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Volume 20. Issue 3

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Spring 2014

ISSN 1094-9739

CIGS Manufacturing: Promises and Reality

With this edition of Applied Cost Modeling, we are publishing the second installment in a series examining the economic issues that are the driving forces behind photovoltaic (PV) adoption. Even technological advances are measured against their impacts on cost per watt, levelized cost of energy (LCOE), and total cost of ownership for energy (TCOe™). In this sixth paper covering business analysis for PV processes, we look at two approaches to manufacturing thin film Copper-Indium-Gallium-diSelenide (CIGS) PV, sputtering and coevaporation, and their potential areas for cost improvement.

Case Study

The case study will use cost and resource modeling to evaluate both sputtered and coevaporated CIGS processes. Both models are based on a 100MW annual factory output. All results were generated through Wright Williams & Kelly, Inc.'s (WWK) Factory Commander® cost and resource software[1].

Cost and Resource Modeling History

Cost and resource modeling is a comprehensive approach to understanding a wide variety of factory level issues. The techniques were pioneered in the 1990's by SEMATECH for integrated circuits (ICs) and by Sandia National Laboratories under the National Center for Advanced Information Components Manufacturing (NCAICM) program for flat panel displays (FPDs). The concept was

First published in Photovoltaics International, 21st edition.

[Continued on page 3]

Publisher

Published quarterly by:

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Available at:
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Calendar of Events

June 2014

23-25 PV America
Boston Convention and Exhibition Center
Boston, MA

July 2014

8-10 SEMICON West, Intersolar North America
Moscone Hall
San Francisco, CA

August 2014

12 Silicon Valley Strategic Advisers
SEMI Headquarters
San Jose, CA
(Open meeting held monthly on the second Tuesday - http://svstrategicadvisers.com/)

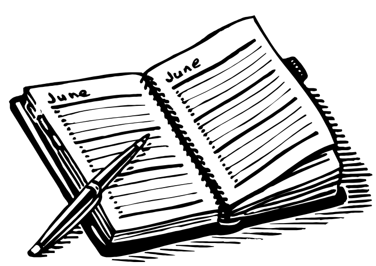
26-28 Intersolar South America
Expo Center Norte
São Paulo, Brazil

September 2014

22-26 EU PVSEC
RAI Convention & Exhibition Center
Amsterdam, The Netherlands

October 2014

7-9 SEMICON Europa
ALPEXPO
Grenoble, France



developed to initially assist these two capital-intensive industries in improving their ability to compete globally and maintain a U.S. supply of high tech components.

While a joint approach between SEMATECH and NCAICM was considered, substantial limitations to the SEMATECH approach known as CR/M convinced the NCAICM program to take a separate development. Core requirements such as detailed material tracking/costing, modeling of rework loops, mergers of multiple process flows, and better output reporting capabilities were among the challenges that separated SEMATECH's more limited goals from a more robust methodology that addressed both new and existing operations. Further, SEMATECH considered CR/M a strategic asset and chose to limit access to members and select suppliers. Sandia, while recognizing the value of the software, also understood that wider adoption would advance the technology more rapidly.

As a result, the Sandia Factory Cost Model (FCM) was developed as a 'decision tool', in order to make cost competitive decisions regarding new manufacturing initiatives. The FCM was one of several cost modeling tools and projects developed under the NCAICM program. WWK acquired the intellectual property (IP) rights to Sandia's work in 1996 and commercialized FCM under the trade name Factory Commander®. By using recognized standards as the basis for Factory Commander (industrial engineering, accounting, etc), the application has proven to be robust, making it applicable to all discrete manufacturing and assembly operations, including PV.

Cost and Resource Models

Cost and resource models assess the resources needed, people, equipment, materials, etc., to complete a process or task. Resources have roles, availability, and costs associated with them. Cost and resource models are demand-based applications, and to the extent possible, all resource requirements are tied to the production demand. As such, cost and resource models calculate all the resources required to meet the specified demand, typically expressed as a production schedule.

At the heart of cost and resource modeling are activities. Activity is an accounting term with the manufacturing equivalent being the process step. Each activity requires resources, resources cost money. Activities are summed together to determine costs. Revenues are determined by selling prices of products. By including all inflows and outflows of cash, a complete financial analysis can be performed (net present value, breakeven, payback period, net cash flow, pro forma income statement, etc.) in addition to traditional industrial engineering metrics (floor space, equipment counts, etc.). Four common business practices are subsets of cost and resource modeling.

