Information Exchange for Your Application & Use of Cost Modeling

Since 1991

APPLIED Co$t MODELING

Volume 19. Issue 3

Inside

Spring 2013

ISSN 1094-9739

Manufacturing Cost Advantages of "Solar Breeder" Factories for Deployment in Utility Scale Solar Farms

With this edition of Applied Cost Modeling, we are publishing the second installment in a series on the application of cost and resource modeling to crystal silicon-based (c-Si) photovoltaic (PV) supersized module manufacturing.

Case Study

This case study will evaluate the cost and resource models for supersized 1 kW PV modules and conventional PV modules. Both models are based on a 40 MW annual factory output. The data used in the supersized module analysis is based on information available to Spire Corporation. The standard 40 MW module line analysis is based on the National Renewable Energy Laboratory's (NREL) Solar American Initiative (SAI) Public Model. All results were generated through Wright Williams & Kelly, Inc.'s (WWK) Factory Commander® cost and resource software[2]. Where differences in model approaches existed (overhead, cell costs), the authors standardized the approach to provide apples-to-apples results.

<u>Cost and Resource Modeling History</u>

Cost and resource modeling is a comprehensive approach to understanding a wide variety of factory level issues that was originally pioneered by SEMATECH in the 1990's and then adapted and extended by Sandia National Laboratories. The concept was developed to initially assist integrated

First published in Photovoltaics International, 10th edition.

[Continued on page 3]

Editorial Board

Publisher

Published quarterly by:

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

Phone 925-399-6246
Fax 925-396-6174
E-mail support@wwk.com

Available at:
http://www.wwk.com
Select "Newsletter"

Calendar of Events

June 2013

16-21 IEEE - PVSC
Tampa Convention Center
Tampa, FL

19-21 Intersolar Europe
Messe Munich
Munich, Germany

July 2013

9-11 SEMICON/West & Intersolar North America
Moscone Hall
San Francisco, CA

August 2013

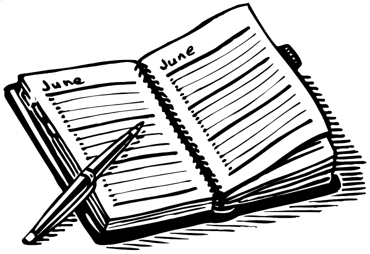
1-3 SOLARCON India
KTPO Exhibition Complex
Bangalore, India

September 2013

30 EU PVSEC
Parc des Expositions
Paris, France

October 2013

1-4 EU PVSEC
Parc des Expositions
Paris, France



circuits (ICs) and then flat panel displays (FPDs), two capital-intensive industries, to improve their ability to compete globally and maintain a U.S. supply of high tech components. SEMATECH, in particular, considered it such a strategic asset that only members and select suppliers had access to the software.

Factory Commander® is a commercialization of the Factory Cost Model (FCM) developed at Sandia National Laboratories in the mid 90s. The FCM was expressly developed for the U.S. Flat Panel Display Industry for making cost competitive decisions regarding new FPD manufacturing initiatives. The FCM was one of several cost modeling tools and projects developed under the National Center for Advanced Information Components Manufacturing (NCAICM) program. The NCAICM initiative was located at Sandia and was a collaboration with the members of the United States Display Consortium (USDC).

The original plan of the NCAICM cost modeling project was to adapt the SEMATECH Cost and Resource Model, or CR/M, for application in the FPD industry. CR/M's main purpose was to do Greenfield fab planning or early-stage analysis for semiconductor products in existing factories. The plan at NCAICM included using the CR/M as is, or with minor modifications, and introducing the software and the concept of cost and resource modeling to the FPD industry in the U.S.

However, through the initial research into the needs of the potential FPD clients it became clear that using the CR/M, even with modifications, would not suffice for FPD manufacturers. Needs such as detailed material tracking/costing, modeling of rework loops, mergers of multiple process flows, and better output reporting capabilities, would have required significant changes to CR/M. As a result the NCAICM cost modeling project set out to development its own application called FCM.

WWK acquired the intellectual property (IP) rights to Sandia's work in 1996 and commercialized FCM under the trade name Factory Commander®. With over 15 years of further enhancements, cost and resource modeling has been rendered technology neutral and 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 production schedule.

At the heart of cost and resource modeling are activities. 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[1] (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).

What both SEMATECH and Sandia determined is that while this type of modeling had been done previously with spreadsheets, it was bit like taking a 2 dimensional approach to a 4 dimensional problem. There was a need for a relational database system that was not limited to simple factories or start-ups but could analyze complex situations including multiple products with multiple process flows, rework loops, and yield loss at specific points in the line, etc.

Factories are dynamic, with near constant change in product volumes, product mix, yields, productivity rates (cycles of learning), process flows, material costs, labor efficiency, product value, etc. There are non-products run in the factory, such as R&D, engineering evaluations, and monitor units. There are reentrant 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 smaller 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 5). 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.

Factory Commander® Inputs

The following are the results of the cost and resource analysis run on the 1 kW and 245 W lines. Table 1 highlights the high-level input parameters. While the data available from the SAI Public Model suggests a cell cost of $5.82, WWK evaluated both scenarios using a cell market price of $5.03/cell (or $1.20/W).

