CIGS manufacturing: Promises and reality

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ABSTRACT
Economic issues are the driving forces behind 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™). This sixth paper in a series covering business analysis for PV processes looks at two approaches to manufacturing thin-film copper-indium-gallium-diselenide (CIGS) PV – sputtering and co-evaporation – and their potential areas for cost improvement.

The promise of CIGS [1]

In contrast to the non-crystallinity of amorphous silicon (a-Si), thin-film copper-indium-gallium-diselenide (CIGS) is a polycrystalline material consisting of small crystallites. CIGS has several characteristics that make it a valuable PV material. One is its absorption coefficient, which is among the highest for semiconductor materials: 99% of the light incident on CIGS is absorbed in the first micrometre of the device. Thus cells with a thickness of that order of magnitude are possible. Another favourable characteristic is that CIGS has one of the highest current densities of any semiconductor material, with the potential to produce high current outputs. Third, these films retain their performance properties better than most semiconductors. And last, CIGS is amenable to large-area automated production.

Efficiencies in excess of 20% have been reported for small-area experimental cells made of thin-film CIGS. A principal problem with the material is its low open-circuit voltage. However, this deficiency seems to be correctable through improving compositional uniformity by, for example, removing oxygen.

The CIG portion is usually formed on a base electrode of molybdenum (Mo), chosen for its refractory nature and good electrical conductivity. Thin-film CIGS is a p-type semiconductor and a junction is formed at the surface by deposition of a very thin layer of cadmium sulphide (CdS). This creates an n-p homojunction just inside the CIGS material, rather than a simple heterojunction. The device is completed by deposition of a transparent conducting oxide (TCO), such as zinc oxide (ZnO), on top of the junction to help collect the light-generated current. Fig. 1 shows a typical CIGS solar module cross section.

Figure 1. CIGS module cross section.

In a manner similar to the definition and monolithic integration of thin-film a-Si cells, individual CIGS cells are defined and serially interconnected via three patterning steps. The first scribe (in Mo) is performed by a laser beam, while the second and third scribes (to remove CIGS and separate the ZnO) can be performed mechanically or by laser. Again, metal foils are bonded to the first and last cells, and the module is encapsulated using a top cover glass, laminated with encapsulant.

The principle of operation of the device is similar to that of conventional crystalline silicon (c-Si) solar cells. Light is absorbed in the CIGS layer, creating free electrons and holes. The electrons diffuse in the CIGS grains until they find themselves in the electric field within the junction region, at which point they are driven into the CdS/ZnO, thereby building up a voltage between the ZnO electrode and the Mo base electrode.

Why is CIGS appealing? [2]

If you realize the initial success of First Solar, you realize that a thin-film cell having a higher efficiency than cadmium telluride (CdTe) with the potential to eliminate the toxic element cadmium would be of great interest. This major drawback has resulted in purchase restrictions on CdTe panels. In the CIGS manufacturing process, CdS is deposited in a very thin layer (30–50nm) compared with CdTe (2μm). A CIGS module therefore contains much less Cd (1/40th the amount) than a same size CdTe module. Currently, the use of CIGS instead of CdTe makes the issue of toxicity a smaller one, and it is expected that in 3–4 years CIGS manufacturers will have established a Cd-free buffer.

The benefits of CIGS modules [3] are:

- The form factor of CIGS solar cells is optimal for rigid and flexible substrates. CIGS cells can be manufactured on low-cost glass

CIGS companies	Absorber formation step method	Substrate
Q-Cells,Solibro	Co-evaporation	Monolithic on glass
Mantz-Wurth Solar	Co-evaporation	Monolithic on glass
Heliovolt	Co-evaporation	Monolithic on glass
Centrotherm	Co-evaporation	Monolithic on glass
Johanna Solar	Co-evaporation	Monolithic on glass
Miasole	Reactive sputtering	Cell based roll to roll
SoloPower	Electroplating	Cell based roll to roll
NanoSolar	Printing	Cell based roll to roll
Stion	Two-step sputtering	Monolithic on glass
AVANCIS	Two-step sputtering	Monolithic on glass
Solar Frontier	Two-step sputtering	Monolithic on glass
Bosch Solar CISTech	Two-step sputtering	Monolithic on glass
TSMC	Two-step sputtering	Monolithic on glass

Table 1. CIGS companies and absorber formation method.

