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APPLIED Co$t MODELING

Volume 18. Issue 3

Inside

Spring 2012

Cost of Ownership for c-Si Wet Processes: Texturization and Cleaning

With this edition of Applied Cost Modeling, we are publishing the second installment in a series on the application of cost of ownership (COO) and overall equipment efficiency (OEE) to crystal silicon-based (c-Si) photovoltaic (PV) texturization and cleaning.

Case Study[1]

Given the number of processes for saw damage removal, texturization and cleaning, a complete COO analysis of each technology along with each configuration is well beyond the scope of this paper. Instead, we have decided to evaluate a configuration for a wet processing sequence which the authors perceive as being commonly used in production today.

COO Review[7]

A more detailed discussion of COO can be found in the first paper in this series in the 6th edition of Photovoltaics International. 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, 7th edition.

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ISSN 1094-9739

Editorial Board

Publisher

Published quarterly by:

Wright Williams & Kelly, Inc.
6200 Stoneridge Mall Road
3rd Floor
Pleasanton, CA 94588

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E-mail support@wwk.com

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Calendar of Events

July 2012

9 **PV Fab Managers Forum**
Intercontinental Hotel
San Francisco, CA

10-12 **SEMICON West**
Mosconi Center
San Francisco, CA

10-12 **Intersolar North America**
Mosconi Center
San Francisco, CA

12 **Understanding and Using COO**
SEMICON West/Intersolar
San Francisco Marriott Marquis
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September 2012

3-5 **SOLARCON India**
Bangalore International Exhibition Centre
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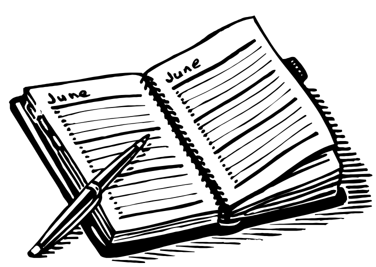
5-7 **SEMICON Taiwan**
TWTC Nangang Hall
Taipei, Taiwan



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[8]

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 sub-metrics 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 6 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 cost are added to LCC and the total is normalized by the production volume, it becomes COO.

Wet Processing for Texturization and Cleaning

As stated previously, an obvious requirement for high efficiency in photovoltaic modules is low reflectance. Single-crystal silicon solar cells achieve very low reflectance through use of textured surfaces and/or antireflection coatings[10]. These principals have been understood and employed for more than a decade.

The rest of this paper will examine the current cost structure and potential for cost reductions in a state-of-the-art, production proven wet processing tool from Akrion Systems, the GAMA-Solar.

Cost of Ownership Inputs

The following are the results of the COO analysis run on the GAMA-Solar wet processing station. Table 1 highlights the major input parameters.

In addition to the Table 1 parameters, where required, the author used example values from SEMI E35 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 author’s experience that these example values do not impact the COO results on a relative basis.