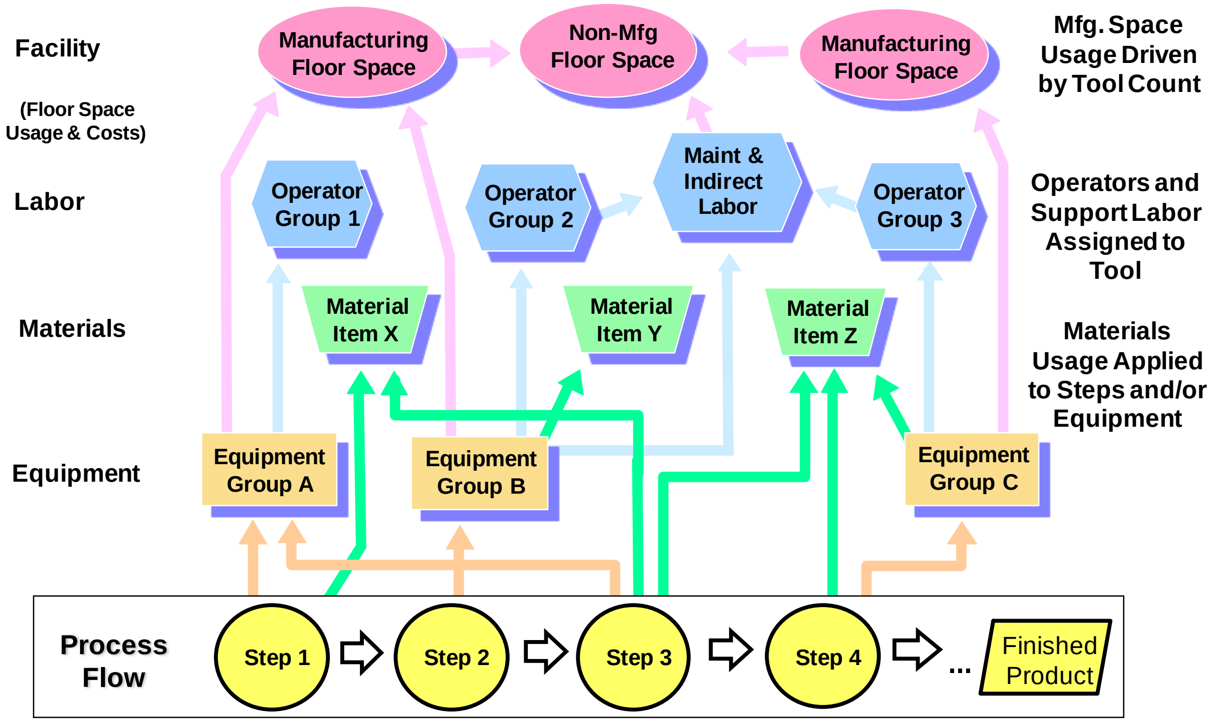


Figure 5: Activity Based Resource Relationships

Parameter	Spire 1 kW	SAI Public Model (NREL)
Factory Size	40 MW	100 MW scaled to 40 MW
Production Demand/Year	40,000 modules	163,265 modules
Module Size	1 kW	245 W (mean)
Cell Cost	$5.03	$5.82 ($6.67 when scaled)[4]
Cell Size	156 mm	156 mm
Yield Loss	4%	4%

Table 1: Major Cost and Resource Model Inputs

In addition to the Table 1 parameters, there are highly detailed inputs for both models including process routes, equipment performance and costs, labor requirements, facilities costs, utilities, etc. Table 2 provides the process routes used in both models. While not identical, there is a reasonable match between the major functions as would be expected

Cost Drivers

Examination of the product summary outputs in Figures 6 and 7 highlight the product cost differences between the two models. One difference in the models is that the SAI line specifies the raw wafer as a starting material since it is an integrated cell and module line and the Spire line has it modeled as part of the total cell cost which is an input into the first module process step. The important numbers to compare are the normalized unit costs which represent the module cost per watt and are $1.809 and $1.805 for the SAI and Spire models respectively, identical for all practical purposes.

Spire 1 kW	SAI Public Model (NREL)
	Incoming cell inspection
Glass washing	Glass washing
EVA cover cut & place	Tab & string cells
String assembly & inspection	Module layup
String inspection & layup	Busing & inspection
Busing	Module lamination
EVA backsheet cut & place	Module curing
Prelamination inspection	Module trim & taping
Prelamination buffer	Frame module
Lamination	Module termination
Postlamination buffer	Module power test
Trimming	Module safety test
Framing	Package & label module
Boxing	
Simulation	
Hipot	
Pre-packaging inspection	
Sorting & packaging	
Installation	

Table 2: Process Routes

Drilling down gives us insight into which process steps are the main cost drivers and which components of cost are the most important. This is shown in Figures 8 and 9, which represent the unit cost per step and is the equivalent of the COO[1] for each step. For both models, the layup station is a top cost driver. The extremely high cost of this step in the Spire model is a result of the cost of finished cells being introduced at this step vs. a starting material in the SAI model. Also in the top 3 cost drivers is framing, which has a higher cost in the Spire model as would be expected with a larger module size.

