The semiconductor and photovoltaics industries have a lot of similarities throughout the manufacturing processes. Acting under guidance from the advisory board, *Photovoltaics International* will feature articles from semiconductor companies presenting best-practice knowledge garnered from the semiconductor industry. This particular paper marks the beginning in a series of papers looking at cost of ownership issues.

Cost of ownership and overall equipment efficiency: a photovoltaics perspective

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ABSTRACT

It is not surprising that the photovoltaics industry has adopted many of the same metrics developed for the semiconductor industry. With suppliers serving both markets, Semiconductor Equipment and Materials International (SEMI) organized the PV Group to, among other things, look at the portability of standards between these two industries. This paper will examine the application of two such standards, the Guide to Calculate Cost of Ownership (COO) Metrics for Semiconductor Manufacturing Equipment (SEMI E35) [1] and the Standard for Definition and Measurement of Equipment Productivity (SEMI E79) [2]. This latter standard is also known as overall equipment efficiency (OEE). Recent work at the National Renewable Energy Laboratory (NREL) regarding cost reduction also references SEMI E35. The application of these standards is examined using a case study comparing an in-line doping furnace and a phosphorus ($POCl_3$) batch furnace.

History

In the mid-1980s, companies became more concerned with understanding the COO concept. COO is the analysis of all costs associated with the acquisition, use and maintenance of a good or service. This analysis takes more than price into consideration, also considering product quality, failure costs, administrative costs, and maintenance, among other factors.

It has now been discovered that low price does not always mean the lowest total cost or satisfactory performance. COO is a tool that allows a company to determine the most cost-effective product or service. Activity-based costing and activity-based cost management also support the concept that cost allocation should be linked to the activity that causes the cost to be incurred.

Recent trends have increased the interest in COO:

- Quality emphasis: the tighter the specification, the higher the quality, and the higher the supplier price. How tight a specification should be to see lower reject rates, improved quality, and higher customer satisfaction is a question answered by COO analysis.
- Supply base rationalization: reduce the number of suppliers but use suppliers that have high quality standards, low cost, and responsive service. COO analyses help to determine which suppliers to keep.
- Increased global competition: Japanese businesses have a thorough understanding of how to manage total costs on a purchasing and total product basis. This is a part of their accounting practice. Companies competing on a global basis must have access to cost data to determine their competitive position in the market.

COO models in the semiconductor industry began at Intel, where, in the mid-1980s, a concentrated analysis began of the total cost of acquiring, maintaining, and operating purchased equipment. Intel's objective was explicit: develop a purchasing methodology that establishes a sound, quantitative, business-like basis for equipment acquisition. The COO concept first came to Sematech when one of Intel's employees was assigned to the consortium's strategic/competitive analysis area.

The original Sematech COO models developed were not very user-friendly. However, they improved over time and received wide acceptance. During the early 1990s, Sematech decided not to introduce any changes to their model so users could become familiar and comfortable with the software. They determined that this would not occur if the software was always in a state of flux [3].