1. Cost of Ownership[2] (COO) is essentially the cost of an individual activity.
2. Capacity analysis determines the total resources needed to meet the production demand. Typically, capacity analysis refers to equipment, but it can also include staffing, support, and material needs.
3. Budgeting, including capital budgets, is a function of the capacity needs and the costs associated with meeting them.
4. Product planning, where product demand is the key driver of the resource requirements and may involve product mix variability (ramp up/ramp down).

Both SEMATECH and Sandia recognized the limitations of spreadsheets - it was bit like taking a 2 dimensional approach to a 4 dimensional problem. Both chose a relational database approach to overcome the ‘simple factory’ limitation. The relational database approach made it possible to account for the complex and dynamic nature of factories, with near constant change in product volumes, product mix, yields, productivity rates (cycles of learning), process flows, step yields, material costs, labor efficiency, product value, etc. It also helped address real world issues such as non-products run in the factory, including R&D, engineering evaluations and monitor units. There are re-entrant process flows, rework, merged process flows and sophisticated process monitoring plans. Products can be binned into different levels and are often transformed (cells turn into modules, wafers into die, large panels of glass into small displays). Equipment can be underutilized and even pulled offline, material consumptions can change, labor requirements can change and the price paid for any of these items can change with inflation and volume pricing contracts.

There are outside factors, such as licensing IP, overheads, currency rates, etc. that all impact product cost. Once these factors are identified, the cost and resource model quantifies resource requirements and allocates those resources to individual products (see Figure 1). It should be noted that cost and resource models are deterministic and cannot explicitly estimate the dynamic aspects of production such as product queuing or work-in-process (WIP)[3].

In the midst of all of these complexities are several challenges. First, cost and resource models need to speak multiple languages and conform to differing standards. Accounting standards and nomenclature are much different than the standards and language used at the process step level (equipment and process engineering). So, one could consider a cost and resource model as a translation vehicle that transforms technical considerations into business results, allowing engineering and finance to communicate more clearly. Cost and resource modeling allows a new dynamic in decision-making; a virtual business model as an enabling technology.

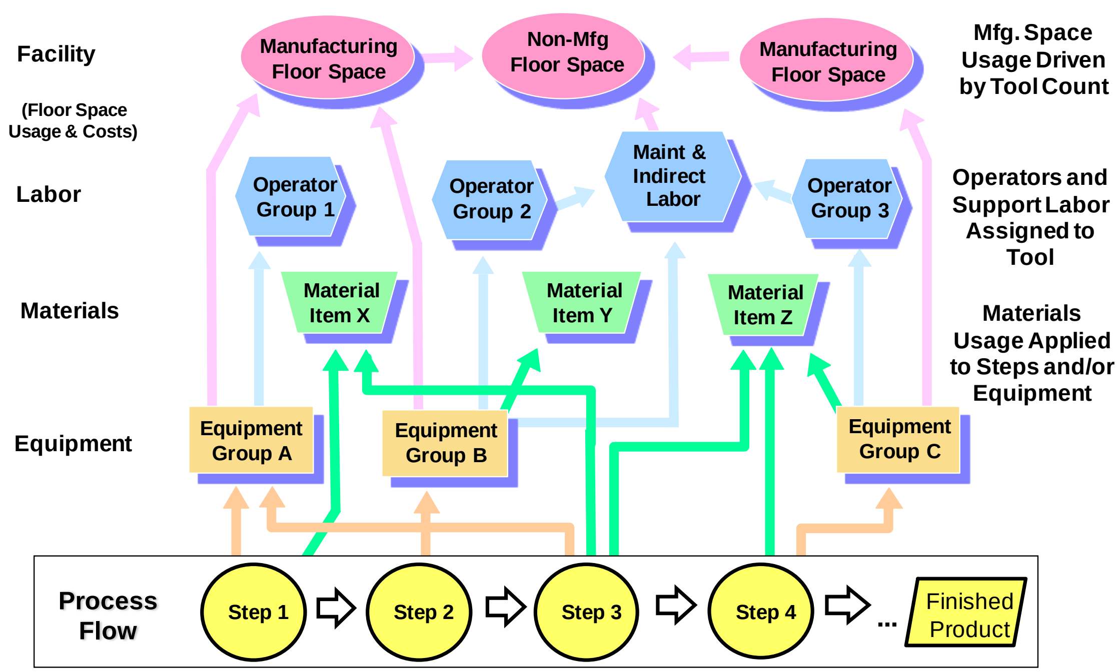


Figure 1: Activity Based Resource Relationships

Sputtering Model Results

The following reports provide a summary and detailed cost analyses for the sputter/selenization furnace case (refer to Table 2 in the Winter 2014 Edition of Applied Cost Modeling for input data summary). Report 1 shows the high level cost breakdowns for capital costs, operation & maintenance, labor, materials & supplies, and overhead. The cost per panel is $101.67 and a cost per watt-peak of $0.68. It should be noted that costs presented in this paper were generated at a specific point in time and are subject to change on a continuous basis. As such, these costs should be considered on a relative basis.