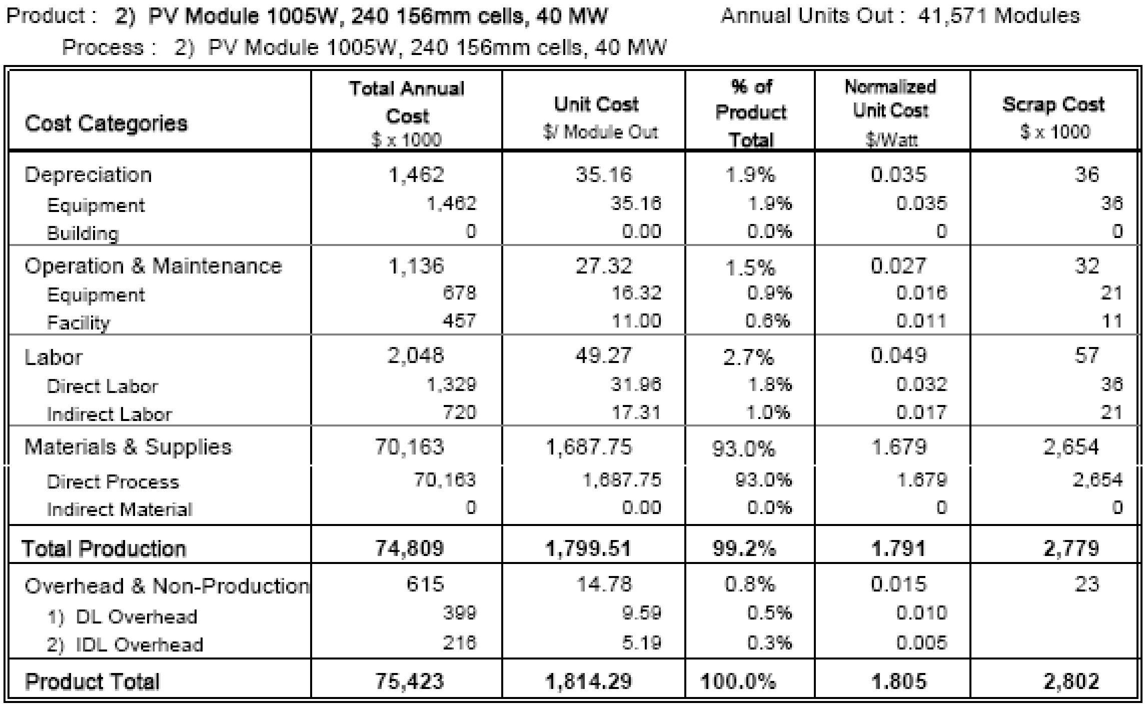
Cost Driver Sensitivities

In this section we will concentrate on two sensitivity analyses based on the 1 kW model. The first looks at the normalized unit cost as a function of cell costs. In this case, the term normalized does not mean reducing the base case to a factor of 1 but normalizing the per module costs to an equivalent cost per watt. The cell cost was varied through a ±20% range and the impact on the normalized unit cost is displayed. In this case, a 15% reduction in cell costs reduces the finished module cost per watt by approximately 10%. Figure 10 shows the normalized unit cost ($/W) against the change in total material cost driven by the change in cell costs.

As a measure of line balance, we also looked at the normalized cost per watt as a function of production demand. We varied the start rate from the initial 40 MW plan to a +250%. In this case, a 250% increase in starts only reduces the finished module cost per watt by 3.3%. This is an indication that the 40 MW supersized module line design has been appropriately balanced and the individual equipment throughputs are well matched. See Figure 11.

Installation

As demonstrated in Figures 6 and 7, the production of a supersized module is shown to match the cost structure of the mature standard module. Given additional cycles of learning that could be employed in the supersized module line, it would be a reasonable assumption that the long term manufacturing costs for the supersized module have greater room for improvement. In addition, current estimates indicate that