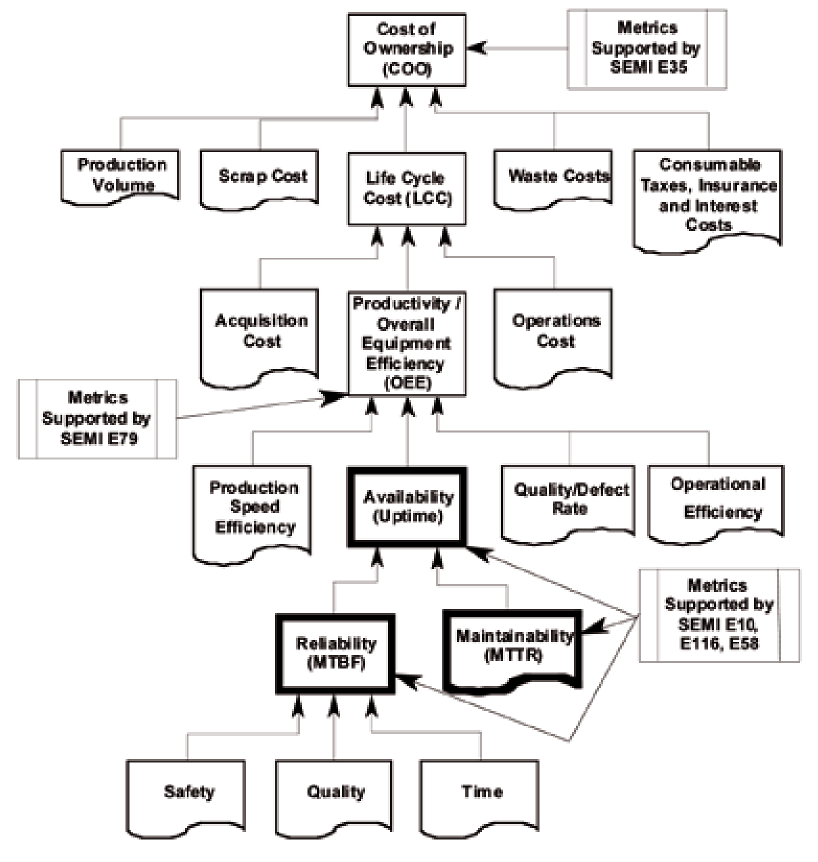

Figure 1. Hierarchy of equipment performance metrics [5].

Once COO was an accepted part of the semiconductor industry, Sematech decided to move forward in providing enhanced versions of COO software. To that end, Sematech contracted Wright Williams & Kelly in 1994 to provide ongoing worldwide support and training for COO as well as enhanced software products. These enhanced software models have been commercially available on a worldwide basis since 1995 and were updated to include other manufacturing areas, including photovoltaics, in 2000.

OEE [4] was created in Japan during the late 1960s by Nippondenso, a major manufacturer of automobile parts, as part of the development of total productive maintenance (TPM). TPM focuses on eliminating 16 major losses that affect production efficiency.

- Seven major losses affecting equipment effectiveness.
- Planned equipment idle time for preventive maintenance, overhaul, and operator meetings.
- Five major losses affecting manpower efficiency.
- Three major losses of material and energy utilization.

Originally OEE was a metric used to determine how much loss was related to the equipment and where these losses occurred. OEE measured the seven major losses of equipment and categorized them into four areas: availability, utilization, throughput rate, and yield.

Semiconductor companies in the United States became very interested in OEE during the mid-1990s, so a task force was formed and SEMI E79 was created to establish a common metric and define OEE as a true equipment efficiency measurement that included all aspects of equipment performance. There were two areas of the original OEE metric that the semiconductor industry felt needed to be addressed to make OEE more useful.

- Include planned equipment idle time in the OEE calculation. This identified opportunities to increase equipment utilization by streamlining activities and reducing ineffective scheduled downtime.
- Base all measurements on time. This area affected the yield measurement that had previously been calculated as good parts produced/total parts produced. As a review of SEMI E79 will show, using time to calculate yield provides an opportunity to identify a greater loss of efficiency.

Many variations of OEE are used around the world across all types of industries. We have found that the SEMI E79 standard is all-inclusive and adaptable for use in many applications including those in the photovoltaics industry.

Basic COO algorithm

Estimating a tool's COO is neither complex nor difficult. With attention to a few significant details, users can determine the life-cycle cost of owning a photovoltaic process tool. The basic COO algorithm is described by:

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

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

Fixed costs include purchase, installation and facility costs that are normally amortized over the life of the equipment. Variable costs such as material, labour, repair, utility and overhead expenses are costs incurred during equipment operation. While correctly a subset of variable costs, yield loss cost is a measure of the value of units lost through breakage and misprocessing and is broken out separately to demonstrate the importance of yield to both the numerator and denominator. Process life is the length of time the process is in operation. Throughput is based on the time needed to meet a process requirement such as depositing a nominal film thickness. Composite yield is the operational yield of the process and includes breakage and misprocessing. Utilization is the ratio of production time compared to total available time.

Definition: E79

Productivity is defined as good unit production rate in relation to the available capacity of the equipment. One of the most popular productivity metrics is OEE, which is based on reliability (mean time between failures, or MTBF), maintainability (mean time to repair, or MTTR), throughput, utilization and yield. All these factors are grouped into the following four submetrics of OEE: availability (joint measure of reliability and maintainability), operational efficiency, throughput rate efficiency, and yield/quality rate.