Report 2 looks at the cost breakdowns for each step in the manufacturing flow and highlights the highest cost items. The highest cost step is the selenization furnace at $24.28 per panel with almost equal contributions from equipment costs (28 at $1M/equipment) and direct materials consumption. Direct materials will be examined in more detail in report 3 later in this paper. The next highest cost step is framing which is the same for both models and will be ignored for the rest of the analyses. The third highest step is TCO deposition at $12.68, again with almost equal contributions from equipment costs (28 at $500K/equipment) and direct materials consumption. This is also the same for both models and will be ignored for the rest of the analyses. The last item of interest is the CIG sputtering step with a cost of $7.65 and a direct materials contribution of $4.32.

Report 3 breaks down the material item costs, annual usage, annual costs, and cost per panel. With regards to materials cost, the largest component for the CIGS formation steps is hydrogen selenide representing $6.93 per panel or greater than 6% of the total panel manufacturing costs. Combined, the CIGS materials are $11.53/panel or a little more than 11% of the total panel cost.

Coevaporation Model Results

The second model is based on CIGS formation using a coevaporation equipment set. The following reports provide a summary and detailed cost analyses for the coevaporation case. Report 4 shows the high level cost breakdowns for capital costs, operation & maintenance, labor, materials & supplies, and overhead. The cost per panel is $105.17 and a cost per watt-peak of $0.70.

Report 5 looks at the cost breakdowns for each step in the manufacturing flow and highlights the highest cost items. The highest cost step is coevaporation at $33.80 per panel with almost equal contributions from equipment costs (5 at $9M/equipment) and direct materials consumption. Direct materials will be examined in more detail in report 6 later in this paper. It should be noted that the coevaporation step replaced 2 steps in the sputtering model. Those two steps exceeded $31. The significant difference is over $2.00 in additional equipment costs for the coevaporation process.

Report 6 breaks down the material item costs, annual usage, annual costs, and cost per panel. With regard to materials cost, the largest components for the coevaporation step are the Indium source at $4.29 per panel and the Selenium source at $4.10. Together they represent almost 8% of the total panel manufacturing costs. Combined, the CIGS materials are $9.41/panel or approximately 9% of the total panel cost. Much of this cost is associated with the efficiency of the coevaporation process where only 40% of the material consumed ends up on the panel for Cu, In, and Ga and only 20% for Se.

ISSN 1094-9739

Cost Categories	Total Annual Cost $ x 1000	Unit Cost $/ Panel Out	% of Product Total	Normalized Unit Cost $/Watt	Scrap Cost $ x 1000
Depreciation	12,664	18.996	18.7%	0.127	515
Equipment	11,245	16.868	16.6%	0.112	462
Building	1,419	2.129	2.1%	0.014	54
Operation & Maintenance	4,349	6.524	6.4%	0.043	176
Equipment	3,578	5.367	5.3%	0.036	147
Facility	771	1.157	1.1%	0.008	29
Labor	8,134	12.200	12.0%	0.081	232
Direct Labor	5,059	7.588	7.5%	0.051	146
Indirect Labor	3,075	4.613	4.5%	0.031	86
Materials & Supplies	33,882	50.823	50.0%	0.339	762
Bottom Glass	2,418	3.627	3.6%	0.024	227
Direct Process	30,518	45.776	45.0%	0.305	534
Indirect Material	947	1.420	1.4%	0.009	0
Total Production	**59,029**	**88.543**	**87.1%**	**0.590**	**1,685**
Product Overhead	8,749	13.123	12.9%	0.087	225
Equipment Sales Tax	8,749	13.123	12.9%	0.087	
Product Total	**67,778**	**101.667**	**100.0%**	**0.678**	**1,910**