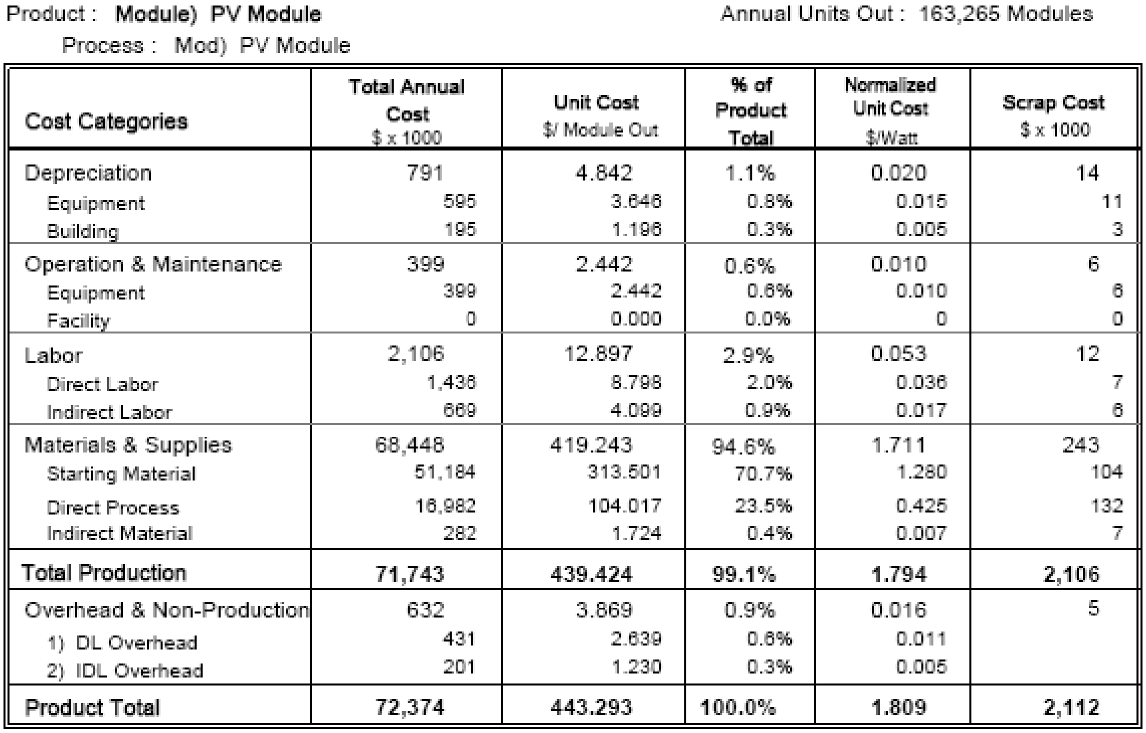


Product : **2) PV Module 1005W, 240 156mm cells, 40 MW** Annual Units Out : 41,571 Modules

Process : 2) PV Module 1005W, 240 156mm cells, 40 MW

Cost Categories	Total Annual Cost $ x 1000	Unit Cost $/ Module Out	% of Product Total	Normalized Unit Cost $/Watt	Scrap Cost $ x 1000
Depreciation	1,462	35.16	1.9%	0.035	36
Equipment	1,462	35.16	1.9%	0.035	36
Building	0	0.00	0.0%	0	0
Operation & Maintenance	1,136	27.32	1.5%	0.027	32
Equipment	678	16.32	0.9%	0.016	21
Facility	457	11.00	0.6%	0.011	11
Labor	2,048	49.27	2.7%	0.049	57
Direct Labor	1,329	31.96	1.8%	0.032	36
Indirect Labor	720	17.31	1.0%	0.017	21
Materials & Supplies	70,163	1,687.75	93.0%	1.679	2,654
Direct Process	70,163	1,687.75	93.0%	1.679	2,654
Indirect Material	0	0.00	0.0%	0	0
Total Production	**74,809**	**1,799.51**	**99.2%**	**1.791**	**2,779**
Overhead & Non-Production	615	14.78	0.8%	0.015	23
1) DL Overhead	399	9.59	0.5%	0.010	
2) IDL Overhead	216	5.19	0.3%	0.005	
Product Total	**75,423**	**1,814.29**	**100.0%**	**1.805**	**2,802**