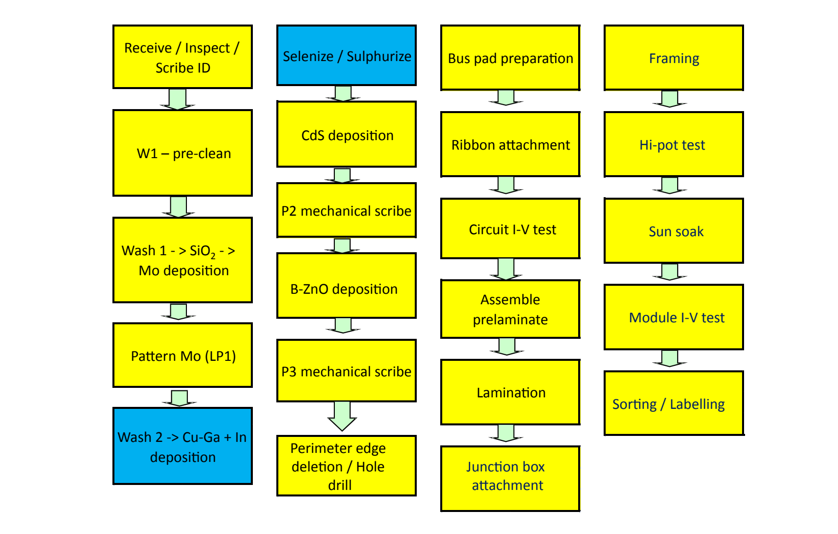

Figure 2. Sputtered CIGS process flow.

substrates, which gives access to the largest PV markets, enables use of existing mounting systems, is compatible with existing PV system infrastructure, and has the ability to dominate the building-integrated photovoltaics (BIPV) market in the future.

- CIGS yields the highest efficiency among all thin-film solar technologies. The cells can absorb over 99% of the solar spectrum and they have the highest current density. CIGS laboratory samples rank the highest in conversion efficiency among all other thin-film solar technologies.

- CIGS modules can be produced at competitive costs, even in the 100MW/year volume range with high local content, avoiding dependence on Si wafer or Si cell manufacturers.

- CIGS modules have demonstrated reliable and stable field performance for nearly 20 years.

> “CIGS yields the highest efficiency among all thin-film solar technologies.”

Today and tomorrow

Listed below is the current state of CIGS manufacturing and some short-term projections.

- 14% module efficiency in production (Manz)

- 15.7% record module efficiency (TSMC)

- Annual efficiency improvement rate in the last five years has averaged 0.4% per year – outpacing p-type c-Si in the last three years

- Energy harvest data from Manz test installations:
  - Middle East: 7% better than p-type c-Si
  - Southern Europe: 5% better than p-type c-Si
  - Southern China: 10% better than p-type c-Si

- Operating expense (OPEX) has reached CdTe levels; further efficiency improvements will result in lower OPEX ($0.50/watt-peak in 2014, $0.45/watt-peak in 2015)
- Future OPEX potential with scaled module format (1 × 1.6m^2): < $0.30/watt-peak
- Best footprint (150MW) factory building: < 1m^2/MW output
- Best headcount (all in production): < 1.5/MW output
- Lowest market entrance barrier: competitive OPEX reached at factory output of 150MW

CIGS production processes

There are two major approaches to CIGS manufacturing: 1) multi-target sputtering followed by a selenization furnace, and 2) co-evaporation. A number of companies have used, or are using, these processes, and the data used in this paper (while based on publicly available sources) are representative of the corresponding companies in Table 1.

Multi-target sputtering/selenization furnace

The process flow used in this paper is based on Fig. 2, with only the CIGS formation steps (see blue cells) being changed. The key parameters for each step (some cells in Fig. 2 represent more than one step) are shown in Table 2.

As can be seen from Table 2, the line balance for a 100MW factory is very good, with almost all tools having a 120 or 60 panel per hour throughput. It takes approximately 120 panels per hour in a 24×7 operation to approximate a 100MW factory size, given 150W per panel and utilization between 70 and 80%. Two exceptions are the selenization furnace and the TCO deposition tools.

"The co-evaporation process replaces the CIG sputtering step and the selenization furnace step with a single process step."

Co-evaporation

The second approach is based on CIGS formation using a co-evaporation tool. Referring to the previously described Fig. 2, the co-evaporation process replaces the CIG sputtering step and the selenization furnace step with a single process step utilizing all four elements required to form the CIGS film.