Report 1: Product Cost Summary

		Total Unit Cost ($/Panel)		Category Unit Cost ($/Panel)								
Process Step	Tool Group ID	All Categories	Cumulative Production	Equipment Depreciation	Building Depreciation	Operation & Maint.	Direct Labor	Indirect Labor	Direct Materials	Ind. Materials & Supplies	Product Overhead	Scrap Cost
	Starting Material Cost :	3.627	3.627						3.627			
1 - Receive / inspect / scribe ID	Scriber	0.105	3.732	0.015	0.008	0.009	0.000	0.059	0.000	0.000	0.014	0.034
2 - W1 - Pre Clean	GlassWash	0.423	4.154	0.045	0.008	0.018	0.237	0.058	0.000	0.000	0.057	0.037
3 - Wash1	MoCleaner	0.148	4.303	0.045	0.008	0.018	0.000	0.058	0.000	0.000	0.020	0.000
3.1 - SiO2 -> Mo deposition	MoSputter	3.921	8.224	1.465	0.075	0.507	0.237	0.058	1.055	0.000	0.525	0.074
4 - Pattern Mo (LP1)	LaserScriberP1	1.039	9.262	0.421	0.033	0.152	0.237	0.057	0.000	0.000	0.139	0.083
5 - Wash2	CIGCleaner	0.147	9.410	0.045	0.008	0.018	0.000	0.057	0.000	0.000	0.020	0.000
5.1 - Cu-Ga + In deposition	CIGSputter	7.645	17.055	1.437	0.075	0.498	0.237	0.057	4.317	0.000	1.023	0.153
6 - Selenize/Sulfurize	SASFurnace	24.277	41.332	6.970	1.050	2.788	1.660	1.346	7.213	0.000	3.250	0.372
7 - CdS deposition	Cji	2.115	43.447	0.689	0.104	0.276	0.474	0.111	0.178	0.000	0.283	0.391
8 - P2 mechanical scribe	LaserScriberP2	0.778	44.225	0.251	0.033	0.098	0.237	0.055	0.000	0.000	0.104	0.398
9 - B-ZnO deposition	MOCVD-TCO	12.682	56.907	3.366	0.364	1.269	1.660	1.092	3.235	0.000	1.698	0.512
10 - P3 mechanical scribe	LaserScriberP3	0.758	57.664	0.239	0.033	0.094	0.237	0.054	0.000	0.000	0.101	0.519
11 - Perimeter edge deletion	Laser4J	1.000	58.665	0.318	0.066	0.137	0.237	0.107	0.000	0.000	0.134	0.059
11.1 - Hole Drill	HoleDrill	0.608	59.273	0.318	0.000	0.101	0.000	0.107	0.000	0.000	0.081	0.000
12 - Bus pad prep and clean	Cutter	0.429	59.701	0.136	0.055	0.073	0.000	0.107	0.000	0.000	0.057	0.000
13 - Ribbon Attach	RibbonAttach	0.997	60.698	0.136	0.000	0.043	0.000	0.107	0.578	0.000	0.133	0.000
14 - Circuit IV test	CircuitTester	0.267	60.966	0.094	0.000	0.030	0.000	0.107	0.000	0.000	0.036	0.061
14.1 - Front glass clean	GlassWash2	0.288	61.253	0.090	0.016	0.037	0.000	0.107	0.000	0.000	0.039	0.000
15 - Assemble pre-laminate	PLATool	10.458	71.711	0.090	0.000	0.029	0.000	0.107	8.833	0.000	1.400	0.000
16 - Lamination	Laminator	1.448	73.159	0.294	0.032	0.111	0.711	0.107	0.000	0.000	0.194	0.073
17 - Junction Box attachment	JBATool	5.318	78.478	0.024	0.016	0.016	0.237	0.107	4.207	0.000	0.712	0.000
18 - Framing	FrameTool	18.647	97.125	0.024	0.104	0.064	0.237	0.107	15.616	0.000	2.496	0.000
19 - Hi-pot test	HiPot	0.497	97.622	0.047	0.016	0.023	0.237	0.107	0.000	0.000	0.066	0.000
20 - Sun Soak	SSTool	0.499	98.120	0.047	0.017	0.024	0.237	0.107	0.000	0.000	0.067	0.000
21 - Module IV test	ModuleTester	0.675	98.796	0.170	0.011	0.060	0.237	0.107	0.000	0.000	0.090	0.099
22 - Sorting & Label	SLTool	0.541	99.336	0.094	0.000	0.030	0.237	0.107	0.000	0.000	0.072	0.000
23 - Packaging	Packaging	2.331	101.667	0.000	0.000	0.000	0.000	0.053	0.545	1.420	0.312	0.000
	Total Unit Cost :	101.667		16.868	2.129	6.524	7.588	4.613	49.403	1.420	13.123	

Report 2: Unit Cost per Step

Process Step / Material Item	Item Cost * ($)	Annual Quantity Used	Annual Material Cost ($ x 1000)	Material Cost per Panel ($/Panel)
Starting Material, Bottom Glass	3.3 / Panel	732,673 Panels	2,417.8	3.627
5.1 - Cu-Ga + In deposition				
3 - Cu-Ga Target 1	27,000 / unit	10.6 units	286.2	0.429
4 - Cu-Ga Target 2	18,600 / unit	71 units	1,314.4	1.972
5 - Indium Target	28,700 / unit	44.5 units	1,277.7	1.917
6 - Selenize/Sulfurize				
6 - Hydrogen Sulfide	0.09 / liter	2,065,858 liters	185.9	0.279
7 - Hydrogen Selenide	1.63 / liter	2,836,178 liters	4,623.0	6.934
* Item cost includes inflation (if non-zero rate) and cost adjustment factors			10,105.0	15.157