OEE is defined by SEMI E79 as "the fraction of total time that equipment is producing effective units at theoretical efficiency rates." From a high-level perspective, OEE can be reduced to the following equation:

OEE = Theoretical Production Time for Effective Units /Total Time

or

OEE = Availability Efficiency x Performance Efficiency x Quality Efficiency

Availability efficiency

Availability efficiency, defined as "the fraction of equipment uptime that the equipment is in a condition to perform its intended function," is represented in the following equation:

Availability efficiency = equipment uptime/total time.

Performance efficiency

Performance efficiency, defined as "the fraction of equipment uptime that the

Parameter	**In-line Diffusion System**	**$POCl_3$**
Throughput	1,500 wafers/hour	800 wafers/hour
Wafer size	156mm	156mm
Wafer cost	$3	$3
Mean time between failure (MTBF)	4,500 hours	336 hours
Mean time to repair (MTTR)	3 hours	5 hours
Equipment cost	$1,200,000	$1,300,000
Equipment yield	99.96%	99.96%
Utilities	$142,820/year/system	$211,086/year/system
Dopant mixture	$66,340/year/system	$100,622/year/system
Quartzware, cleans, breakage	$0	$130,200/year/system
Maintenance	Owner provided	Owner provided

Table 1. Major COO inputs.

	In-line	$POCl_3$
Cost per system	$1,200,000	$1,300,000
Number of systems required	1	1
Total depreciable costs	$1,220,000	$1,390,000
Equipment utilization capability	97.97%	96.02%
Production utilization capability	97.67%	95.72%
Composite yield	99.96%	99.96%
Good wafer equivalents out per week	246,026	128,598
Good wafer equivalent cost		
With scrap	$0.04	$0.16
Without scrap	$0.04	$0.16
Average monthly cost		
With scrap	$47,304.38	$89,782.17
Without scrap	$46,021.02	$89,111.35
Process scrap allocation		
Equipment yield	100%	100%
Defect limited yield	–	–
Parametric limited yield	–	–
Equipment costs (over life of equipment)	$1,353,646	$1,570,127
Per good wafer equivalent	$0.02	$0.03
Per good cm^2 out	$0.00	$0.00
Recurring costs (over life of equipment)	$2,619,922.17	$5,971,574.65
Per good wafer equivalent	$0.03	$0.13
Per good cm^2 out	$0.0002	$0.0007
Total costs (over life of equipment)	$3,973,568	$7,541,702
Per good wafer equivalent (COO)	$0.04	$0.16
Per good wafer equivalent supported	$0.04	$0.16
Per good cm^2 out	$0.0002	$0.0008
Per productive minute	$1.11	$2.14

Table 2. COO comparative results.

Cost drivers per good wafer equivalent for in-line	
Material/consumables	$0.0189
Depreciation	$0.0136
Labor	$0.0059
Maintenance	$0.0019
Floor space costs	$0.0014
Scrap	$0.0012
Support personnel	$0.0012
System qualification costs	$0.0001
Other materials	$0.0001
Training	$0.0000
ESH preparation and permits	$–
Moves and rearrangements	$–
Other support services	$–
Cost drivers per good wafer equivalent for $POCl_3$	
Material/consumables	$0.0745
Labor	$0.0442
Depreciation	$0.0296
Maintenance	$0.0046
Floor space costs	$0.0035
Support personnel	$0.0022
Scrap	$0.0012
Other materials	$0.0004
Training	$0.0002
System qualification costs	$0.0002
ESH preparation and permits	$–
Moves and rearrangements	$–
Other support services	$–

Table 3. Pareto of cost drivers.

equipment is processing actual units at theoretically efficient rates," is represented in the following equation:

Performance efficiency = operational efficiency x rate efficiency

or

Performance efficiency = (production time/equipment uptime) x (theoretical production time for actual units/production time).

Quality efficiency

Quality efficiency, defined as "the theoretical production time for effective units divided by the theoretical production time for actual units," is represented in the following equation:

Performance efficiency = theoretical production time for effective units/theoretical production time for actual units.