As can be seen by comparing Table 3 with Table 2, the co-evaporation process has eliminated one step and reduced the equipment set by 24 tools. However, the co-evaporation equipment is more expensive than the equipment it is replacing.

Step description	Tool group	Process throughput [panels/hr]	Step yield	Availability	Number of tools	Purchase capital [k$/tool]	Main materials
Receive / Inspect / Scribe ID	Scriber	120	99.10%	90.0%	1	65.0	
W1 - pre-clean	GlassWash	120	99.10%	90.0%	1	190.0	
Wash 1	MoCleaner	120	100.00%	90.0%	1	190.0	
SiO_2 -> Mo deposition	MoSputter	120	99.10%	90.0%	1	6,213.0	Moly target, silicon target
Pattern Mo (LP1)	LaserScriberP1	120	99.10%	90.0%	1	1,786.0	
Wash 2	CIGCleaner	120	100.00%	90.0%	1	190.0	
Cu-Ga + In deposition	CIGSputter	120	99.10%	90.0%	1	6,098.0	Cu-Ga target 1, Cu-Ga target 2, In target
Selenize / Sulphurize	SASFurnace	5	99.10%	90.0%	28	1,056.0	Hydrogen sulfide, hydrogen selenide
CdS deposition	Cji	60	99.10%	90.0%	2	1,462.0	Thiourea, cadmium sulphate, ammonium solution
P2 mechanical scribe	LaserScriberP2	120	99.10%	90.0%	1	1,065.0	
B-ZnO deposition	MOCVD-TCO	6	99.10%	90.0%	28	510.0	
P3 mechanical scribe	LaserScriberP3	120	99.10%	90.0%	1	1,012.0	MOCVD TCO 1, MOCVD TCO 2
Perimeter edge deletion	Laser4J	60	99.90%	90.0%	2	675.0	
Hole drill	HoleDrill	60	100.00%	90.0%	2	675.0	
Bus pad prep and clean	Cutter	60	100.00%	90.0%	2	288.0	
Ribbon attachment	RibbonAttach	60	100.00%	90.0%	2	288.0	Copper ribbon, tin solder, indium solder
Circuit I-V test	CircuitTester	60	99.90%	90.0%	2	200.0	
Front glass clean	GlassWash2	60	100.00%	90.0%	2	190.0	
Assemble pre-laminate	PLATool	60	100.00%	90.0%	2	190.0	Ethyl vinyl acetate, top glass
Lamination	Laminator	60	99.90%	90.0%	2	623.0	
Junction box attachment	JBATool	60	100.00%	90.0%	2	50.0	Pottant, junction box,
Framing	FrameTool	60	100.00%	90.0%	2	50.0	Frame
Hi-pot test	HiPot	60	100.00%	90.0%	2	100.0	
Sun soak	SSTool	60	100.00%	90.0%	2	100.0	
Module I-V test	ModuleTester	60	99.90%	90.0%	2	360.0	
Sorting / Labelling	SLTool	60	100.00%	90.0%	2	200.0	

Table 2. Sputtering/selenization input parameters.

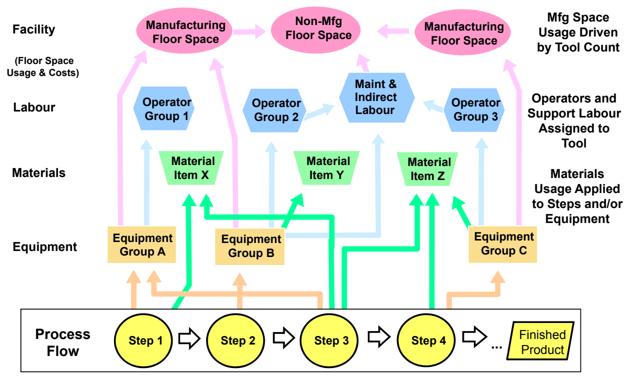

Figure 3. Activity-based resource relationships.

Case study

The case study will use cost and resource modelling to evaluate both sputtered and co-evaporated 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 [4].