Figure 6: 245 W Module Cost

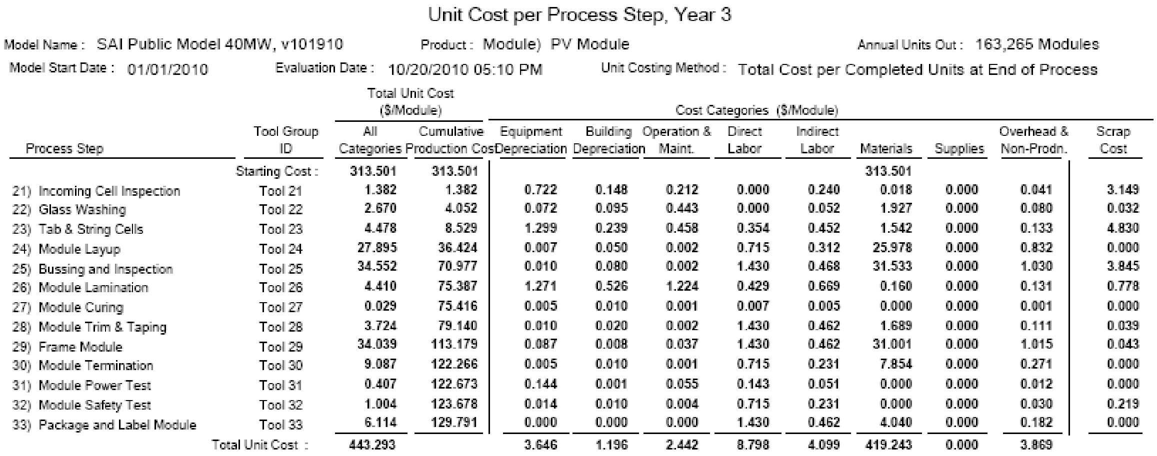


Product : **Module) PV Module** Annual Units Out : 163,265 Modules

Process : Mod) PV Module

Cost Categories	Total Annual Cost $ x 1000	Unit Cost $/ Module Out	% of Product Total	Normalized Unit Cost $/Watt	Scrap Cost $ x 1000
Depreciation	791	4.842	1.1%	0.020	14
Equipment	595	3.646	0.8%	0.015	11
Building	195	1.196	0.3%	0.005	3
Operation & Maintenance	399	2.442	0.6%	0.010	6
Equipment	399	2.442	0.6%	0.010	6
Facility	0	0.000	0.0%	0	0
Labor	2,106	12.897	2.9%	0.053	12
Direct Labor	1,436	8.798	2.0%	0.036	7
Indirect Labor	669	4.099	0.9%	0.017	6
Materials & Supplies	68,448	419.243	94.6%	1.711	243
Starting Material	51,184	313.501	70.7%	1.280	104
Direct Process	16,982	104.017	23.5%	0.425	132
Indirect Material	282	1.724	0.4%	0.007	7
Total Production	**71,743**	**439.424**	**99.1%**	**1.794**	**2,106**
Overhead & Non-Production	632	3.869	0.9%	0.016	5
1) DL Overhead	431	2.639	0.6%	0.011	
2) IDL Overhead	201	1.230	0.3%	0.005	
Product Total	**72,374**	**443.293**	**100.0%**	**1.809**	**2,112**

Figure 7: 1 kW Module Cost



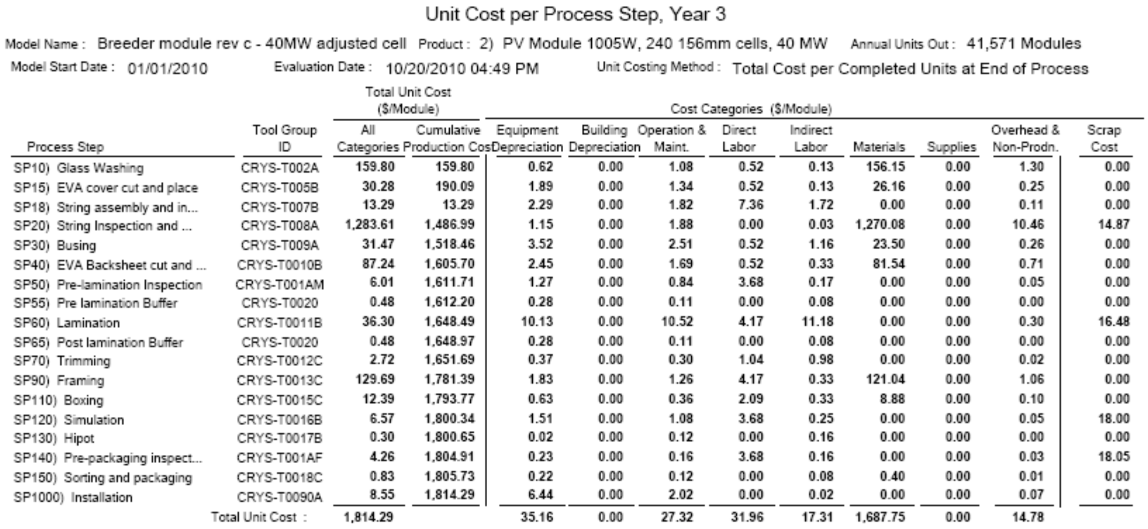
Unit Cost per Process Step, Year 3

Model Name : SAI Public Model 40MW, v101910 Product : Module) PV Module Annual Units Out : 163,265 Modules

Model Start Date : 01/01/2010 Evaluation Date : 10/20/2010 05:10 PM Unit Costing Method : Total Cost per Completed Units at End of Process

		Total Unit Cost ($/Module)		Cost Categories ($/Module)								
Process Step	Tool Group ID	All Categories	Cumulative Production Cos	Equipment Depreciation	Building Depreciation	Operation & Maint.	Direct Labor	Indirect Labor	Materials	Supplies	Overhead & Non-Prodn.	Scrap Cost
	Starting Cost :	313.501	313.501						313.501			
21) Incoming Cell Inspection	Tool 21	1.382	1.382	0.722	0.148	0.212	0.000	0.240	0.018	0.000	0.041	3.149
22) Glass Washing	Tool 22	2.670	4.052	0.072	0.095	0.443	0.000	0.052	1.927	0.000	0.080	0.032
23) Tab & String Cells	Tool 23	4.478	8.529	1.299	0.239	0.458	0.354	0.452	1.542	0.000	0.133	4.830
24) Module Layup	Tool 24	27.895	36.424	0.007	0.050	0.002	0.715	0.312	25.978	0.000	0.832	0.000
25) Bussing and Inspection	Tool 25	34.552	70.977	0.010	0.080	0.002	1.430	0.468	31.533	0.000	1.030	3.845
26) Module Lamination	Tool 26	4.410	75.387	1.271	0.526	1.224	0.429	0.669	0.160	0.000	0.131	0.778
27) Module Curing	Tool 27	0.029	75.416	0.005	0.010	0.001	0.007	0.005	0.000	0.000	0.001	0.000
28) Module Trim & Taping	Tool 28	3.724	79.140	0.010	0.020	0.002	1.430	0.462	1.689	0.000	0.111	0.039
29) Frame Module	Tool 29	34.039	113.179	0.087	0.008	0.037	1.430	0.462	31.001	0.000	1.015	0.043
30) Module Termination	Tool 30	9.087	122.266	0.005	0.010	0.001	0.715	0.231	7.854	0.000	0.271	0.000
31) Module Power Test	Tool 31	0.407	122.673	0.144	0.001	0.055	0.143	0.051	0.000	0.000	0.012	0.000
32) Module Safety Test	Tool 32	1.004	123.678	0.014	0.010	0.004	0.715	0.231	0.000	0.000	0.030	0.219
33) Package and Label Module	Tool 33	6.114	129.791	0.000	0.000	0.000	1.430	0.462	4.040	0.000	0.182	0.000
	Total Unit Cost :	443.293		3.646	1.196	2.442	8.798	4.099	419.243	0.000	3.869	