As we see above, many parameters are required 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, which may cause the system to appear disjointed. However, this is not true as these metrics all fit nicely into a hierarchal tree.

Fig. 1 depicts the hierarchy tree of the equipment performance metrics. As the schematic shows, 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, this 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.

Case study: in-line doping furnace vs. batch $POCl_3$ furnace

Starting silicon wafers are usually p-type, that is, boron-doped. It is then customary to form the p-n junction by introducing phosphorus, an n-type impurity, from the front surface. At sufficiently high temperatures, phosphorus atoms can diffuse into the solid silicon wafer. For a typical diffusion time of 15-30 minutes the penetration depth is very small (approximately 0.5μm) as required for optimal solar cell operation. The conventional way of performing phosphorus diffusion is to use a quartz diffusion furnace. A common dopant source is a liquid chemical containing phosphorus ($POCl_3$), which is conveniently carried into the furnace by bubbling nitrogen through it. In addition, oxygen is injected into the furnace so that it reacts with the $POCl_3$ and forms phosphorus oxide (P_2O_5). At the surface of the wafers the P_2O_5 turns into silicon dioxide (SiO_2) and atomic phosphorus, which can diffuse into the wafer. The oxide that is left on the wafers is usually removed chemically after the diffusion [6].

An alternative to the batch $POCl_3$ furnace is BTU International's Meridian in-line diffusion system, which combines a direct-spray phosphorus coater integrated with a conveyor belt diffusion furnace. The coater includes backside, topside, and drying capability. This analysis will examine which of these is the most desirable on the merits of COO and OEE.

Cost of ownership inputs

The following are the results of the COO analysis run on the in-line and $POCl_3$ furnaces. Table 1 highlights the major input parameters. It should be noted that the major application in COO and OEE analyses is for relative comparisons, that is, before vs. after an upgrade or change, or between competing solutions. By using these metrics as a relative measure, the modeller is not required to build the 'perfect' model or obtain 100% of all possible data to 100% accuracy.

In addition to the parameters presented in Table 1, where required, the author used example values from SEMI E35 for administrative rates and overhead. These values were 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.

Cost drivers

Examination of the detailed TWO COOL cost of ownership models in Table 2 highlights the main cost and productivity differences between the two approaches. (TWO COOL is a commercial software package from Wright Williams & Kelly.) The throughput differences between the furnaces drive a relatively small fixed cost per cell delta ($0.02 vs. $0.03). The majority of the cost advantages of the in-line system come in the area of operational or variable costs ($0.03 vs. $0.13).

Table 3 takes a closer look at the cost breakdown according to the 13 categories specified in SEMI E35. The top 5 Pareto costs for both systems are materials/consumables, which includes utilities, supplies, consumables, and waste disposal; depreciation, which is impacted by equipment costs, throughput rate, and utilization; labour; maintenance, including repair parts and technician labour; and floor space. The only difference in ranking is that labour is a higher cost in the $POCl_3$ furnace as would be expected when comparing batch and in-line systems.

The top three cost drivers account for over 90% of the total cost of ownership in both analyses. For this reason, we will focus our attention on those areas as we examine the cost sensitivities to input parameters that drive material/consumable, depreciation, and labour costs.

Cost driver sensitivities

Since the $POCl_3$ furnace shows the higher COO, the following sensitivity analyses will be run from the perspective of what needs to be done to the $POCl_3$ furnace to drive down its cost structure. The first analysis looks at dopant cost in two ways: the amount used per wafer and the cost per gram (see Figs. 2 and 3).

As can be seen from these figures, $POCl_3$ price and consumption changes cannot close the COO gap. Looking at quartzware, another material/consumable cost, it is clear that horizontal furnaces have costs associated with quartz liners and boats. Not only are there acquisition costs, but further concerns are cleaning costs and the risks associated with breakage during the cleaning process. Likewise, there is a finite life for quartzware (see Fig. 4).

The remaining major cost driver in materials/consumables is electricity. It should be noted that any change in the cost per kilowatt-hour will impact both furnace types by an equal percentage. Fig. 5 shows the sensitivity of the $POCl_3$ furnace COO to annual electricity costs.

