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Inside

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When Capacity Buys Are Not an Option: Technical Trends in c-Si Cell Manufacturing and Their Implications

With this edition of Applied Cost Modeling, we are publishing the second installment in a series examining the business considerations associated with the adoption of new processes, equipment, or materials for crystal silicon-based (c-Si) photovoltaic (PV) cell manufacturing.

Case Study

Our "one to watch" process is nanopore formation using the Natcore Technology's Black Silicon process as an example. In order for nanopore formation to be something worth adopting in the near future, it must pass not just the technical requirements, but a business objective of a high payback. We explore this objective through a preliminary cost of ownership (COO) analysis.

<u>COO Review</u>[1]

A more detailed discussion of COO can be found in the first paper in this series in the 6th edition of Photovoltaics International[2]. To review, the basic COO algorithm is described by:

$$C_U = \frac{C_F + C_V + C_Y}{L \times TPT \times Y_C \times U}$$

First published in Photovoltaics International, 19th edition.

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Calendar of Events

January 2014

12-15 Industry Strategy Symposium (ISS)
Ritz Carlton
Half Moon Bay, CA

February 2014

17-18 PV Fab Managers Forum
Kerry Hotel
Shanghai, China

March 2014

18-20 SEMICON China
Shanghai New International Expo Centre
Shanghai, China

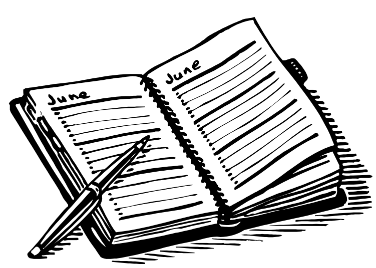
30 North American Standards Spring Meetings
SEMI Headquarters
San Jose, CA

April 2014

1-3 North American Standards Spring Meetings
SEMI Headquarters
San Jose, CA

May 2014

14-16 SNEC International PV Power Generation Conference & Exhibition
Shanghai New International Expo Centre
Shanghai, China



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Where:

C_U = Cost per good unit (wafer, cell, module, etc.)
C_F = Fixed cost
C_V = Variable cost
C_Y = Cost due to yield loss
L = Process life
TPT = Throughput
Y_C = Composite yield
U = Utilization

Overall Equipment Efficiency (OEE) Review[3]

One of the most popular productivity metrics is OEE. It is based on reliability (MTBF), maintainability (MTTR), throughput, utilization, and yield. All these factors are grouped into the following four submetrics of OEE.

1. Availability (joint measure of reliability and maintainability)
2. Operational efficiency
3. Throughput rate efficiency
4. Yield/quality rate

As we see above, it requires many parameters to calculate OEE. If the accuracy requirement is not a critical factor, use the following formula to calculate an approximate OEE value:

OEE = Number of Good Units Output in a Specified Period of Time / (Theoretical Throughput Rate x Time Period)

Relationship Between Metrics

There are many equipment performance metrics at different levels. They may appear disjointed; however, that is not true. They all fit nicely into a hierarchal tree.

Figure 1 depicts the hierarchy tree of the equipment performance metrics. As shown in the figure, when a time dimension is added to quality and safety, it becomes reliability. Reliability and maintainability jointly make up availability. When production speed efficiency and production defect rate are combined with availability, it becomes productivity (OEE). Acquisition and operational costs make up Life Cycle Cost (LCC). When scrap, waste, consumables, tax, and insurance costs are added to LCC and the total is normalized by the production volume, it becomes COO.

Cost of Ownership Inputs

The following are the results of the COO analysis run on the Black Silicon process. Table 1 highlights the major input parameters.

Parameter	
Throughput	1,300 wafers per hour
Wafer Size	156 mm
Process Lifetime	7 years
Mean Time Between Failure (MTBF)	200 hours
Mean Time to Repair (MTTR)	10 hours
Equipment Cost	\$2M
Equipment Yield	99.90%
Utilities (lifetime)	~\$1.3M
Consumables (lifetime)	~\$2.4M
Maintenance (lifetime)	~\$1.6M

Table 1: Major COO Inputs

In addition to the Table 1 parameters, where required, the authors used example values from SEMI E35[1] for administrative rates and overhead. These values where provided by SEMI North American members and may not be applicable to other geographic regions. However, it is the authors' experience that these example values do not impact the COO results on a relative basis.