Cost and resource modelling history

Cost and resource modelling is a comprehensive approach to understanding a wide variety of factory-level issues. The techniques were pioneered in the 1990s by SEMATECH for integrated circuits (ICs) and by Sandia National Laboratories under the National Center for Advanced Information Components Manufacturing (NCAICM) programme for flat panel displays (FPDs). The concept was developed to initially assist these two capital-intensive industries in improving their ability to compete globally and maintain a US 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 programme to take up a separate line of development. Core requirements such as detailed material tracking/costing, modelling 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

Step description	Tool group	Process throughput [panels/hr]	Step yield	Availability	Number of tools	Purchase capital [k$/tool]	Main materials
Receive / Inspect / Scribe ID	Scriber	120	99.10%	90.0%	1	65.0	
W1 - pre-clean	GlassWash	120	99.10%	90.0%	1	190.0	
Wash 1	MoCleaner	120	100.00%	90.0%	1	190.0	
SiO_2 -> Mo deposition	MoSputter	120	99.10%	90.0%	1	6,213.0	Moly target, silicon target
Pattern Mo (LP1)	LaserScriberP1	120	99.10%	90.0%	1	1,786.0	
Wash 2	CIGCleaner	120	100.00%	90.0%	1	190.0	
Cu-Ga + In + Se deposition	CIGSEvaporation	25	99.10%	90.0%	5	9,000.0	Sources for Cu, In, Ga, Se
CdS deposition	Cji	60	99.10%	90.0%	2	1,462.0	Thiourea, cadmium sulphate, ammonium solution
P2 mechanical scribe	LaserScriberP2	120	99.10%	90.0%	1	1,065.0	
B-ZnO deposition	MOCVD-TCO	6	99.10%	90.0%	28	510.0	
P3 mechanical scribe	LaserScriberP3	120	99.10%	90.0%	1	1,012.0	MOCVD TCO 1, MOCVD TCO 2
Perimeter edge deletion	Laser4J	60	99.90%	90.0%	2	675.0	
Hole drill	HoleDrill	60	100.00%	90.0%	2	675.0	
Bus pad prep and clean	Cutter	60	100.00%	90.0%	2	288.0	
Ribbon attachment	RibbonAttach	60	100.00%	90.0%	2	288.0	Copper ribbon, tin solder, indium solder
Circuit I-V test	CircuitTester	60	99.90%	90.0%	2	200.0	
Front glass clean	GlassWash2	60	100.00%	90.0%	2	190.0	
Assemble pre-laminate	PLATool	60	100.00%	90.0%	2	190.0	Ethyl vinyl acetate, top glass
Lamination	Laminator	60	99.90%	90.0%	2	623.0	
Junction box attachment	JBATool	60	100.00%	90.0%	2	50.0	Pottant, junction box
Framing	FrameTool	60	100.00%	90.0%	2	50.0	Frame
Hi-pot test	HiPot	60	100.00%	90.0%	2	100.0	
Sun soak	SSTool	60	100.00%	90.0%	2	100.0	
Module I-V test	ModuleTester	60	99.90%	90.0%	2	360.0	
Sorting / Labelling	SLTool	60	100.00%	90.0%	2	200.0	

Table 3. Co-evaporation input parameters.

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

1. Cost of ownership (COO) is essentially the cost of an individual activity. For a detailed discussion of the history, standards and algorithms of COO and overall equipment efficiency (OEE), see Jimenez [5].

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 a bit like taking a two-dimensional approach to a four-dimensional problem. Both chose a relational database approach to overcome the 'simple factory' limitation. This 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, labour 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 vary, labour requirements can change and the price paid for any of these items can fluctuate with inflation and volume-pricing contracts.

There are outside factors – such as licensing IP, overheads and currency rates – 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 Fig. 3). 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). (Estimations of dynamic measures such as WIP and cycle

Cost Categories	$ x 1000 Total Annual Cost	$/ Panel Out Unit Cost	% of Product Total	$/Watt Normalized Unit Cost	$ x 1000 Scrap Cost
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	5.3%	0.036	176
Equipment	3,578	5.367	1.1%	0.008	147
Facility	771	1.157	6.4%	0.043	29
Labour	8,134	12.200	7.5%	0.081	232
Direct Labour	5,059	7.588	4.5%	0.051	146
Indirect Labour	3,075	4.613	12.0%	0.031	86
Materials & Supplies	33,882	50.823	50.0%	0.305	762
Bottom Glass	30,518	45.776	3.6%	0.024	227
Direct Process	2,418	3.627	45.0%	0.009	534
Indirect Material	947	1.420	1.4%	0.339	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. Sputtering model: product cost summary.