As can be seen from the sensitivity analysis graphs, it would be difficult for the $POCl_3$ furnace to close the cost gap with any reasonable improvement in the area of material/consumables. Therefore, we will turn our attention to the factors impacting depreciation: purchase price and throughput (see Fig. 6 and 7).

Purchase price has minimal impact on COO in high throughput tools, especially those with higher variable costs. However, as can be seen in Fig. 7,

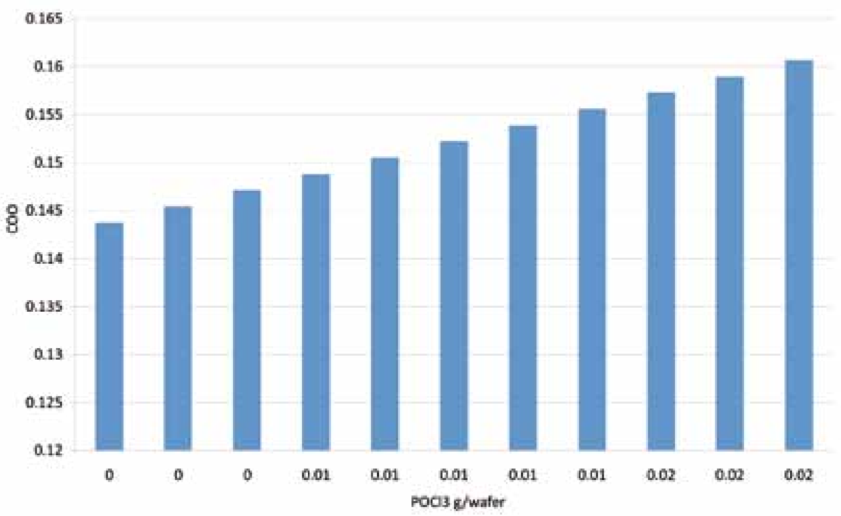

Figure 2. Sensitivity analysis of $POCl_3$ (4g/tube, 200 wafers, $750/Kg) usage per wafer vs. COO.

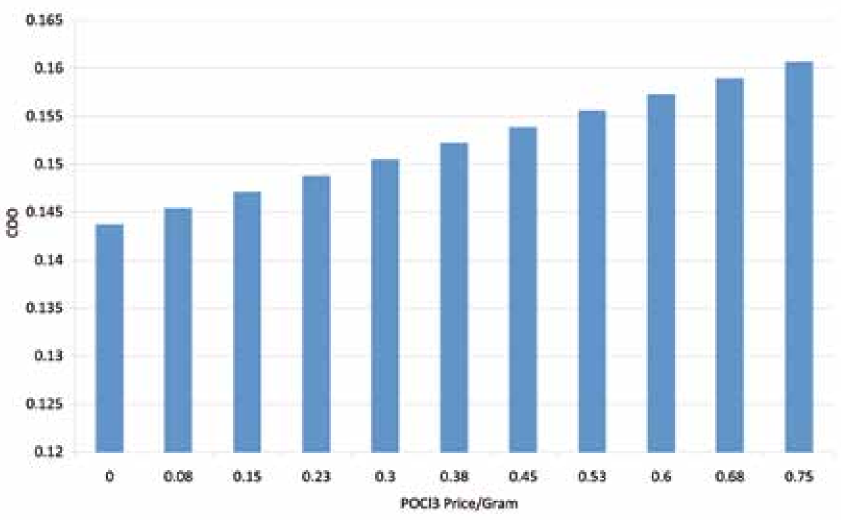

Figure 3. Sensitivity analysis of $POCl_3$ (4g/tube, 200 wafers, $750/Kg) price per gram vs. COO.