Report 3: Material Item Costs

Cost Categories	Total Annual Cost $ x 1000	Unit Cost $/ Panel Out	% of Product Total	Normalized Unit Cost $/Watt	Scrap Cost $ x 1000
Depreciation	14,131	21.006	20.0%	0.140	576
Equipment	12,712	18.896	18.0%	0.126	513
Building	1,419	2.109	2.0%	0.014	63
Operation & Maintenance	5,976	8.883	8.4%	0.059	248
Equipment	4,045	6.012	5.7%	0.040	163
Facility	1,931	2.871	2.7%	0.019	85
Labor	8,134	12.091	11.5%	0.081	191
Direct Labor	5,059	7.520	7.1%	0.050	129
Indirect Labor	3,075	4.571	4.3%	0.030	62
Materials & Supplies	32,736	48.663	46.3%	0.324	642
Bottom Glass	2,418	3.594	3.4%	0.024	206
Direct Process	29,363	43.648	41.5%	0.291	436
Indirect Material	955	1.420	1.4%	0.009	0
Total Production	**60,977**	**90.642**	**86.2%**	**0.604**	**1,657**
Product Overhead	9,776	14.531	13.8%	0.097	242
Equipment Sales Tax	9,776	14.531	13.8%	0.097	
Product Total	**70,752**	**105.173**	**100.0%**	**0.701**	**1,899**

Report 4: Product Cost Summary

<u>Sensitivity Analyses</u>

Both models were based on a module efficiency of 15%, which is approximately half way between the Manz-reported 14% and the TSMC-reported 15.7% record. Since module efficiency has a major impact on the cost per watt-peak, Figure 2 looks at efficiency from the starting point of 15% to near the small scale record of approximately 20% for the sputtering model.

In this example, each 1% improvement in panel efficiency drops the cost per watt-peak by approximately $0.04.

Next we examine the impact of throughput improvements on the selenization furnace. Since 28 pieces of equipment are needed to meet the 100MW factory output, any improvement in throughput should yield a reasonable cost reduction. We could have

ISSN 1094-9739

Process Step	Tool Group ID	Total Unit Cost ($/Panel) All Categories	Cumulative Production	Category Unit Cost ($/Panel) Equipment Depreciation	Building Depreciation	Operation & Maint.	Direct Labor	Indirect Labor	Direct Materials	Ind. Materials & Supplies	Product Overhead	Scrap Cost
Starting Material Cost :		3.594	3.594						3.594			
1 - Receive / inspect / scribe ID	Scriber	0.121	3.715	0.015	0.003	0.009	0.000	0.076	0.000	0.000	0.017	0.033
2 - W1 - Pre Clean	GlassWash	0.468	4.183	0.044	0.003	0.018	0.259	0.076	0.000	0.000	0.067	0.038
3 - Wash1	MoCleaner	0.164	4.347	0.044	0.003	0.018	0.000	0.075	0.000	0.000	0.024	0.000
3.1 - SiO2 -> Mo deposition	MoSputter	3.925	8.272	1.451	0.030	0.502	0.259	0.075	1.046	0.000	0.561	0.074
4 - Pattern Mo (LP1)	LaserScriberP1	1.067	9.339	0.417	0.013	0.150	0.259	0.074	0.000	0.000	0.153	0.084
5 - Wash2	CIGCleaner	0.163	9.501	0.044	0.003	0.018	0.000	0.074	0.000	0.000	0.023	0.000
5.1 - Cu-Ga + In + Se deposition	CIGSEvaporati	33.797	43.298	10.512	1.712	5.675	1.296	0.354	9.412	0.000	4.835	0.390
7 - CdS deposition	Cji	2.147	45.445	0.683	0.041	0.273	0.519	0.146	0.178	0.000	0.307	0.409
8 - P2 mechanical scribe	LaserScriberP2	0.805	46.251	0.249	0.013	0.097	0.259	0.072	0.000	0.000	0.115	0.416
9 - B-ZnO deposition	MOCVD-TCO	13.096	59.347	3.336	0.144	1.257	1.815	1.436	3.235	0.000	1.873	0.534
10 - P3 mechanical scribe	LaserScriberP3	0.785	60.132	0.236	0.013	0.093	0.259	0.071	0.000	0.000	0.112	0.541
11 - Perimeter edge deletion	Laser4J	1.025	61.156	0.315	0.026	0.136	0.259	0.141	0.000	0.000	0.147	0.061
11.1 - Hole Drill	HoleDrill	0.649	61.806	0.315	0.000	0.100	0.000	0.141	0.000	0.000	0.093	0.000
12 - Bus pad prep and clean	Cutter	0.432	62.237	0.135	0.022	0.073	0.000	0.141	0.000	0.000	0.062	0.000
13 - Ribbon Attach	RibbonAttach	1.045	63.283	0.135	0.000	0.043	0.000	0.141	0.578	0.000	0.150	0.000
14 - Circuit IV test	CircuitTester	0.308	63.591	0.093	0.000	0.030	0.000	0.141	0.000	0.000	0.044	0.064
14.1 - Front glass clean	GlassWash2	0.318	63.909	0.089	0.006	0.037	0.000	0.141	0.000	0.000	0.045	0.000
15 - Assemble pre-laminate	PLATool	10.608	74.517	0.089	0.000	0.028	0.000	0.141	8.833	0.000	1.518	0.000
16 - Lamination	Laminator	1.554	76.071	0.291	0.013	0.110	0.778	0.141	0.000	0.000	0.222	0.076
17 - Junction Box attachment	JBATool	5.429	81.500	0.023	0.006	0.016	0.259	0.141	4.207	0.000	0.777	0.000
18 - Framing	FrameTool	18.838	100.338	0.023	0.041	0.063	0.259	0.141	15.616	0.000	2.695	0.000
19 - Hi-pot test	HiPot	0.556	100.894	0.047	0.006	0.023	0.259	0.141	0.000	0.000	0.079	0.000
20 - Sun Soak	SSTool	0.557	101.451	0.047	0.007	0.024	0.259	0.141	0.000	0.000	0.080	0.000
21 - Module IV test	ModuleTester	0.737	102.188	0.168	0.004	0.059	0.259	0.141	0.000	0.000	0.105	0.102
22 - Sorting & Label	SLTool	0.610	102.798	0.093	0.000	0.030	0.259	0.140	0.000	0.000	0.087	0.000
23 - Packaging	Packaging	2.375	105.173	0.000	0.000	0.000	0.000	0.070	0.545	1.420	0.340	0.000
Total Unit Cost :		105.173		18.896	2.109	8.883	7.520	4.571	47.243	1.420	14.531	