Process Step	Tool Group ID	Total Unit Cost ($/Panel): All Categories	Total Unit Cost ($/Panel): Cumulative Prod. Cost	Category Unit Cost ($/Panel): Equipment Depreciation	Building Depreciation	Operation & Maint.	Direct Labour	Indirect Labour	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. Sputtering model: unit cost per step.

Process Step / Material Item	Item Cost * ($)		Annual Quantity Used		Annual Material Cost ($ x 1000)	Material Cost per Panel ($/Panel)	Fraction of Product Material Cost (%)
Starting Material, Bottom Glass	3.3	/ Panel	732,673	Panels	2,417.8	3.627	23.92 %
5.1 - Cu-Ga + In deposition							
3 - Cu-Ga Target 1	27,000	/ unit	10.6	units	286.2	0.429	2.83 %
4 - Cu-Ga Target 2	18,600	/ unit	71	units	1,314.4	1.972	13.00 %
5 - Indium Target	28,700	/ unit	44.5	units	1,277.7	1.917	12.64 %
6 - Selenize/Sulfurize							
6 - Hydrogen Sulphide	0.09	/ litre	2,065,858	litres	185.9	0.279	1.83 %
7 - Hydrogen Selenide	1.63	/ litre	2,836,178	litres	4,623.0	6.934	45.74 %
					10,105.0	15.157	100.00 %

* Item cost includes inflation (if non-zero rate) and cost adjustment factors

Report 3. Sputtering model: material item costs.

Cost Categories	$ x 1000 Total Annual Cost	$/ Panel Out Unit Cost	% of Product Total	$/Watt Normalized Unit Cost	$ x 1000 Scrap Cost
Depreciation	14,131	21.006	18.0%	0.126	576
Equipment	12,712	18.896	2.0%	0.014	513
Building	1,419	2.109	20.0%	0.140	63
Operation & Maintenance	5,976	8.883	5.7%	0.040	248
Equipment	4,045	6.012	2.7%	0.019	163
Facility	1,931	2.871	8.4%	0.059	85
Labour	8,134	12.091	7.1%	0.081	191
Direct Labour	5,059	7.520	4.3%	0.050	129
Indirect Labour	3,075	4.571	11.5%	0.030	62
Materials & Supplies	32,736	48.663	46.3%	0.291	642
Bottom Glass	29,363	43.648	3.4%	0.024	206
Direct Process	2,418	3.594	41.5%	0.009	436
Indirect Material	955	1.420	1.4%	0.324	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. Co-evaporation model: product cost summary.

time require the use of discrete-event simulation as employed by Factory Explorer®, a commercial software package from Wright Williams &Kelly, Inc. [6].)

> "Cost and resource modelling allows a new dynamic in decision-making: a virtual business model as an enabling technology."

In the midst of all of these complexities lie several challenges. First, cost and resource models need to speak multiple languages and conform to different standards. Accounting standards and nomenclature are much different from the standards and language used at the process step level (equipment and process engineering). One could therefore 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 modelling allows a new dynamic in decision-making: a virtual business model as an enabling technology.

Sputtering model results

The following reports provide a summary and detailed cost analyses for the sputtering/selenization furnace case (refer to Table 2 for the input data summary). Report 1 shows the high-level cost breakdowns for capital costs, operation and maintenance, labour, materials and supplies, and overheads. The cost per panel is $101.67, with 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 tools at $1m/tool) 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 tools at $500k/tool) 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 regard 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.

Co-evaporation model results

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

> "The significant difference is over $2.00 in additional equipment costs for the co-evaporation process."

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 co-evaporation at $33.80 per panel with almost equal contributions from equipment costs (five tools at $9m/tool) and direct-materials

		Total Unit Cost ($/Panel)		Category Unit Cost ($/Panel)								
Process Step	Tool Group ID	All Categories	Cumulative Prod. Cost	Equipment Depreciation	Building Depreciation	Operation & Maint.	Direct Labour	Indirect Labour	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	CIGSEvaporatio	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. Co-evaporation model: unit cost per step.