ISSN 1094-9739

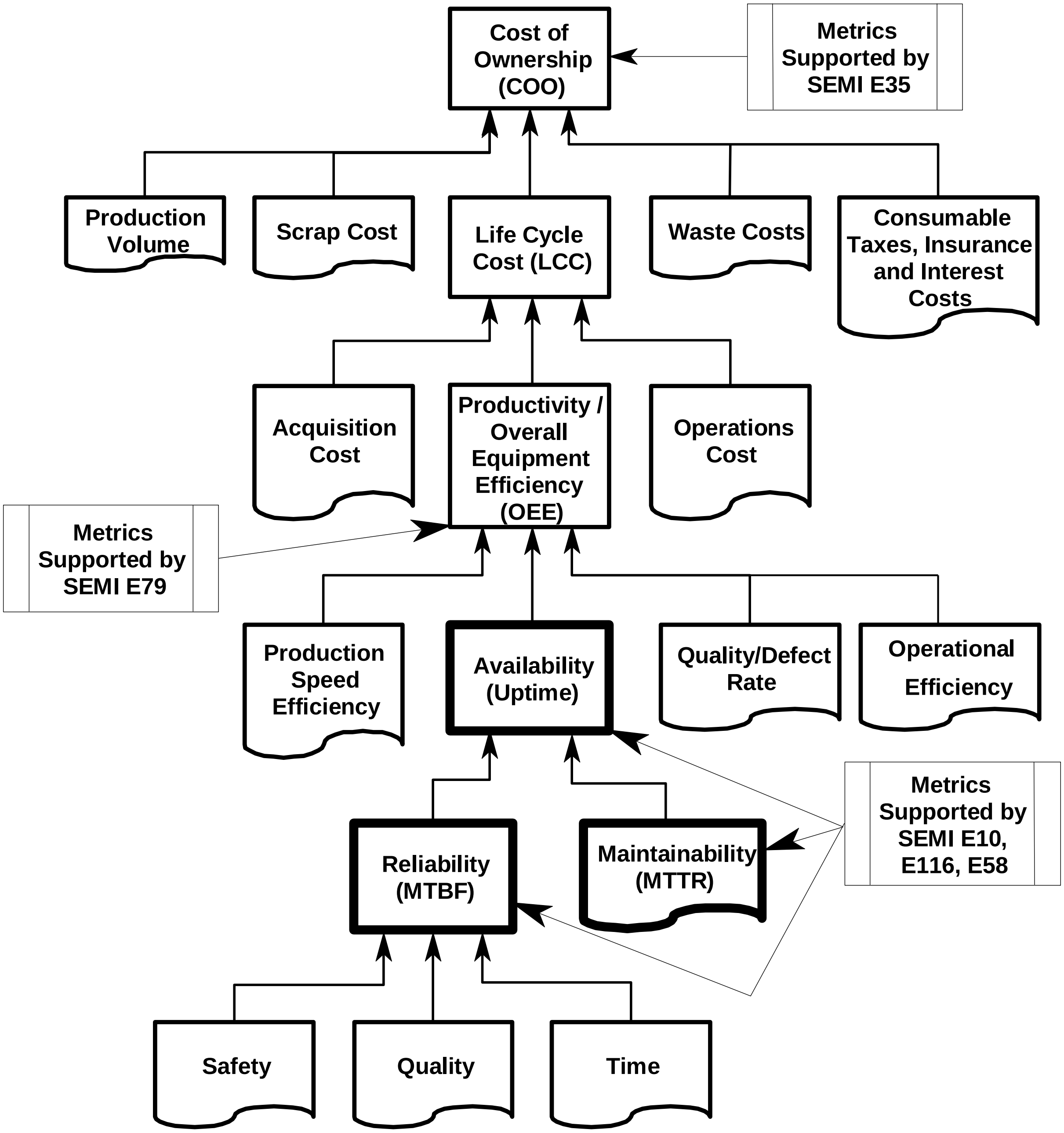


Figure 6: Hierarchy of Equipment Performance Metrics[9]

Cost Drivers

Examination of the detailed TWO COOL®[11] cost of ownership model in Table 2 highlights the main cost and productivity factors. Recurring costs are approximately 1.5x initial capital costs over the life of the process. 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 Labor; Depreciation, which is impacted by equipment costs, throughput rate, and utilization; Materials/Consumables, which includes utilities, supplies, consumables, and waste disposal; Maintenance, including repair parts and technician labor; and Floor space.

Parameter	GAMA-Solar
Throughput	1,200 wafers/hour
Wafer Size	156mm
Wafer Cost	$3
Mean Time Between Failure (MTBF)	1,500 hours
Mean Time to Repair (MTTR)	4 hours
Equipment Cost	$1,500,000
Equipment Yield	99.96%
Utilities	$30,700/year/system
Consumables	$103,563/year/system
Maintenance	Owner provided

Table 1: Major COO Inputs

The top 3 cost drivers account for almost 90% of the total cost of ownership. For this reason, we will focus our attention on those areas as we examine the cost sensitivities to input parameters that drive Labor, Depreciation, and Material/Consumable costs.

<u>Cost Driver Sensitivities</u>

The first factor to be examined is labor content, which represents 40% of the total cost of these integrated process steps. Labor is defined as direct operator labor and the model is based on one operator overseeing one machine. Since these are highly automated machines with sufficient throughput to support a 30MW line, it is not likely that the factory would be significantly larger in order to allow for further amortization of labor content. However, figure 7 does examine COO sensitivity to labor content should such opportunities present themselves.