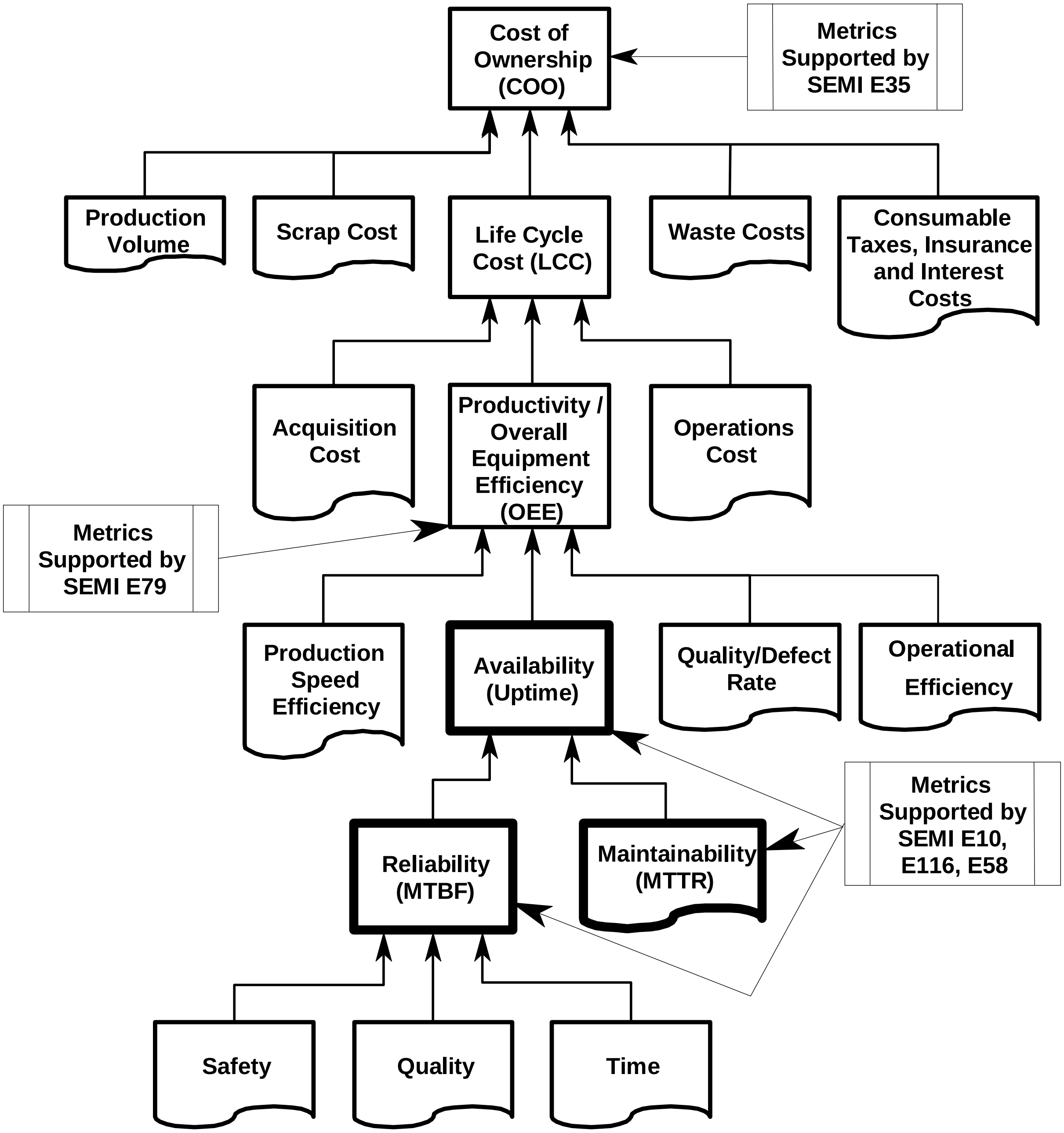

Figure 1: Hierarchy of Equipment Performance Metric[4]

Cost Drivers

Examination of the detailed TWO COOL®[5] COO model in Table 2 highlights the main cost and productivity factors. Recurring costs are approximately 3x initial capital costs over the life of the process, which are driven primarily by the cost of consumables.

Next we will look more closely at the top cost drivers and opportunities for improvement.

