and expertise of Applied Materials to provide comprehensive process knowledge off-the-shelf. It enables increased yield through its modular configuration, tighter process distributions, virtually zero wafer breakage and reduced silicon consumption by processing thinner wafers (to 120 µm, with potential for going even thinner) at high yield.

Pegaso innovations include increased print quality, accuracy and precision driven by high-efficiency cells with double printing and selective emitter structures. It enables new cell technologies, such as back contact structures such as Metal Wrap Through (MWT) and Emitter Wrap Through (EWT), with new process tools, such as lasers, that can be implemented with minimal reconfiguration. The Pegaso system is also configurable for both high productivity and/or the most advanced process capability, depending on a manufacturer's needs.

Lowest Breakage Rate for Higher Net Throughput

Compared to the market average breakage rate of 0.3%, the Pegaso breakage rate is 0.1%. Pegaso uses these advanced technologies to achieve the industry's lowest breakage rate:

- In the line loader, a belt removes the cells from the slide cassettes instead of a lifting bar. This eliminates a source of pressure and potential breakage.
- Grippers use compressed air and take advantage of the Bernoulli effect to pick up the cells, resulting in softer handling.
- Wafer flippers also use the Bernoulli effect, reducing the potential for breakage.
- A new optical centering device keeps wafers in their proper place through the whole process, ensuring high positioning repeatability.
- When the squeegee pushes paste through the screen onto the wafer, too much pressure can damage the wafer. Finest pressure control of the squeegee prevents wafer damage.
- Quality inspection in the printer module provides immediate feedback on a wafer's integrity. The module detects a wafer's defects that would likely cause downtime due to wafer breakage during a processing step while being discarded by the final cell tester. Defect detection at the beginning of the line allows a sensitive reduction of the breakage rate because only high-quality wafers will go through the printing process. This also saves consumables costs because no paste will be used on a wafer identified as cracked.

Higher Uptime

Pegaso also provides higher uptime, with greater than 95 percent availability and more than 90 percent OEE. Uptime gain is aided by several tool features including complete lane independence, plug-and-play modules and functional groups/subgroups, enhanced accessibility, safe calibration mode with Smart Safety implementation, absolute encoders for critical components and ergonomic screen change (print head rotation).

Information Technology Project Savings

Manufacturers often must pay outside Information Technology (IT) consulting companies to collect and synchronize process data from disconnected servers. Pegaso makes that cost unnecessary with embedded metrology and dedicated software tools. Applied Materials' calculations show that this can save manufacturers up to $425 per 1 MW fab expansion.

A standard single-wire CGA interface provides full remote connectivity and centralized data collection to the real-time front end server. This embedded metrology allows better overall performance and integration, with better control of print quality. The innovative control system architecture of this platform dramatically boosts manufacturers' ability to gather process intelligence, with excellent data quality and sampling rates.

High-level software, including the human-machine interface (HMI), also uses a CGA common platform. It is built in and ready to interface with E3™, Expert Connect and fab management tools such as Applied Materials' SmartFactory™. Leveraging the advanced architecture of Pegaso, manufacturers can use systems such as Applied Materials' E3 to actively monitor and notify engineers of process deviations as well as to automatically optimize process recipes using metrology feedback. This level of process information, active process monitoring, and control allows manufacturers to optimize their processes to a level that has not been achieved in the past.

Modular Configuration

The Pegaso modular platform is upgradeable to meet unique customer requirements and enable the cell technology roadmap with advanced process applications. Modules can be upgraded to laser and new print technologies. All modules are independently controlled, and all sub-modules have local control. This modularity means easier maintenance and service, with easier software customization.

When manufacturers must change process sequences or change the number of process steps— for example, moving from single printing to double printing, adding one metrology step or extending the number of sorting classes — difficult and expensive reconfiguration is eliminated. Common spare parts for multiple process steps also reduces inventory costs (direct costs) and inventory management (indirect costs).

Larger Scale Production

Factories are sometimes constrained by layout restrictions and cannot move to machines with a larger footprint. Pegaso requires less fab floor per wafer produced than other platforms available today. Pegaso enables greater than 2,900 cell per hour (gross) line operation, working from both sides. This high wafer throughput rate is enabled by two print heads, two conveyor lanes, a planar motor and moving shuttles, and Theta alignment controlled by the print head. This fully dual design also provides 50 percent throughput even when one side is down for maintenance or service. The Pegaso platform supports larger-scale factories producing 500 MW – 1 GW, with greater productivity, availability, and reduced use of factory space.

CALCULATING VALUE

Other platforms with very similar TCO might bring different value to customers. Table 3 shows several Applied Materials calculations that quantify benefits not normally captured by a TCO spreadsheet. The table shows, for example, that improvements in process yield and reducing direct consumables costs can bring a competitive advantage greater than $100,000 through newer and innovative screen printing metallization. Overall, benefits such as easy integration of new process steps, an extendable platform and consumables cost savings could result in about a $2 million advantage over 5 years versus a traditional cell manufacturing platform that is not highly innovative.

Table 3. *Estimated dollar benefit of Pegaso innovations*

Area of Benefit	Description	Expected benefit over 5 years vs. industry standard
Platform: High mechanical yield	Profit gain on unbroken wafers	$1,628,650
Platform: Easy addition of process step	Heavy reconfiguration once in 5 years, such as an upgrade to double printing	$46,800
Platform: “Single-wire concept”	Savings on IT projects	$37,800
Platform: Extendibility	Longer amortization (actual)	$800,000
Printer: Consumables savings	Extended lifetime of print screens	$33,333
Printer: Better process yield	Extra profit	$84,240
Total expected benefit per tool [In addition to TCO]		**$2,630,823**

CONCLUSION

Challenges and opportunities from newer cell structures, adoption of newer and additional processes and a higher sensitivity to process optimization suggest that evaluating TCO is no longer sufficient to assess the quality of a manufacturing tool which is a great investment. Such an investment should be evaluated in the light of its potential for generating differential value along the years.

This paper has cited a number of areas where evaluating a tool solely on TCO does not capture the tool's value. In fact, quantifying some of these values shows that the added value of the tool may even be comparable with the tool procurement cost itself.

Applied Materials, through significant innovation, is anticipating the market with new concepts that help accelerate the $/Wp reduction towards and beyond grid parity.

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