Report 5: Unit Cost per Step

Process Step / Material Item	Item Cost * ($)	Annual Quantity Used	Annual Material Cost ($ x 1000)	Material Cost per Panel ($/Panel)
Starting Material, Bottom Glass	3.3 / Panel	732,673 Panels	2,417.8	3.594
5.1 – Cu-Ga + In + Se deposition				
37 - Evap Cu	29 / kg	3,886,579 g	112.7	0.168
38 - Evap In	510.9 / kg	5,653,206 g	2,888.2	4.293
39 - Evap Ga	387.4 / kg	1,483,967 g	574.9	0.855
40 - Evap Se	125 / kg	22,047,503 g	2,755.9	4.097
* Item cost includes inflation (if non-zero rate) and cost adjustment factors			8,749.6	13.006

Report 6: Material Item Costs

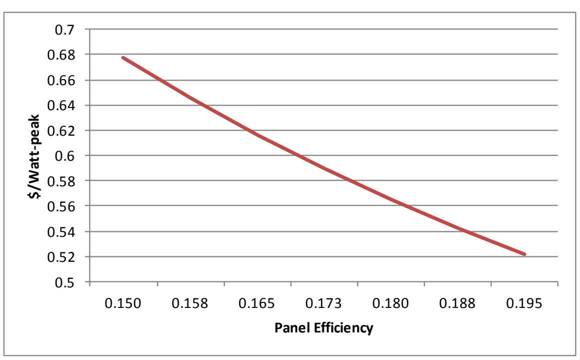


Figure 2: Panel Efficiency Sensitivity Analysis

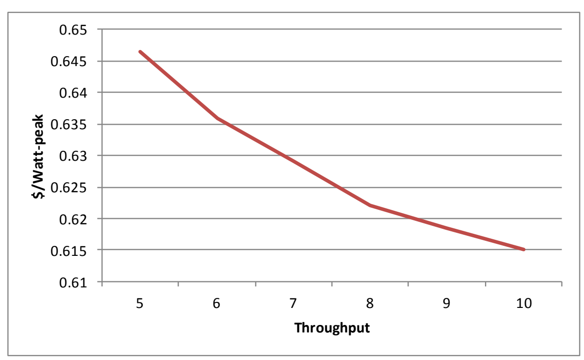


Figure 3: Selenization Throughput Sensitivity Analysis

also looked at reducing the equipment purchase price with the same relative results but that is less likely of an outcome. Figure 3 shows that doubling throughput from five to ten panels per hour decreases cost per watt-peak by nearly 5%. While that degree of increase may not be practical, the move from five to six panels per hour does provide an overall cost reduction of approximately 1.6%. It should be noted that the baseline model called for 28 furnaces to provide excess capacity in case of equipment down time. This sensitivity analysis removed that constraint and allowed the model to calculate the actual needed number of equipment. This issue will be discussed in the next section.