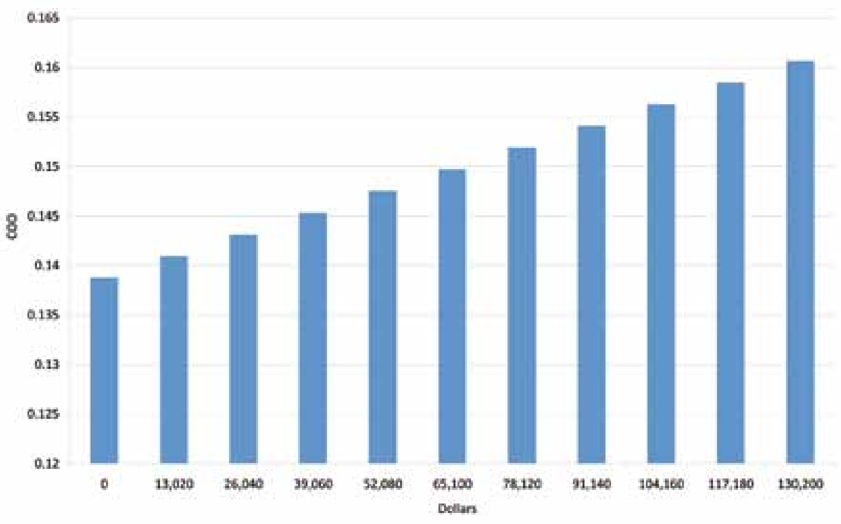

Figure 4. Sensitivity analysis of quartzware furnace (4 tube) annual cost vs. COO.

improvements in throughput have a significant impact on COO. The sensitivity analysis depicted in Fig. 7 does not, however, include any increased material consumption that might be needed to achieve the increased throughput (e.g., longer furnace tube with more wafers using more $POCl_3$ or higher cost quartzware).

So, if the $POCl_3$ furnace is to match or exceed the COO of the in-line system, it will need to focus resources on improvements in throughput as well as incremental reductions in material/consumable costs. However, $POCl_3$ furnaces have been in operation longer than in-line systems and have, therefore, undergone more cycles of learning. It might be reasonable to assume that yield would be higher in such a system. The preceding analyses were based on an identical yield of 99.96%. Fig. 8 examines what level of yield degradation would be needed in the in-line system to raise its COO to that of the batch system.

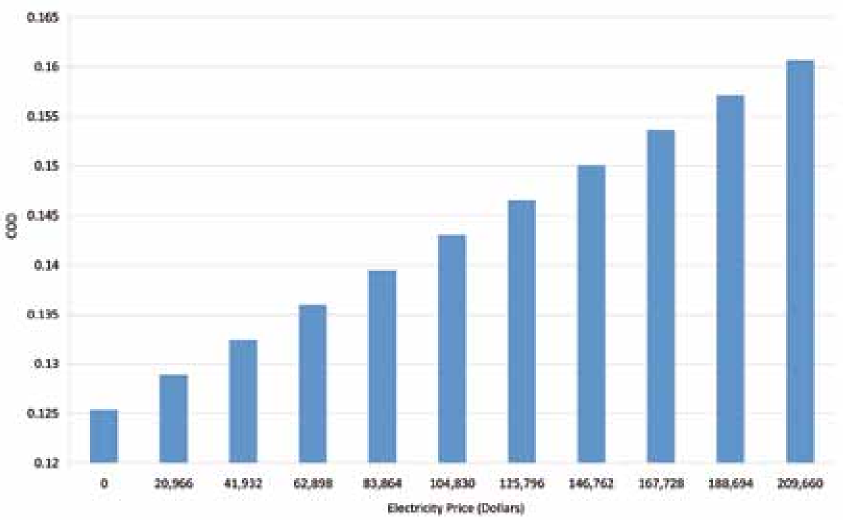

Figure 5. Sensitivity analysis of annual electricity cost vs. COO.

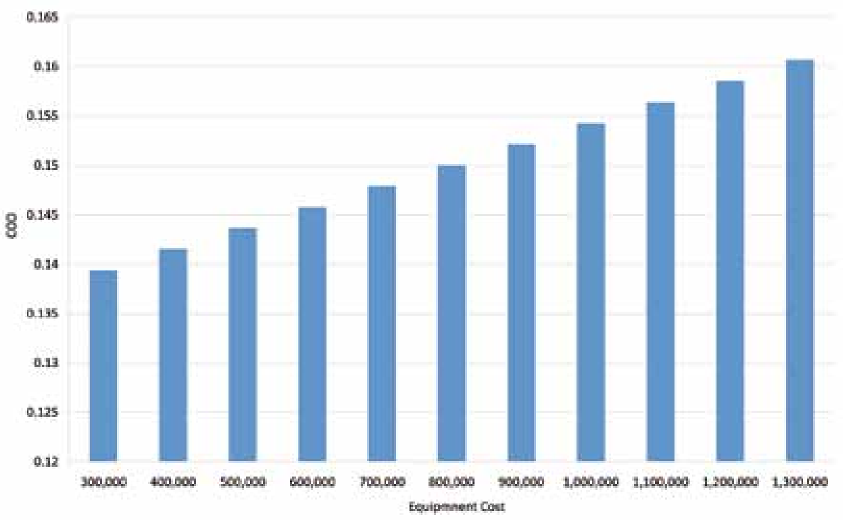

Figure 6. Sensitivity analysis of equipment purchase price vs. COO.