If the factory can scale to accommodate 2 machines (or an equivalently larger single machine), increasing the labor efficiency from 1 to 2 machines would improve COO by 20%. Given such a significant sensitivity, looking at scaling and automation issues would be a major opportunity for cost reductions.

Next we look at the factors impacting depreciation; purchase price and throughput. (see figures 8 and 9).

Purchase price has a modest impact on COO in high throughput tools, especially those with higher variable costs. The cost impact in this case is approximately $0.004 (6%) per $300,000 (20%) change in purchase price.

However, as can be seen in figure 9, improvements in throughput can have a significant impact on COO, with a $0.006 (7%) change for a 100wph change (8%) around the nominal value. What is assumed in the above sensitivity analysis is that the amount of chemistry consumption per wafer remains the same across all throughputs. If higher per wafer chemistry consumptions are needed to achieve the increased throughput (increased consumption of acids, bases, and IPA), then this becomes a multi-variable analysis and beyond the scope of this paper.

The last area of examination for cost sensitivities is supplies and consumables. Table 4 below shows the annual costs per system by supply item.

Cost Per System	1,500,000	Dollars
Number Of Systems Required	1	Systems
Total Depreciable Costs	1,532,500	Dollars
Equipment Utilization Capability	96.72	Percent
Production Utilization Capability	96.72	Percent
Composite Yield	99.96	Percent
Good Wafer Equivalents Out Per Week	194,908.54	G.W.E.'s
Good Wafer Equivalent Cost		
With Scrap	0.07362	Dollars
Without Scrap	0.07242	Dollars
Average Monthly Cost		
With Scrap	62,353	Dollars
Without Scrap	61,336	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)	1,664,627	Dollars
Per Good Wafer Equivalent	0.02340	Dollars
Per Good cm2 Out	0.0001	Dollars
Recurring Costs (Over Life of Equipment)	3,573,012	Dollars
Per Good Wafer Equivalent	0.05022	Dollars
Per Good cm2 Out	0.0003	Dollars
Total Costs (Over Life of Equipment)	5,237,639	Dollars
Per Good Wafer Equivalent (Cost Of Ownership)	**0.07362**	**Dollars**
Per Good Wafer Equivalent Supported	0.07362	Dollars
Per Good cm2 Out	0.0004	Dollars
Per Productive Minute	1.47	Dollars

Table 2: COO Results

Cost Drivers per Good Wafer Equivalent		
Labor	0.02940	Dollars
Depreciation	0.02154	Dollars
Material/Consumables	0.01491	Dollars
Maintenance	0.00338	Dollars
Floor Space Costs	0.00167	Dollars
Support Personnel	0.00134	Dollars
Scrap	0.00120	Dollars
Training	0.00010	Dollars
System Qualification Costs	0.00009	Dollars
ESH Preparation and Permits	0.00000	Dollars
Moves And Rearrangements	0.00000	Dollars
Other Materials	0.00000	Dollars
Other Support Services	0.00000	Dollars