Lastly, we look at one of the perceived major areas for improvement in the coevaporation process, the efficiency with which the CIGS materials are deposited on the panel. The baseline model used 40% material use efficiency for Copper-Indium-Gallium and 20% for Selenium. As can be seen in Table 1 there is a modest cost benefit in increasing the deposition efficiency, between $0.005-0.01 for each 5% improvement in deposition efficiency. The amount of material used, even at lower efficiencies, is just a few grams per 1m^2 panel.

	40%, 20%	45%, 25%	50%, 30%	55%, 35%	60%, 40%	90%, 90%
Cu - g/panel	5.50	4.89	4.40	4.00	3.67	2.44
In - g/panel	8.00	7.11	6.40	5.82	5.33	3.56
Ga - g/panel	2.10	1.87	1.68	1.53	1.40	0.93
Se - g/panel	31.20	24.96	20.80	17.83	15.60	6.93
$/Watt-peak	$ 0.701	$ 0.692	$ 0.685	$ 0.680	$ 0.676	$ 0.660

Table 1: CIGS Co-Evaporation Efficiency Sensitivity Analysis

Other Process Options

While we chose to use standard processes that have been in existence for some time, there are other choices that have the potential to reduce costs. One such example is to move from a framed to a frameless panel. The framing costs represent over $0.10/watt-peak, eliminating these costs would bring the total cost down to $0.573/watt-peak. Additionally, if the equipment set is optimized to allow for higher factory loading (higher reliability, better predictability of availability), the cost per watt-peak can further be reduced to $0.51.

Manz has reported further enhancements to the process including the use of lasers for all patterning steps, edge delete and hole drill, which removes the CIGS pre-clean step as well as building the barrier into the Mo deposition eliminating the SiO2 deposition. Other improvements include a change in TCO materials, a reduction in CIGS materials usage through a linear source, the replacement of solder with silver glue, and the replacement of ethylene vinyl acetate (EVA) and butyl edge tape with thermoplastic material. As a result, Manz forecasts OPEX of below $0.50/watt-peak even for a 14% efficiency module.

Conclusions

The photovoltaics industry has gone through immense changes in recent years, yet it is still developing rapidly in many ways. While previous papers in this series have focused on c-Si manufacturing and assembly issues, with this paper we looked at an alternative PV technology which holds the promise of superior energy generation in high ambient heat and high direct normal irradiance (DNI) locations as well as offering competitive costs.

The models presented here are based on manufacturing costs on a watt-peak basis and indicate that fully burdened CIGS manufacturing costs are still above the sales price for many c-Si modules. The case study in this paper has shown that there is not likely to be one major cost breakthrough for either of the CIGS manufacturing processes presented here but, rather, a series of lesser improvements are needed to bring the costs down to the level $0.30/watt-peak indicated as the potential for an optimized panel format.

It should be noted that cost per watt-peak was used as a convenient manufacturing metric since the conditions of final installation are highly variable (and outside the scope of this paper). However, the author highly suggests that all cost comparisons for the final installed equipment (utility scale, commercial/residential rooftop, etc.) be compared with metrics more suited to issues of system ownership (LCOE, TCOe™). These metrics take into consideration actual energy production (site specific), annual efficiency degradation, balance of system (BOS) costs, installation, maintenance, etc.

References

1. Factory Commander® is a commercial software package from Wright Williams & Kelly, Inc.
2. For a detailed discussion of the history, standards, and algorithms of COO and overall equipment efficiency (OEE) please see D. Jimenez, "Cost of Ownership and Overall Equipment Efficiency: A Photovoltaics Perspective," Photovoltaics International, Ed. 6.
3. Estimations of dynamic measures such as WIP and cycle time require the use of discrete-event simulation as employed by Factory Explorer®, a commercial software package from Wright Williams & Kelly, Inc.

Note: The models used in this paper are available as part of licensing Factory Commander® software from WWK.

Recent Revisions to the SEMI E10 and SEMI E79 Standards

The SEMI Equipment Reliability, Availability, Maintainability, and Productivity (RAMP) Task Force recently completed revisions to the E10 and E79 SEMI Standards.