Figure 8: 245 W Module Unit Cost per Step



Unit Cost per Process Step, Year 3

Model Name : Breeder module rev c - 40MW adjusted cell Product : 2) PV Module 1005W, 240 156mm cells, 40 MW Annual Units Out : 41,571 Modules

Model Start Date : 01/01/2010 Evaluation Date : 10/20/2010 04:49 PM Unit Costing Method : Total Cost per Completed Units at End of Process

		Total Unit Cost ($/Module)		Cost Categories ($/Module)								
Process Step	Tool Group ID	All Categories	Cumulative Production Cos	Equipment Depreciation	Building Depreciation	Operation & Maint.	Direct Labor	Indirect Labor	Materials	Supplies	Overhead & Non-Prodn.	Scrap Cost
SP10) Glass Washing	CRYS-T002A	159.80	159.80	0.62	0.00	1.08	0.52	0.13	156.15	0.00	1.30	0.00
SP15) EVA cover cut and place	CRYS-T005B	30.28	190.09	1.89	0.00	1.34	0.52	0.13	26.16	0.00	0.25	0.00
SP18) String assembly and in...	CRYS-T007B	13.29	13.29	2.29	0.00	1.82	7.36	1.72	0.00	0.00	0.11	0.00
SP20) String Inspection and ...	CRYS-T008A	1,283.61	1,486.99	1.15	0.00	1.88	0.00	0.03	1,270.08	0.00	10.46	14.87
SP30) Busing	CRYS-T009A	31.47	1,518.46	3.52	0.00	2.51	0.52	1.16	23.50	0.00	0.26	0.00
SP40) EVA Backsheet cut and ...	CRYS-T0010B	87.24	1,605.70	2.45	0.00	1.69	0.52	0.33	81.54	0.00	0.71	0.00
SP50) Pre-lamination Inspection	CRYS-T001AM	6.01	1,611.71	1.27	0.00	0.84	3.68	0.17	0.00	0.00	0.05	0.00
SP55) Pre lamination Buffer	CRYS-T0020	0.48	1,612.20	0.28	0.00	0.11	0.00	0.08	0.00	0.00	0.00	0.00
SP60) Lamination	CRYS-T0011B	36.30	1,648.49	10.13	0.00	10.52	4.17	11.18	0.00	0.00	0.30	16.48
SP65) Post lamination Buffer	CRYS-T0020	0.48	1,648.97	0.28	0.00	0.11	0.00	0.08	0.00	0.00	0.00	0.00
SP70) Trimming	CRYS-T0012C	2.72	1,651.69	0.37	0.00	0.30	1.04	0.98	0.00	0.00	0.02	0.00
SP90) Framing	CRYS-T0013C	129.69	1,781.39	1.83	0.00	1.26	4.17	0.33	121.04	0.00	1.06	0.00
SP110) Boxing	CRYS-T0015C	12.39	1,793.77	0.63	0.00	0.36	2.09	0.33	8.88	0.00	0.10	0.00
SP120) Simulation	CRYS-T0016B	6.57	1,800.34	1.51	0.00	1.08	3.68	0.25	0.00	0.00	0.05	18.00
SP130) Hipot	CRYS-T0017B	0.30	1,800.65	0.02	0.00	0.12	0.00	0.16	0.00	0.00	0.00	0.00
SP140) Pre-packaging inspect...	CRYS-T001AF	4.26	1,804.91	0.23	0.00	0.16	3.68	0.16	0.00	0.00	0.03	18.05
SP150) Sorting and packaging	CRYS-T0018C	0.83	1,805.73	0.22	0.00	0.12	0.00	0.08	0.40	0.00	0.01	0.00
SP1000) Installation	CRYS-T0090A	8.55	1,814.29	6.44	0.00	2.02	0.00	0.02	0.00	0.00	0.07	0.00
	Total Unit Cost :	1,814.29		35.16	0.00	27.32	31.96	17.31	1,687.75	0.00	14.78	

Figure 9: 1 kW Module Unit Cost per Step

savings of $0.30 to $0.55 per watt can be achieved through the installation of PV systems greater than 20 MW.[5] These savings can be attributed to decreased packaging and shipping costs, a significant reduction in required racking materials, decreased quantity of ground lugs and wire management, and a reduction of power inverter/conditioner units.