Table 3: Pareto of Cost Drivers

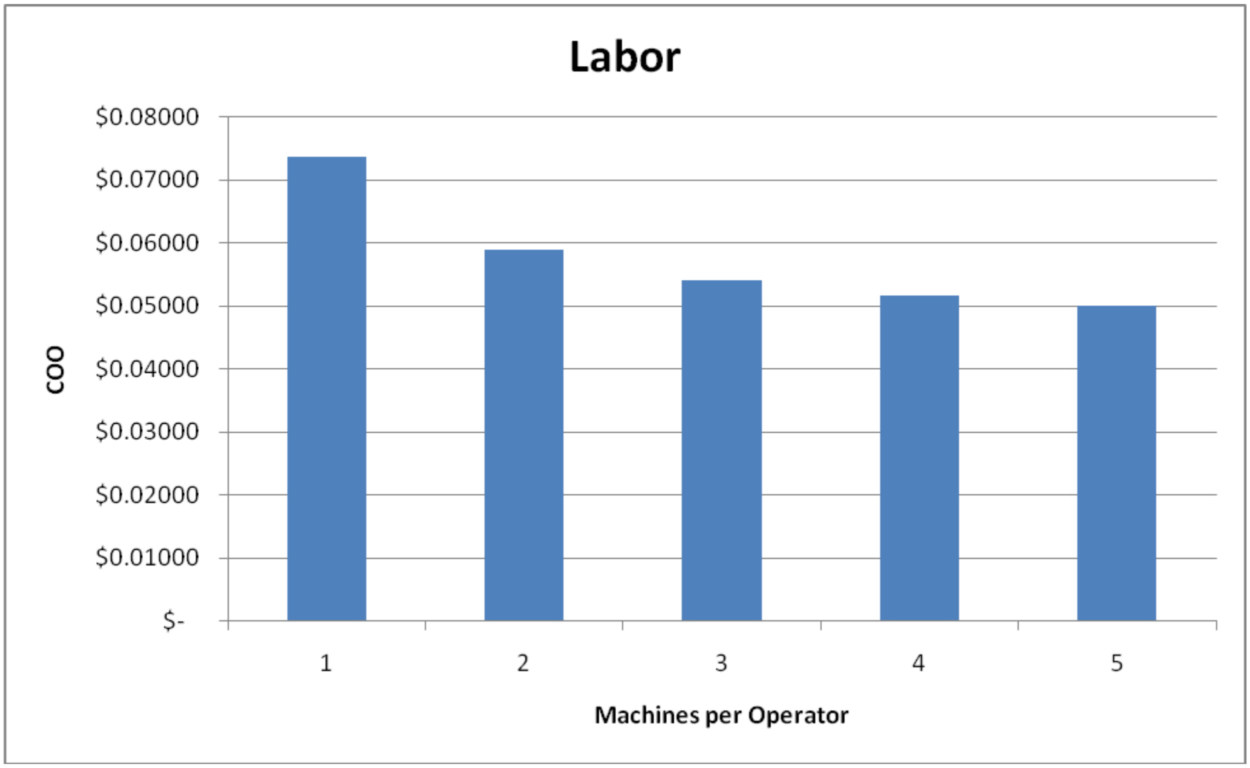


Figure 7: Sensitivity Analysis of Labor vs. COO

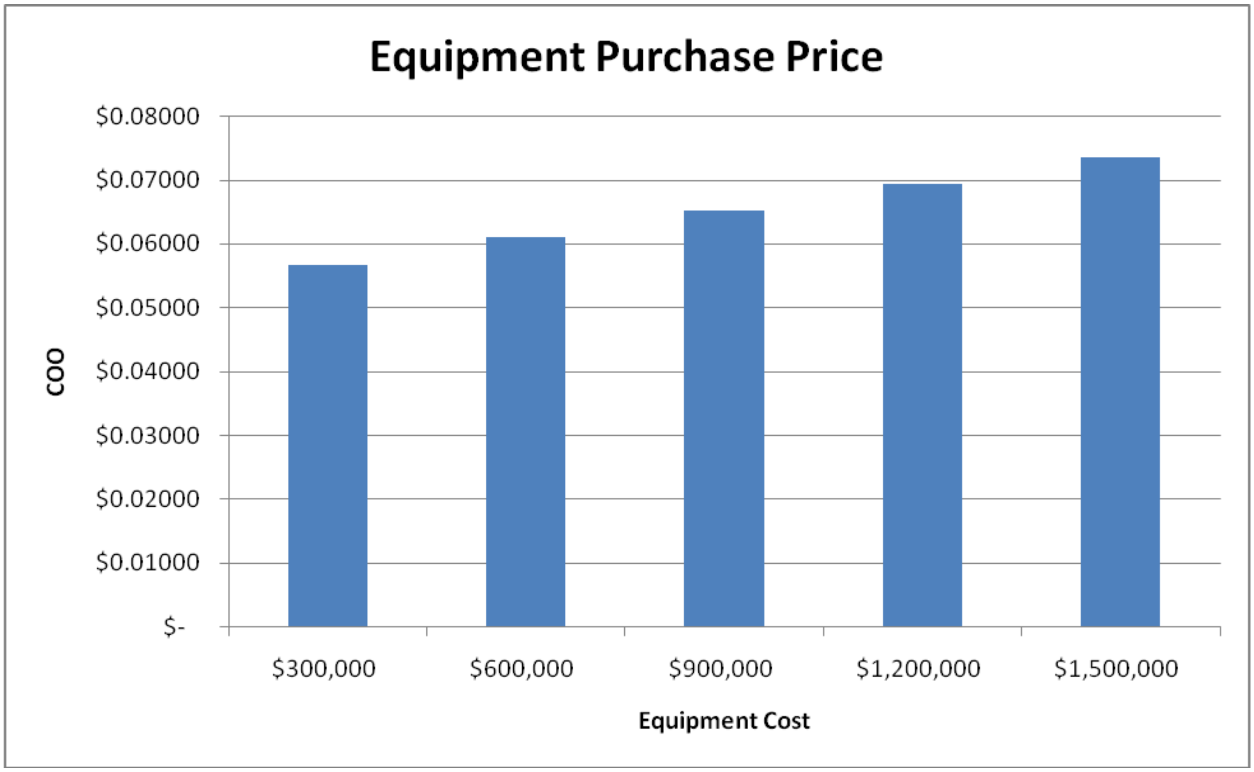


Figure 8: Sensitivity Analysis of Purchase Price vs. COO

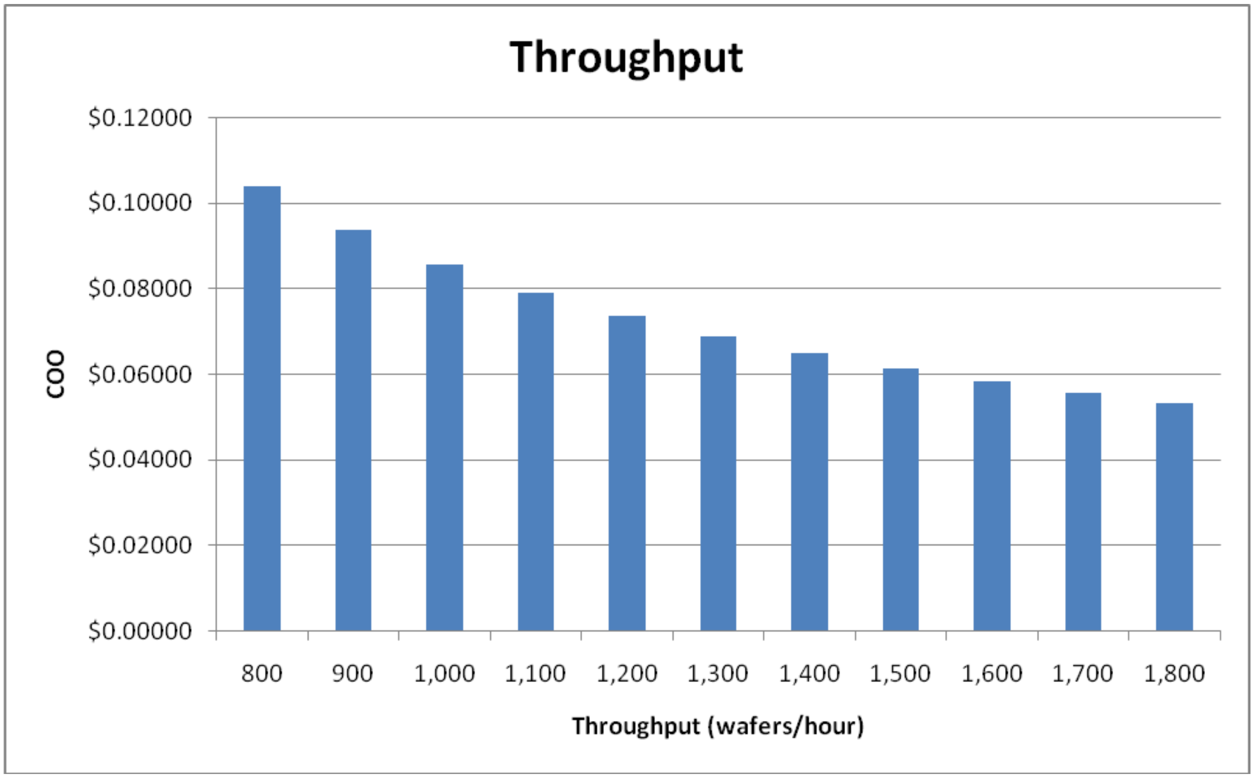


Figure 9: Sensitivity Analysis of Throughput vs. COO

Supply/Consumable	Annual Cost per System
DI Water	$16,046
HCl	$433
HF	$518
IPA	$20,131
KOH	$28,966
CDA	$234
H2O2	$1,638
Acid Drain	$7,127
Caustic Drain	$7,729
Exhaust	$20,741