Table 3 takes a closer look at the cost breakdown according to the 13 categories specified in SEMI E35. The top Pareto costs are Materials/Consumables, which includes utilities, supplies, consumables, and waste disposal; Depreciation, which is

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Cost Per System	2,000,000	Dollars
Number Of Systems Required	1	Systems
Total Depreciable Costs	2,225,000	Dollars
Equipment Utilization Capability	90.99	Percent
Production Utilization Capability	90.99	Percent
Composite Yield	99.90	Percent
Good Wafer Equivalents Out Per Week	198,526.93	G.W.E.'s
Good Wafer Equivalent Cost		
With Scrap	0.12	Dollars
Without Scrap	0.12	Dollars
Average Monthly Cost		
With Scrap	104,919	Dollars
Without Scrap	103,883	Dollars
Process Scrap Allocation		
Equipment Yield	100.00	Percent
Defect Limited Yield	0.00	Percent
Parametric Limited Yield	0.00	Percent
Equipment Costs (Over Life of Equipment)	2,385,041	Dollars
Per Good Wafer Equivalent	0.03	Dollars
Per Good cm2 Out	0.0002	Dollars
Recurring Costs (Over Life of Equipment)	6,428,164	Dollars
Per Good Wafer Equivalent	0.09	Dollars
Per Good cm2 Out	0.0005	Dollars
Total Costs (Over Life of Equipment)	8,813,205	Dollars
Per Good Wafer Equivalent (Cost Of Ownership)	**0.12**	**Dollars**
Per Good Wafer Equivalent Supported	0.12	Dollars
Per Good cm2 Out	0.0007	Dollars
Per Productive Minute	2.63	Dollars

Table 2: COO Results

Cost Drivers per Good Wafer Equivalent		
Material/Consumables	0.050	Dollars
Depreciation	0.031	Dollars
Maintenance	0.022	Dollars
Labor	0.014	Dollars
Floor Space Costs	0.002	Dollars
Support Personnel	0.001	Dollars
Scrap	0.001	Dollars
Training	0.000	Dollars
System Qualification Costs	0.000	Dollars
Other Materials	0.000	Dollars
ESH Preparation and Permits	0.000	Dollars
Moves And Rearrangements	0.000	Dollars
Other Support Services	0.000	Dollars

Table 3: Pareto of Cost Drivers

impacted by equipment costs, throughput rate, and utilization; and Maintenance, including repair parts and technician labor.

The top two cost drivers account for two-thirds of the total COO. For this reason, we will focus our attention on those areas as we examine the cost sensitivities to input parameters that drive Material/Consumable and Depreciation costs.

Cost Driver Sensitivities

The first factors to be examined are supplies and consumables. Table 4 below shows the annual costs per system by supply item.

One of the issues in defining a sensitivity analysis for the above items is their potential interrelationship with other factors. Changing the price/quality of the consumables could impact throughput, consumption, or yield; consumption changes

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Supply/Consumable	Annual Cost per System
Material 1	$103,567
Material 2	$ 79,208
Material 3	$ 54,947
Material 4	$ 37,148

Table 4: Annual Supply/Consumable Costs

could impact throughput and the conversion efficiency of the device. We will examine what cost benefits could be achieved by reducing the consumption or cost per liter of Material 1.

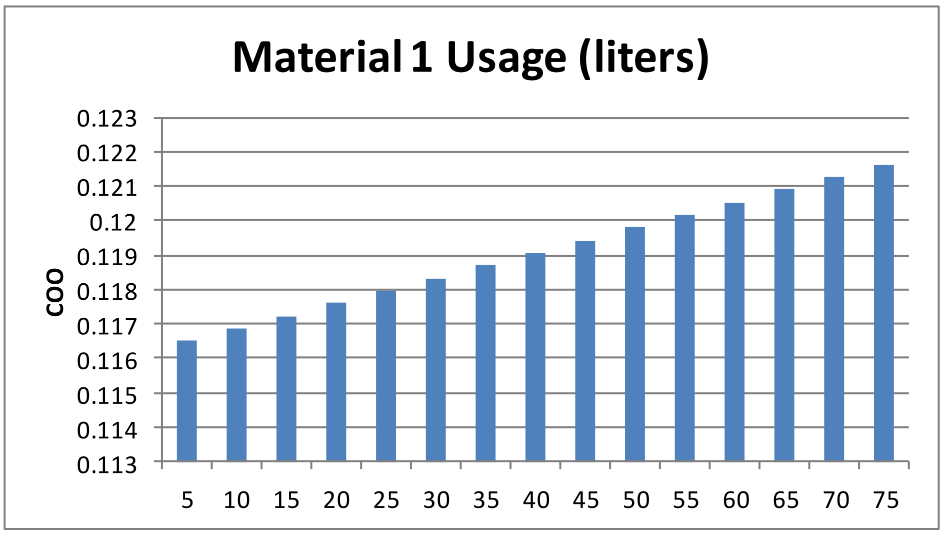

Figure 2: Sensitivity Analysis of Material 1 Quantity vs. COO

As can be seen from the above, the usage of Material 1 has a low impact on the total COO. This sensitivity analysis is based on one tank using Material 1 but there are two tanks that use the majority of this material. So, a 50% reduction in usage provides approximately a 6% reduction in the total COO for the process. While it may not be possible to achieve this level of reduction and maintain process control, it certainly shows an opportunity for cost reduction.