Conclusions

The PV 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 process step improvements in cell manufacturing using COO and overall equipment efficiency (OEE) measures; with this paper we looked at how to leverage innovation in module assembly. These improvements required a more holistic approach to financial analysis as represented by cost and resource modeling, which allowed us to examine differences in process routes, equipment sets, and materials.

One such innovation is the development of a supersized 1 kW PV module with integrated micro-inverters, which was shown to have a

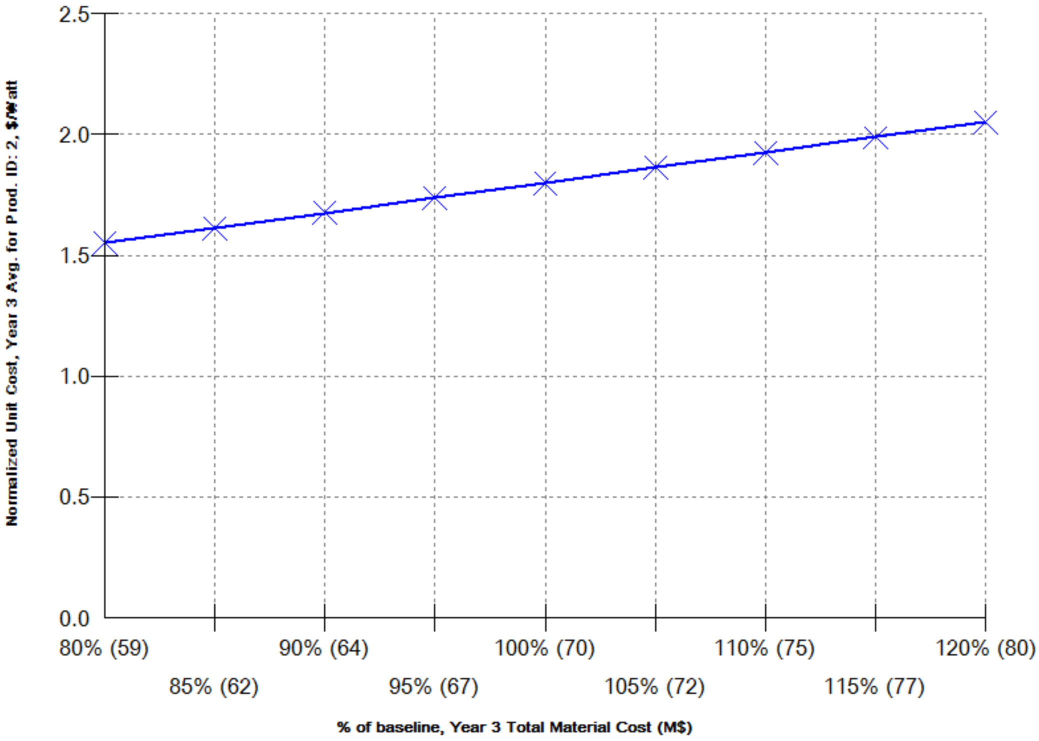


Figure 10: Sensitivity Analysis: Cell Costs

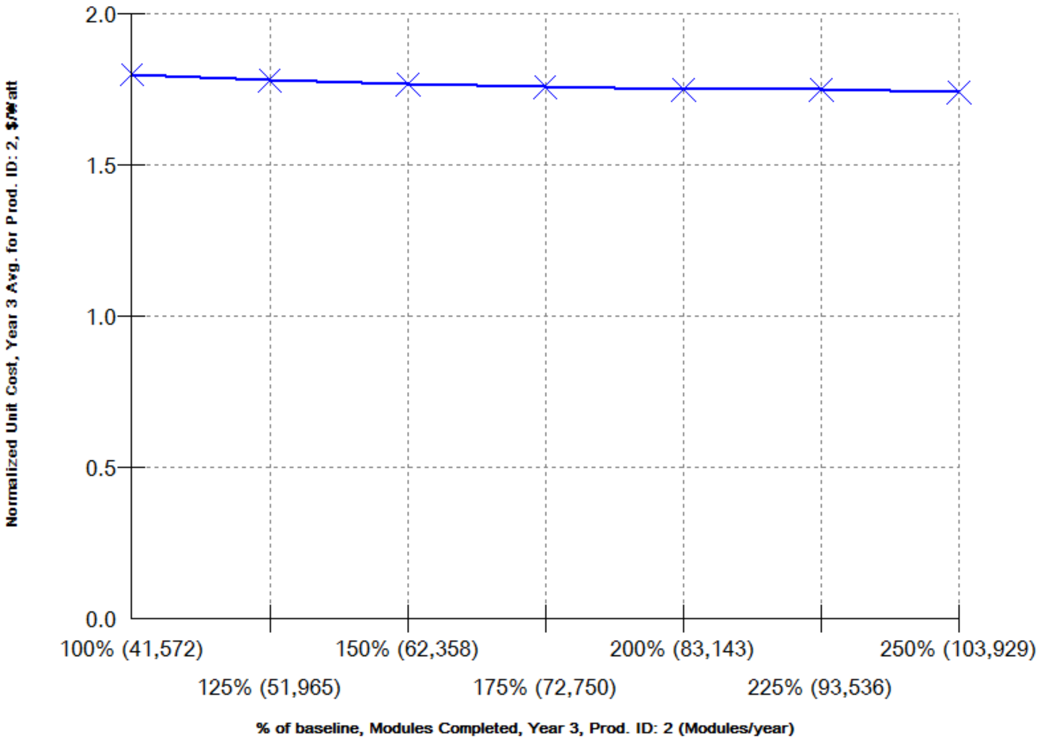


Figure 11: Sensitivity Analysis: Production Demand

nearly identical cost compared to conventional 245 W modules. Once we include the differences in installation costs, the advantage for 1 kW modules in utility scale solar farms, in excess of 20 MW, is approximately $0.30 to $0.55/watt.

References

1. For a detailed discussion of the history, standards, and algorithms of COO and OEE please see D. Jimenez, "Cost of Ownership and Overall Equipment Efficiency: A Photovoltaics Perspective," Photovoltaics International, Ed. 6.
2. Factory Commander® is a commercial software package from Wright Williams & Kelly, Inc.
3. Estimations of dynamic measures such as WIP and cycle time (CT) require the use of discrete-event simulation as employed by Factory Explorer®, a commercial software package from Wright Williams & Kelly, Inc.
4. Cell costs were assumed to be equal between the two scenarios at $5.03.
5. R. Little, M. Nowlan, R. Bradford, and D. Hebert, "The Solar Breeder Factory: Minimizing the Cost of Photovoltaic Energy Generation," *35th IEEE Photovoltaic Specialists Conf.*, 2010.

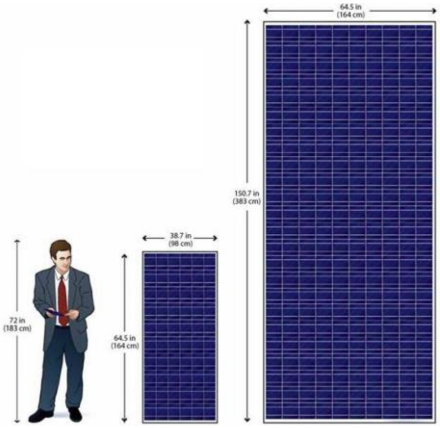
Authors

Mr. Kevin Wolter is the Assistant to the President of Spire Corporation. He has spent seven years working in the clean energy space with much of this experience focusing on manufacturing operations, engineering development, and project management. He holds B.S. degrees in Electrical Engineering and Mechanical Engineering from Kettering University (Flint, MI) and has received his MBA from the Harvard Business School.