Table 4: Annual Supply/Consumable Costs

One of the issues in defining a sensitivity analysis for any of the above items is their interrelationship with other factors. Increasing or decreasing KOH concentrations will have an impact not only on throughput, but also caustic drain costs. Likewise, IPA is volatile at typical process temperatures (up to 90ºC) and that has a significant impact not only on IPA refresh but also exhaust volumes, which require oxidation. It is less likely that KOH concentrations can be significantly impacted due to the fact that it is the etchant, it is more likely that IPA can be impacted since it is acting as a wetting agent. Figures 10 looks at the COO impact of reducing IPA consumption.

In preparing for this paper, our survey of end users indicated that their perception was that IPA was a major cost driver due to its volatility at operating temperatures. Figure 10 was a surprise based on these initial comments and shows that efforts solely focused on IPA usage reduction will not drive a major cost reduction.

However, reducing the volumes of IPA or even eliminating it remains an industry concern. Studies show that alternatives can be found although no solution has been endorsed by manufcaturing sites as of yet. If we assume that an alternative surfactant can be used at 50% the cost of IPA and at

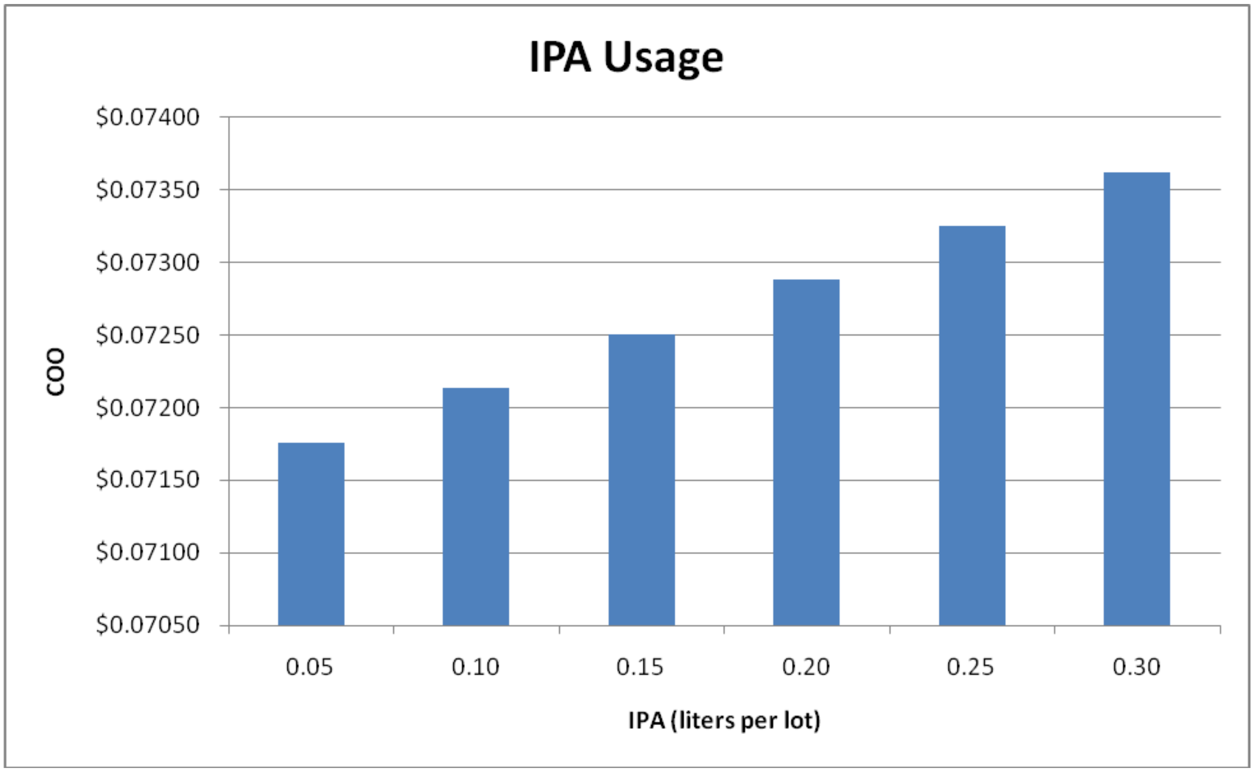


Figure 10: Sensitivity Analysis IPA Usage per Lot vs. COO

10% the volume (with a corresponding 90% reduction in exhaust), we calculate a COO of $0.07035 or a reduction of 4.5%. Again, unless there are environmental or other strategic reasons, it appears replacement of a relatively inexpensive chemical like IPA is not a highly leveraged investment.

Frequently, when using COO a proposed improvement results in an impact on multiple inputs. For example, a feed and bleed approach to refreshing chemistry results in longer bath life and, hence, higher tool utilization. The benefits of this approach can be quickly analyzed as follows: a typical tool uses a bath for about 8-10 hours at the end of which the bath has to be changed. The time needed for the change out is approximately 1-2 hours, including the time needed to verify the right chemical concentration and the desired etch rate. A typical feed and bleed rate is to add additional chemicals of about 50% of the initial mix. This extends bath life and reduces chemical consumption. COO calculations indicates that a feed and bleed system reduces the cost per wafer by nearly 16%.

<u>Overall Equipment Efficiency</u>