Likewise, the price of Material 1 has a similar impact on the total COO. A 50% reduction in price provides an approximate 6% reduction in the total COO for the process. It should be noted that the reason Material 1 has a low impact on COO is that there are several consumables used in the process and Material 1 represents only about one-third of those costs.

Next, we look at the factors impacting depreciation; purchase price and throughput. (see Figures 4 and 5).

Purchase price has a moderate impact on COO in high throughput equipment, especially those with higher variable costs. The cost impact in this case is approximately 1.2% per $100,000 (5%) change in purchase price.

However, as can be seen in Figure 5, improvements in throughput can have a significant impact on COO depending on where on the curve the equipment is operating. In this case, the equipment is operating at an average throughput of 1,300 wafers per hour (wph) and a 100 wph improvement near the average impacts COO by over 5%.

<u>Overall Equipment Efficiency</u>
Table 5 shows the OEE of the Black Silicon process step. As you can see, the OEE is in excess of 90% based on a maximum throughput rate of 1,300 wph. All of the OEE losses in this model are attributed to availability efficiency primarily associated with equipment downtime (scheduled and unscheduled). Since this is a preliminary analysis of the process, OEE and COO

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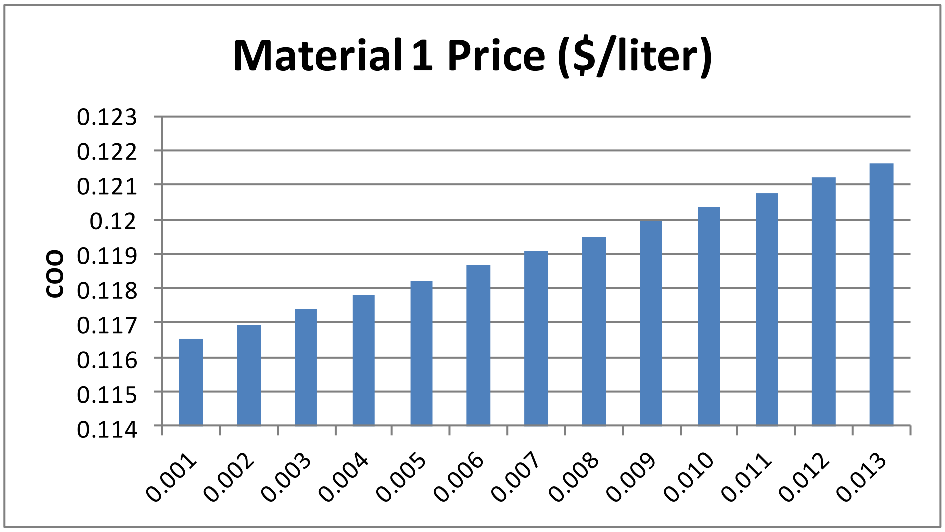