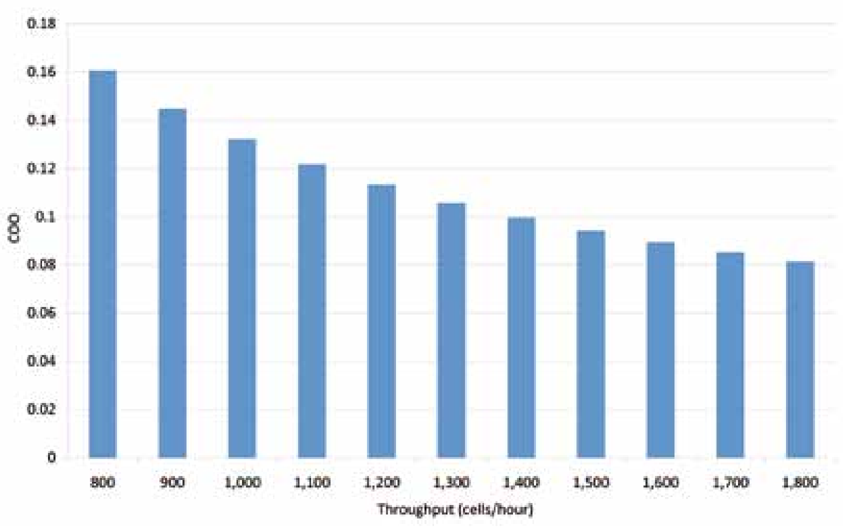

Figure 7. Sensitivity analysis of throughput vs. COO.

The above sensitivity analysis shows the significant impact of yield loss (scrap) on COO. A 3% increase in the scrap rate completely eliminates the operational advantages of the in-line system. The above analysis is based on simple pass/fail criteria and does not attempt to assign variable costs to cell efficiency binning.

Overall equipment efficiency

OEE is frequently used to improve the usage or productivity of an existing equipment set. Better understanding of the OEE of the constraining (or bottleneck) equipment can result in capacity improvements that increase the potential usage of every other equipment set in the factory. For example, a production schedule that improves doping OEE by reducing time lost due to scheduled downtime can increase the capacity of the entire factory. Thus, an improvement of the constraint equipment improves the OEE of all the manufacturing equipment. In the case of linked operations – as seen in PV factories using all in-line systems – the line can be balanced to such a degree that any tool in the line can itself become the constraint. This makes factory planning very difficult and leads to the use of in-line buffers to keep tools loaded regardless of tool interruptions.

In general, not all of the equipment used in manufacturing should have high OEE. Diagnostic equipment can best impact production when it is readily available for use if a manufacturing problem should occur. If several operators are waiting for an available inspection system, then the higher OEE of the inspection system comes as a result of lower OEE for the manufacturing system.

Finally, OEE analysis without cost analysis may result in high OEE at the expense of COO increases. Since OEE is a subset of COO and lacks any activity-based cost-related input or output, it is highly recommended that COO be considered when applying OEE to non-bottleneck or non-near-bottleneck equipment. Since COO is limited by definition to looking at the cost impacts of individual process steps, OEE improvements in bottleneck tools are best measured in terms of cost or revenue impacts by factory-level modelling tools such as WWK's Factory Commander or Factory Explorer software.

Table 4 shows the OEE differences between the in-line and batch furnaces.

The in-line system has an approximately 2% higher OEE. This is driven by differences in availability efficiency driven by differences in mean time-to-failure or interrupt (MTBF or MTBI). Since the doping furnace can be a constraint tool, this 2% OEE improvement could relate to a 2% improvement in factory performance.