Table 5 shows the OEE of the GAMA-Solar. As you can see, the OEE is in excess of 95% which leaves little room for improvement, with only 5 hours per week dedicated to preventive maintenance.

Conclusions

We have examined the need for saw damage removal and follow-on processes including texturization in both wet and plasma based systems. While the technical approach to reducing reflectance at the wafer's surface is well understood, we have shown that initial industry concerns over the cost of IPA may have been misplaced. Through the use of COO, we have shown how the photovoltaics industry has at its disposal a quantitative methodology which can help it make the best choices as it continues down its rapid cost decline curve.

Overall Equipment Efficiency *	**96.68**	**Percent**
Availability Efficiency	**96.72**	**Percent**
Engineering Usage	0.00	Hours/Week
Standby	0.00	Hours/Week
Hours Available/System (Productive Time)	162.49	Hours/Week
Down Time	5.51	Hours/Week
Scheduled Maintenance	5.04	Hours/Week
Unscheduled Maintenance	0.47	Hours/Week
Test	0.00	Hours/Week
Assist	0.00	Hours/Week
Non-Scheduled Time	0.00	Hours/Week
Equipment Uptime	162.49	Hours/Week
Total Time	168.00	Hours/Week
Performance Efficiency *	**100.00**	**Percent**
Throughput At Capacity/System	1200.00	Layers/Hour
Theoretical Throughput *	[1,200.00]	Layers/Hour
Operational Efficiency	100.00	Percent
Rate Efficiency	100.00	Percent
Quality Efficiency	**99.96**	**Percent**
Equipment Yield	99.96	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

Acknowledgements

The authors would like to thank Dr. Oliver Schultz-Wittmann of TetraSun, Dr. Gim Chen and Jeff Vadimsky of Akrion Systems, and Alan Levine of Wright Williams & Kelly, Inc. for their guidance and contributions to this paper.

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11. TWO COOL® is a commercial software package from Wright Williams & Kelly, Inc.

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WWK Hosts Cost of Ownership Seminar at SEMICON West/Intersolar

WWK and SEMI Cosponsor Event for the 20th Consecutive Year

Wright Williams & Kelly, Inc. (WWK), the world's preeminent cost of ownership software and consulting services company, announced today that it will be presenting its highly acclaimed seminar, "Understanding & Using Cost of Ownership," during SEMICON West/Intersolar North America. "Understanding & Using Cost of Ownership" will be held at the San Francisco Marriott on Thursday, July 12 from 9am to 5pm. This seminar covers all aspects of Cost of Ownership (COO) and Overall Equipment Efficiency (OEE) from fundamentals to hands-on applications and has been enhanced to meet the needs of the photovoltaics (PV) industry.