Figure 3: Sensitivity Analysis of Material 1 Price vs. COO

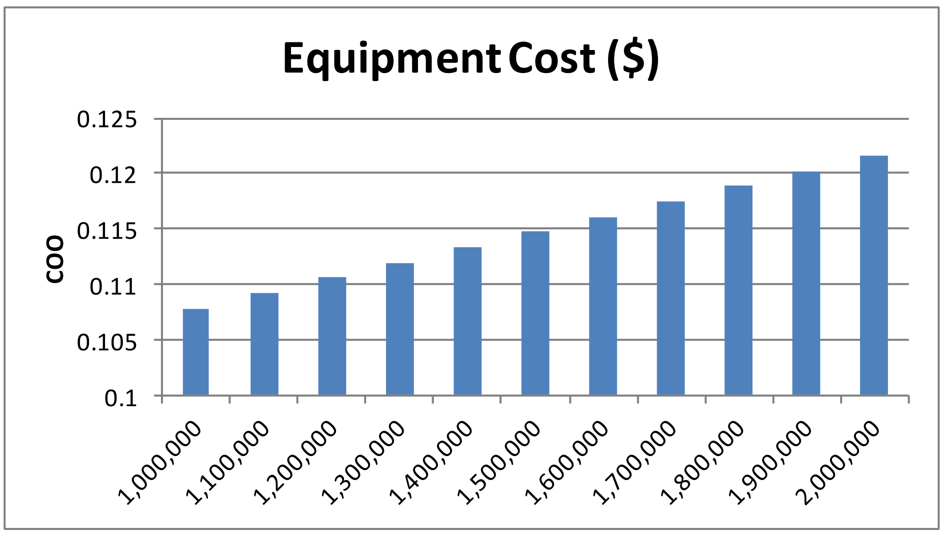

Figure 4: Sensitivity Analysis of Purchase Price vs. COO

values should be taken as potential opportunities only.

Conclusions

The PV industry is in a challenging phase. The overcapacity issues are exacerbated by changing government policies and increased competition external to the PV industry. Solar cell providers who do not evolve will get eaten alive. As counterintuitive as it seems in a period where money is tight, companies need to spend money. They need to invest in newer, higher value technologies and lower cost processes. It is not a choice.

We've tried to pick the investment choices we see as having the largest paybacks in the near term. In each case, they differentiate themselves from baseline processes by improving costs or adding value to the product, in some cases, both.

Continuous improvement has been the norm for solar research and development; it has been more challenging in fixed production

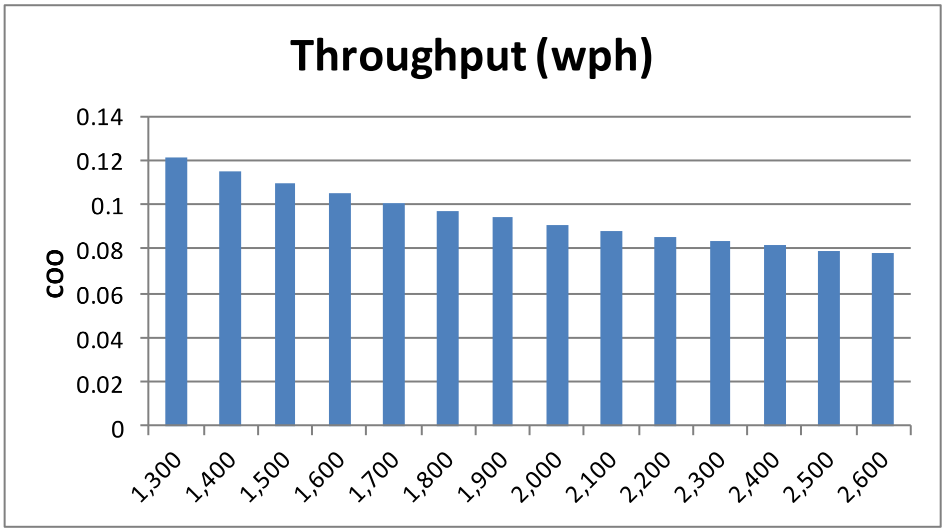

Figure 5: Sensitivity Analysis of Throughput vs. COO

Overall Equipment Efficiency	**90.90**	**Percent**
Availability Efficiency	**90.99**	**Percent**
Engineering Usage	0.00	Hours/Week
Standby	0.00	Hours/Week
Hours Available/System (Productive Time)	152.87	Hours/Week
Down Time	15.13	Hours/Week
Scheduled Maintenance	7.00	Hours/Week
Unscheduled Maintenance	7.92	Hours/Week
Test	0.00	Hours/Week
Assist	0.21	Hours/Week
Non-Scheduled Time	0.00	Hours/Week
Equipment Uptime	152.87	Hours/Week
Total Time	168.00	Hours/Week
Performance Efficiency	**100.00**	**Percent**
Throughput At Capacity/System	1300.00	Layers/Hour
Theoretical Throughput	1300.00	Layers/Hour
Operational Efficiency	100.00	Percent
Rate Efficiency	100.00	Percent
Quality Efficiency	**99.90**	**Percent**
Equipment Yield	99.90	Percent
Defect Limited Yield	100.00	Percent
Parametric Limited Yield	100.00	Percent
Alpha Error Factor	100.00	Percent
Beta Error Factor	100.00	Percent
Redo Rate	0.00	Percent

Table 5: OEE Results

lines. But as factories get larger and the scale increases, it becomes apparent that this continuous improvement will require a near constant evolution within manufacturing operations.

