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Fall 2011

Cost of Ownership and Overall Equipment Efficiency: A Photovoltaics Perspective

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 photovoltaic (PV) cell manufacturing.

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 to 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].

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[Continued on page 3]

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Calendar of Events

January 2012

15-18 Industry Strategy Symposium (ISS)
Ritz-Carlton
Half Moon Bay, CA

16-19 World Future Energy Summit
Abu Dhabi National Exhibition Centre
Abu Dhabi, UAE

February 2012

26-28 Industry Strategy Symposium Europe
Hotel Kempinski Vier Jahreszeiten
Munich, Germany

March 2012

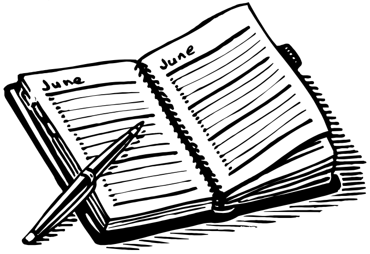
19-21 PV America West
San Jose Convention Center
San Jose, CA

20-22 SEMICON/FPD China
New International Expo Center
Shanghai, China

25-27 PV Fab Managers Forum Europe
Hotel Kempinski Bristol
Berlin, Germany

April 2012

2-5 North American Standards Meeting
SEMI Headquarters
San Jose, CA



An alternative to the batch $POCl_3$ furnace is BTU International's Meridian In-line Diffusion System combining a direct spray phosphorus coater integrated with a conveyor belt diffusion furnace. The coater includes back-side, topside and drying capability. This analysis will examine which 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 Meridian 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 modeler is not required to build the "perfect" model or obtain 100% of all possible data to 100% accuracy.

Parameter	Meridian	$POCl_3$
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 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.

Cost Drivers

Examination of the detailed TWO COOL®[7] COO models in Table 2 highlights the main cost and productivity differences between the two approaches. 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 five 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; Labor; Maintenance, including repair parts and technician labor; and Floor space. The only difference in ranking is that labor is a higher cost in the $POCl_3$ furnace as would be expected when comparing batch and in-line systems.

		In-line	POCl3
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 cm2 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 cm2 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 cm2 Out	$ 0.0002	$ 0.0008
	Per Productive Minute	$ 1.11	$ 2.14

Table 2: COO Comparative Results

The top three cost drivers account for over 90% of the total COO 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 Labor 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 Figures 2 and 3)

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 POCl3	
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

As can be seen from the above figures, $POCl_3$ price and consumption changes cannot in and of themselves close the COO gap. Next we look at another Material/Consumable cost, quartzware. Horizontal furnaces have costs associated with quartz liners and boats, not only the acquisition costs but also cleaning costs and the risks associated with breakage during the cleaning process. Likewise, there is a finite life for quartzware. (see Figure 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. Figure 5 shows the sensitivity of the $POCl_3$ furnace COO to annual electricity costs.

As can be seen from the above sensitivity analyses, 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 Figures 6 and 7).