There is limited seating available for this seminar, so please contact Semiconductor Equipment and Materials International (SEMI) today to guarantee your place in this once-a-year event (http://www.semiconwest.org/node/8541). As an added benefit, WWK's software maintenance clients qualify for a 20% discount off the list price of the seminar if booked directly with WWK. Also, customers placing new orders for TWO COOL® COO software will qualify for one free seat in the class.

With more than 3,000 users worldwide, Wright Williams & Kelly, Inc. is the largest privately held operational cost management software and consulting company serving technology-dependent and technology-driven organizations. WWK maintains long-term relationships with prominent industry resources including SEMATECH, National Institute of Advanced Industrial Science and Technology (AIST), Semiconductor Equipment and Materials International (SEMI), and national labs and universities. Its client base includes nearly all of the top 20 semiconductor manufacturers and equipment and materials suppliers as well as leaders in nanotechnology, micro electro-mechanical systems (MEMS), thin film record heads, magnetic media, flat panel displays (FPD), solid state lighting/light emitting diodes (SSL/LED), and photovoltaics (PV).

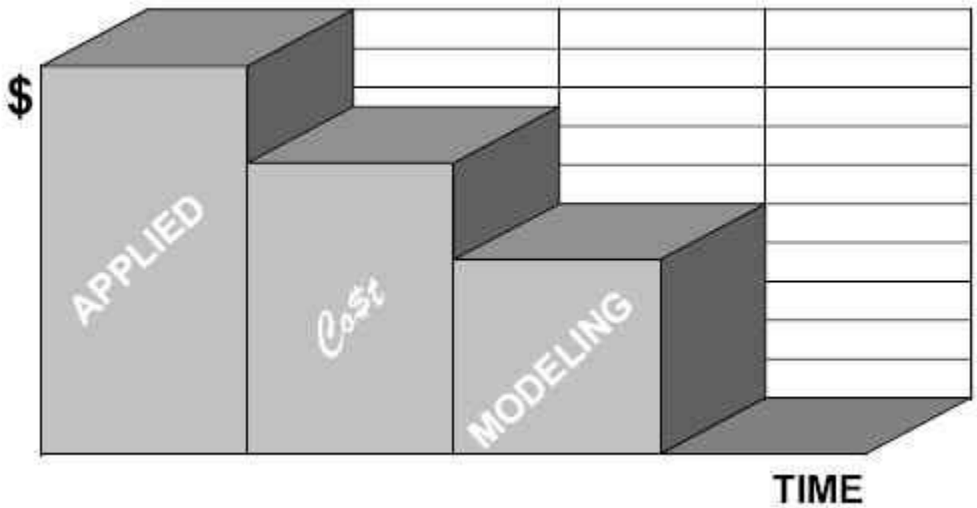
WWK's product line includes TWO COOL® for detailed process step level cost of ownership (COO) and overall equipment efficiency (OEE), PRO COOL® for process flow and test cell costing, Factory Commander® for full factory capacity analysis and activity based costing, Factory Explorer® for cycle time reduction and WIP planning, and TCOe™ for energy production project costs (cost/kilowatt-hour). Additionally, WWK offers a highly flexible product management software package that helps sales forces eliminate errors in product configuration and quotation processes..

ISSN 1094-9739

New Revisions to SEMI COO Standards E35 and E140 Published

The new revisions of SEMI E35-0312 (Equipment/Process COO), SEMI E140-0312 (Gas Delivery System COO), and the free E140 Excel spreadsheet example have been approved and published on the SEMI Standards Web site. Some of the new key technical changes include the addition/revision of several terms, definitions, and acronyms; use of total utilization (vs. operational uptime); how rework is included; changes related to making E35 easier for related industries such as Photovoltaics (PV) to implement; and to fix some known errors.

If you have questions or concerns regarding these new SEMI Standards and/or recommendations for future improvements, please contact the Equipment COO Task Force coleaders. The coleaders are Daren Dance (Wright, Williams & Kelly [WWK]; 435-730-7643; d.dance@wwk.com) and David L. Bouldin (Fab Consulting, 972-727-3591, david.bouldin@sbcglobal.net).



ISSN 1094-9739