The uncertainty this brings in difficult business conditions is not appealing. But it does argue for a well-thought-out, disciplined process on the choices to be made. The roadmaps companies pursue need to be carefully evaluated for the best business decision, which may well differ from the most “talked about” technology. Ultimately, tools like COO and factory level cost modeling will be essential in

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determining product road maps–integrating these methods into both short- and long-term decision processes may prove to be the difference between the companies that don't survive and those that thrive.

Acknowledgements
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References

1. E35, Guide to Calculate Cost of Ownership (COO) Metrics for Semiconductor Manufacturing Equipment, www.semi.org.
2. D. Jimenez, "Cost of Ownership and Overall Equipment Efficiency: A Photovoltaics Perspective," Photovoltaics International, Ed. 6.
3. E79, Standard for Definition and Measurement of Equipment Productivity, www.semi.org.
4. Dr. Vallabh Dhudshia, "Hi-Tech Equipment Reliability: A Practical Guide for Engineers and Managers," iUniverse, 2008.
5. TWO COOL® is a commercial software package from Wright Williams & Kelly, Inc.

Did ASML Just Kill 450mm?

It looks like 450mm wafers just got pushed back as ASML stopped production on the technology. This delay will come as no surprise to anyone closely following the Semiconductor world, all the signs were pointing in the same direction.

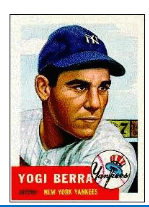
News that ASML had completely pulled the plug was broken by Paul van Gerven on the Dutch site Bits&Chips last week. (a poor translation into English can be found at: http://translate.google.com/translate?sl=nl&tl=en&js=n&prev=_t&hl=en&ie=UTF-8&u=http%3A%2F%2Fwww.bits-chips.nl%2Fartikel%2Fasml-zet-450-mm-ontwikkeling-op-laag-pitje.html)

However, Mr. van Gerven seems to indicate that the brakes were applied by Intel, Samsung, and TSMC. SemiAccurate has been hearing similar news for weeks from the fab side, essentially that 450mm tools had been significantly delayed. The real question is what caused it, technical, financial, cooperative, or other problems?

The complete article from SemiAccurate can be found at: http://semiaccurate.com/2013/12/18/analysis-asml-stops-450mm-dead/

This closely tracks WWK's semiconductor equipment surveys from 2007 to 2011 where an average of 30% of respondents indicated 450mm would never happen and those that did indicate it would moved the date of manufacturing introduction from 2013 to post-2018 during that survey period.

For those that lived through the "original" 300 mm wafer introduction at 250 nm, this is starting to feel like déjà vu all over again. Or perhaps a better Yogi Berra quote on the subject is "it's tough to make predictions, especially about the future."



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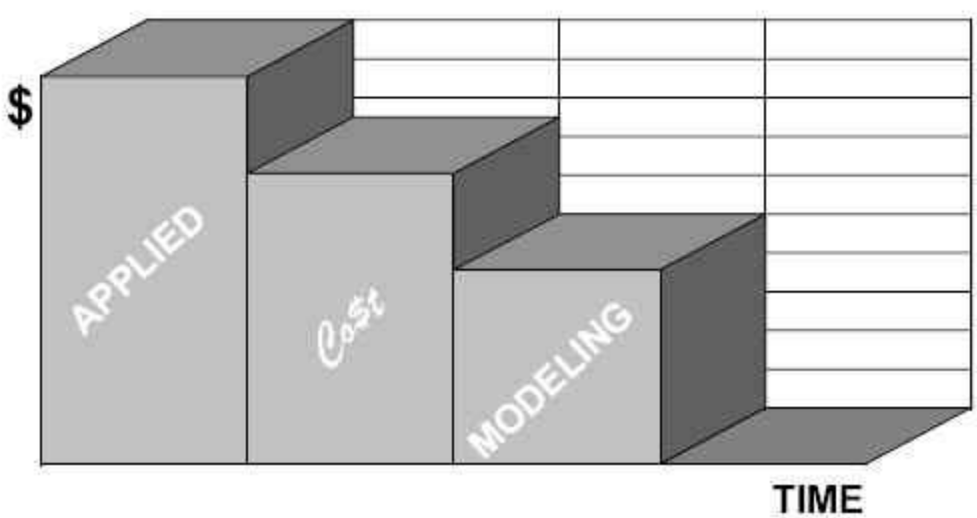

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