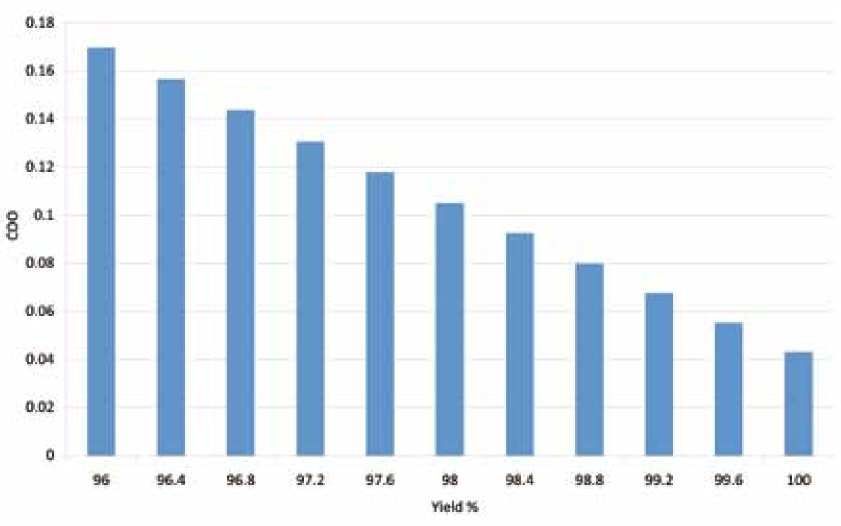

Figure 8. Sensitivity analysis of equipment yield vs. COO.

	In-line	$POCl_3$
Overall equipment efficiency	97.63%	95.68%
Availability efficiency	97.67%	95.72%
Engineering usage (hours/week)	–	–
Standby (hours/week)	–	–
Hours available/system (productive time) (hours/week)	164.08	160.81
Down time (hours/week)	3.92	7.19
Scheduled maintenance (hours/week)	3.00	4.00
Unscheduled maintenance (hours/week)	0.13	2.69
Test (hours/week)	0.50	0.50
Assist (hours/week)	0.28	–
Non-scheduled time (hours/week)	–	–
Equipment uptime (hours/week)	164.08	160.81
Total time (hours/week)	168.00	168.00
Performance efficiency	100%	100%
Throughput at capacity/system (wafers/hour)	1,500	800
Theoretical throughput (wafers/hour)	1,500	800
Operational efficiency	100%	100%
Rate efficiency	100%	100%
Quality efficiency	99.96%	99.96%
Equipment yield	99.96%	99.96%
Defect limited yield	100%	100%
Parametric limited yield	100%	100%
Alpha error factor	100%	100%
Beta error factor	100%	100%
Redo rate	–	–

Table 4. OEE comparative results.

Conclusion

Because COO and OEE were driven by the needs of the IC industry in the late 1980s, it may well be the case that these metrics are more important to the photovoltaics industry. While ICs have some level of differentiation in form and function, the holy grail in PV is cost per watt. With technologists looking to improve cell and module efficiency, the need to ensure that those improvements are not increasing the cost per watt is critical.

This discussion and the examples provided herein have shown how easily COO and OEE can be applied to comparative analyses both in terms of procurement decisions but also in equipment improvement decisions. The broad adoption of these metrics as is being fostered by the SEMI PV Group, NREL and others will go a long way to ensuring that the industry as a whole stays ahead of its cost projections.

References

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David Jimenez is president and cofounder of Wright Williams & Kelly, Inc., the largest privately-held operational cost management software and consulting services company. He has approximately 30 years of industry experience including management positions with NV Philips and Ultratech Stepper. He holds a B.S. in chemical engineering from the University of California, Berkeley and an M.B.A. in finance. Responsible for the design of the semiconductor industry's de facto standard in cost of ownership, TWO COOL, he holds a patent for his work on PRO COOL for Wafer Sort & Final Test. He is a recipient of the Texas Instruments Supplier Excellence Award for his contributions to their cost reduction efforts. For over 18 years, he has been a facilitator in the SEMI sponsored workshop, "Understanding and Using Cost of Ownership." He is also the author of numerous articles in the fields of productivity and cost management.

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