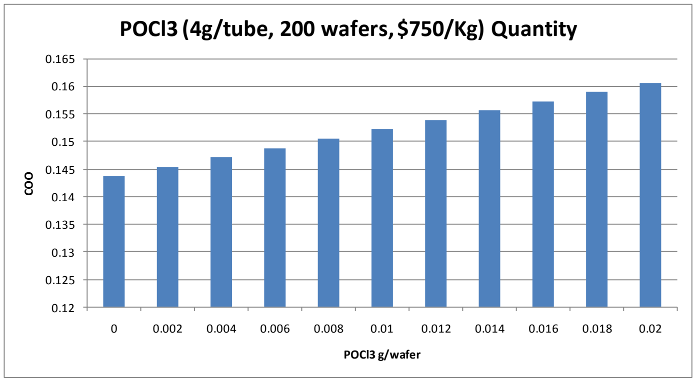


Figure 2: Sensitivity Analysis of $POCl_3$ Usage per Wafer vs. COO

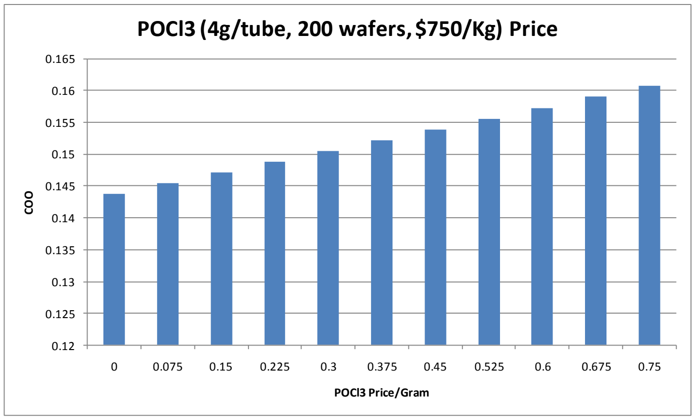


Figure 3: Sensitivity Analysis of $POCl_3$ Price per Gram vs. COO

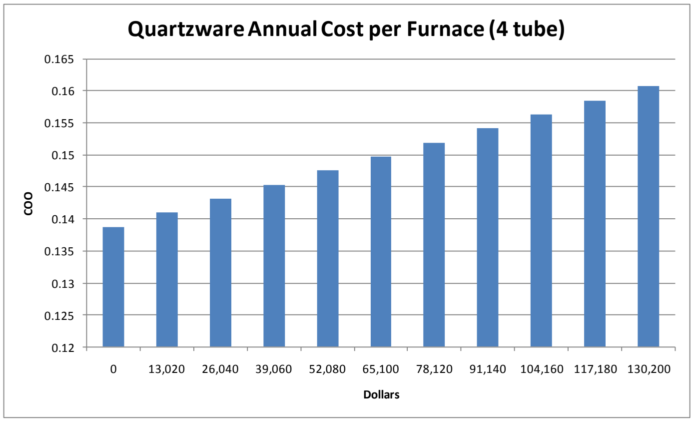


Figure 4: Sensitivity Analysis of Quartzware Annual Cost vs. COO

Purchase price has minimal impact on COO in high throughput equipment, especially those with higher variable costs. However, as can be seen in Figure 7, improvements in throughput have a significant impact on COO. What is not included in the above sensitivity analysis is 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%. Figure 8 below examines what level of yield degradation would be needed in the in-line system to raise its COO to that of the batch system.

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.

<u>Overall Equipment Efficiency</u>

OEE is frequently used to improve the usage or productivity of an existing equipment set. Better understanding of the OEE of the constraining equipment (the 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.

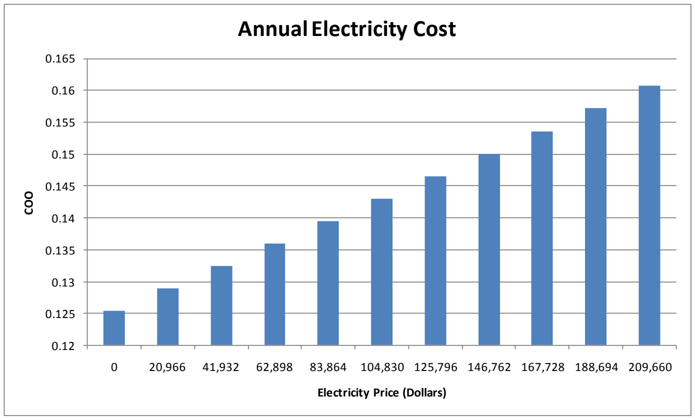


Figure 5: Sensitivity Analysis of Annual Electricity Cost vs. COO

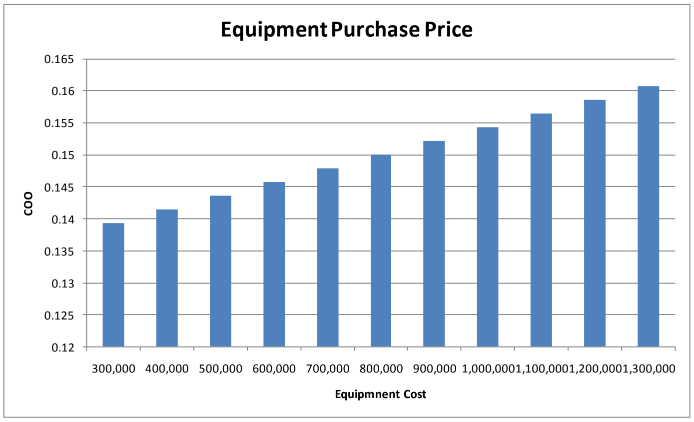


Figure 6: Sensitivity Analysis of Purchase Price vs. COO

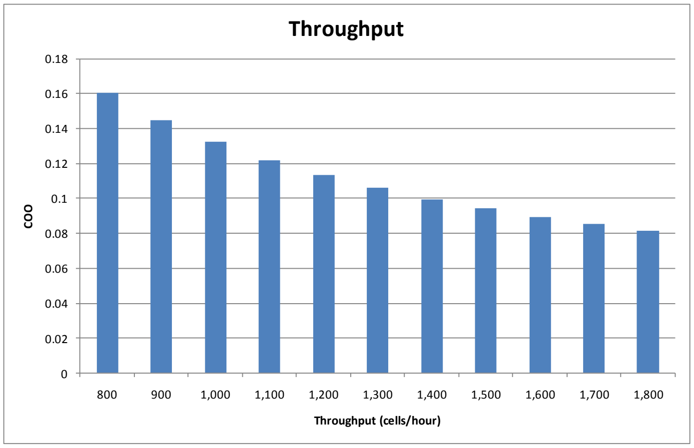


Figure 7: Sensitivity Analysis of Throughput vs. COO

Thus, an improvement at the constraint equipment improves the OEE of all the manufacturing equipment. In the case of linked operations, as is seen in PV factories using all in-line systems, the line can be balanced to such a degree that any equipment in the line can become the constraint. This makes factory planning very difficult and leads to the use of in-line buffers to keep equipment loaded regardless of equipment interruptions