Process Step / Material Item	Item Cost * ($)		Annual Quantity Used		Annual Material Cost ($ x 1000)	Material Cost per Panel ($/Panel)	Fraction of Product Material Cost (%)
Starting Material, Bottom Glass	3.3	/ Panel	732,673	Panels	2,417.8	3.594	27.63 %
5.1 - Cu-Ga + In + Se deposition							
37 - Evap Cu	29	/ kg	3,886,579	g	112.7	0.168	1.28 %
38 - Evap In	510.9	/ kg	5,653,206	g	2,888.2	4.293	33.00 %
39 - Evap Ga	387.4	/ kg	1,483,967	g	574.9	0.855	6.57 %
40 - Evap Se	125	/ kg	22,047,503	g	2,755.9	4.097	31.49 %
					8,749.6	13.006	100.00 %

* Item cost includes inflation (if non-zero rate) and cost adjustment factors

Report 6. Co-evaporation model: material item costs.

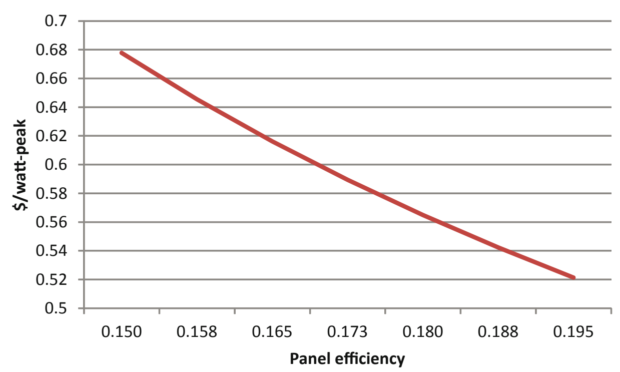

Figure 4. Panel efficiency sensitivity analysis.

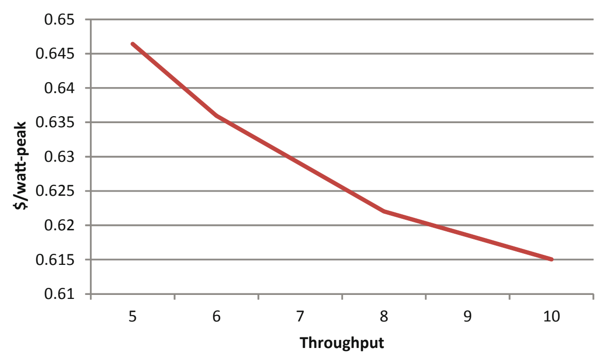

Figure 5. Selenization throughput sensitivity analysis.

consumption. Direct materials will be examined in more detail in Report 6, later in this paper. It should be noted that the co-evaporation step replaced two steps in the sputtering model. Those two steps exceeded $31. The significant difference is over $2.00 in additional equipment costs for the co-evaporation 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 co-evaporation 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 co-evaporation process, where only 40% of the material consumed ends up on the panel in the case of Cu, In and Ga, and only 20% in the case of Se.

Sensitivity analyses

Both models were based on a module efficiency of 15%, which is approximately halfway 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, Fig. 4 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 decreases the cost per watt-peak by approximately $0.04.

Next, the impact of throughput improvements on the selenization furnace will be examined. 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 also looked at reducing the equipment purchase price with the same relative results, but that is less likely as an outcome. Fig. 5 shows that doubling throughput from five to ten panels per hour decreases cost per watt-peak by nearly 5%. While that degree of increase in throughput may not be practical, the move from five to six panels per hour provides 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 downtime. This sensitivity analysis removed that constraint and allowed the model to calculate the actual required amount of equipment. Equipment optimization will be discussed in more detail in the next section.

Lastly, one of the perceived major areas for improvement in the co-evaporation process will be looked at – 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 4 there is a modest cost benefit in increasing the deposition efficiency – between $0.005 and $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.

Other process options

While standard processes which have been in existence for some time were chosen, there are other options that

Material-use efficiency (Cu-In-Ga, Se)						
	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 4. CIGS co-evaporation efficiency sensitivity analysis.

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 be further 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 SiO_2 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 PV industry has gone through immense changes in recent years, yet is still developing rapidly in many ways. While previous papers in this series have focused on c-Si manufacturing and assembly issues, this paper has 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.

> "A series of lesser improvements is necessary for bringing the costs down to the $0.30/watt-peak level."

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 just one major cost breakthrough for either of the CIGS manufacturing processes presented here but, rather, that a series of lesser improvements is necessary for bringing the costs down to the $0.30/watt-peak level, 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 strongly 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.

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