SEMI E10 (Specification for Definition and Measurement of Equipment Reliability, Availability, and Maintainability and Utilization) was primary revised to add example calculations. This example covers a scenario for a five-module multi-path cluster tool (MPCT) with three processing equipment modules, a handler equipment module, and a mainframe equipment module organized into two intended process sets (IPSs).

New to SEMI E79 (Specification for Definition and Measurement of Equipment Productivity) is the introduction of four new metrics called Loss Metrics:

- availability loss
- operation loss
- rate loss
- assignable quality loss

The values of these four metrics plus the Overall Equipment Efficiency add to 100% of total time by definition. They support the comparison of loss categories to each other using total time as a common denominator. They are calculated using the same fundamental quantities used in the existing efficiency metrics and present no new tracking requirements.

The revised E10 and E79 SEMI Standards will be published in July 2014. The next RAMP Task Force meeting is scheduled for July 9 in conjunction with the North America Standards meetings during SEMICON West 2014. If you are interested in participating in the Task Force or other Metrics standards related activities, please contact Michael Tran at SEMI (1.408.943.7019, mtran@semi.org).

SEMI® International Standards

Wright Williams & Kelly Releases
Factory Commander® v3.4

Wright Williams & Kelly, Inc. (WWK) has announced the latest release of its factory-level cost and resource evaluation software, Factory Commander® v3.4. Managers in the semiconductor, flat panel display, solar panel, disk drive, silicon, and other manufacturing and assembly industries use Factory Commander® to quickly and accurately evaluate their strategic and tactical options.

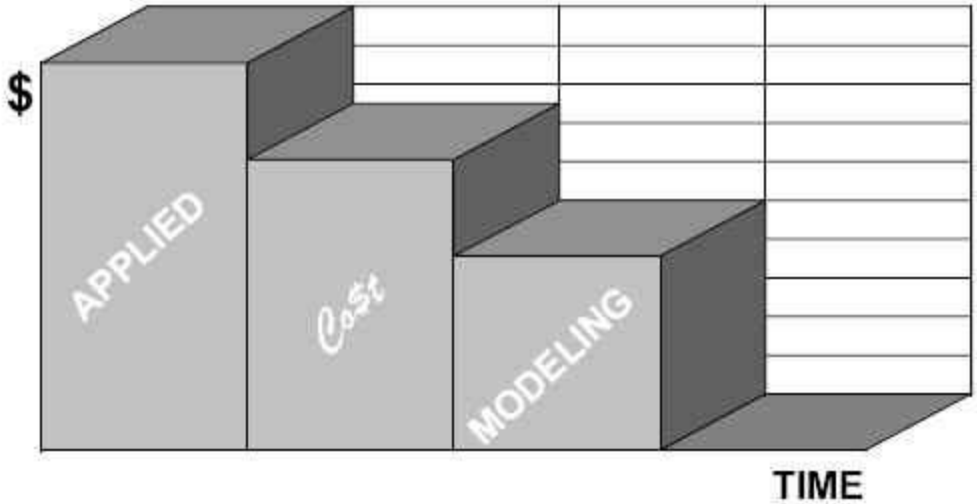
The new features in this release provide an even greater ability to model a wide variety of real-world situations. Some of the key features include:

- Ability to Assign Alternative Equipment to the Process Step – You are now able to make multiple assignment of different types of equipment for a given process step. One aspect of this feature is that it allows capacity differences to be accommodated, thereby achieving more accurate calculations for equipment counts, utilization levels, and costs. Modeling alternative equipment groups can represent several real situations in a manufacturing environment, including an operation where manufactured product may need to be optionally routed at different times between two or more types of equipment within the same period of time. Since often times optional equipment have differences in their cost, manufacturing capacity, floor space usage, etc., it makes the need to model these situations desirable. Also, this feature allows for more accurate accounting of capacity and resource usage for those specific types of equipment. The program now allows for as many as 6 alternative equipment assignments for any given step.

- Ability to Assign Labor to Products – You are now able to model headcounts for a labor group by product-level assignments. This enables direct assignments of staffing to individual products thereby enabling labor distributions that more closely match corporate labor assignment plans. Product-assignments act as a headcount adder, in that values entered are added to the totals derived by other ways of modeling labor in the program.

- Product Classifications – You are now able to classify products in groupings for high-level reporting purposes. This feature enables costs to be roll up for multiple individual products. Classification defined can be assigned to one or more products. New product classification costing reports have been added as standard reports.

- Ability to Compare Data between Models – You can now compare any two Factory Commander® models to determine differences in their inputs and calculated values. This feature allows evaluation of models, typically similar in nature, to help users determine what the actual differences are between the two. Normally, these differences pertain to the inputs of a model, but calculated parameters and output can also be evaluated.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