Not all of the equipment should have high OEE. Diagnostic equipment can best impact production when it is readily available for use if a manufacturing problem should occur. If operators are waiting for an available inspection system, then the higher OEE of the inspection system comes at 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 equipment are best measured in terms of cost or revenue impacts by factory level modeling 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 OEE higher by approximately 2%. 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 equipment, this 2% OEE improvement could relate to a 2% improvement in factory performance.

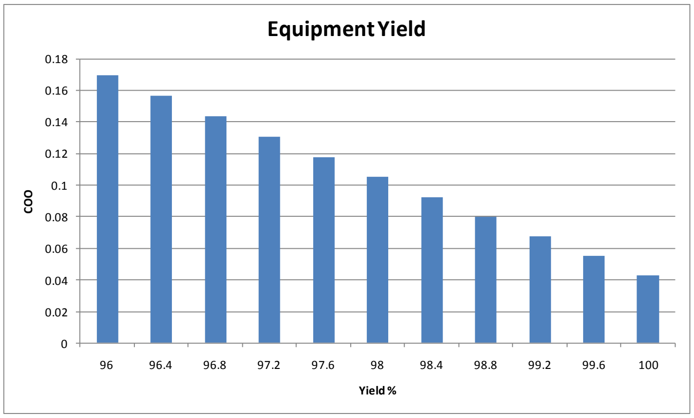


Figure 8: Sensitivity Analysis of Equipment Yield vs. COO

Conclusions

While COO and OEE were driven by the needs of the integrated circuit (IC) industry in the late 1980's, it may well be the case that these metrics are more important to the PV 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.

The above discussion and examples 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, National Renewable Energy Laboratory (NREL), and others, will go a long way to ensuring that the industry as a whole stays ahead of its cost projections.

References

6. Solar Electricity, Second Edition, Edited by Tomas Markvart, University of Southampton, UK.
7. TWO COOL® is a commercial software package from Wright Williams & Kelly, Inc.

			In-line	POCl3
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		-	-

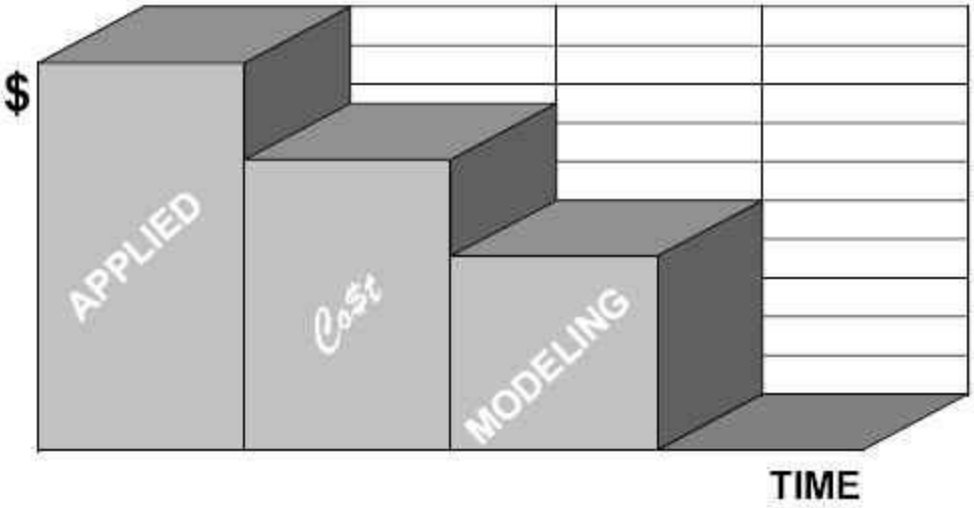
Table 4: OEE Comparative Results

POWERED BY TWO COOL

Breaking News

Wright Williams & Kelly, Inc. has been awarded a grant from Invest in Spain and the European Union's FEDER program. The grant is to promote the establishment of select research, development, and innovation (RD&I) in Spain and the EU. WWK will release additional information in the near future regarding its work with Invest in Spain and the regional economic development agency in Catalonia (ACC1Ó).

Holiday Greetings from Wright Williams & Kelly, Inc.
Thank you for your support.
We share with you our best wishes for a prosperous 2012!
Happy Holidays,
WWK & Affiliates



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