Mr. Eric Tobin is currently a Vice President with Spire Corporation. He has been with the company for over 20 years, most recently involved with operational systems development, and evaluation and development of new market opportunities for Spire's solar equipment. Mr. Tobin holds B.S. and M.S. degrees in Applied Physics from the University of Massachusetts at Lowell.

Mr. Michael Nowlan is Advanced Technology Manager at Spire Solar, Inc. He has been a member of Spire's technical staff for 33 years, working on PV module and equipment development for 32 years. He currently manages the Advanced Technology Center at Spire, which develops new module designs and assembly processes, evaluates new module materials, provides module process training for Spire's equipment customers, and produces limited productions runs of PV modules for a wide range of applications. He holds a B.A. in Physics from the University of Massachusetts at Boston.

Mr. David Jimenez is President and co-Founder 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 MBA in Finance. He was also responsible for the design of the semiconductor industry's de facto standard in cost of ownership, TWO COOL®. He is a recipient of the Texas Instruments Supplier Excellence Award for his contributions to their cost reduction efforts. For over 20 years, he has been a facilitator in the SEMI sponsored workshop, "Understanding and Using Cost of Ownership." Mr. Jimenez can be reached at +1 925-399-6246 or david.jimenez@wwk.com.



New PVMC/WWK Article in Photovoltaics International

Photovoltaics International's 21st edition will contain a paper written by the Photovoltaic Manufacturing Consortium (PVMC) and WWK. This paper will be the sixth in a series covering business analysis for PV processes. The abstract is: While thin film copper, indium, gallium, selenide (CIGS) PV has historically been projected to be more cost effective than c-Si PV, those cost projections have been based on aggressive capital and panel efficiency targets. However, cost projections are typically based on "Greenfield" factories and the real world does not follow this model for incremental improvements. This paper will examine the cost differences in these two sets of assumptions.

With leadership from SEMATECH and the College of Nanoscale Science and Engineering (CNSE) of the University at Albany, support and participation from over 40 companies and organizations from throughout the solar community, and over $300 million in projected state, federal, and industry funding, PVMC is well positioned to provide significant, positive and sustainable impact on the growth of the U.S. PV industry.