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Examining the cost manufacturing advantages of 'solar breeder' factories for deployment in utility-scale solar farms

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ABSTRACT

This paper, the fourth in a series covering cost modelling studies for photovoltaics [1–3], examines a new approach to module assembly based on the concept of 'supersized' 1kW PV modules. Using supersized modules (1.6m × 3.8m) and integrated microinverters, this novel approach has the estimated potential to save utility solar installations up to US$0.55/watt. The paper will conclude with a detailed cost and resource case study comparing two 40MW module lines, one employing 'solar breeder' technology and the other producing conventional-sized modules.

Conventional PV module overview

The PV module is an assembly of electrically interconnected solar cells enclosed in a weatherproof package to protect it from the effects of the environment. The module circuit design specifies the number of cells connected in series, the number of cells connected in parallel, and the frequency of parallel interconnects. The number of cells in series determines the module operating voltage. The cell area and the number of cells in parallel are proportional to the module current output. Any practical series-parallel configuration can be fabricated to meet specific module design requirements.

A cutaway view of a standard module is shown in Fig. 1. Tempered low-iron glass is used for the front cover (or superstrate) to provide permanently transparent protection for the optical surface of the module. The remainder of the laminate consists of clear ethylene vinyl acetate (EVA) encapsulant, the cell circuit, a second layer of EVA, a fibreglass sheet, and a back-cover film.

"Larger modules could provide significant cost savings by lowering materials, balance of system and installation expenses."

EVA, which is supplied in sheet form, acts as both a transparent soft encapsulant and an adhesive for bonding the layers together. The lamination process is designed to thoroughly remove air from between all layers. The fibreglass sheet prevents the cell circuit from damaging the cover film during the module's lifetime. When the EVA encapsulant is heated for lamination, it melts and impregnates the fibreglass, providing a strong bond that extends from the cell backs, through the fibreglass, to the back cover. A foam tape gasket protects the module edges, where the back-cover film meets the glass. This tape cushions the glass panel and decouples it from the module frame to prevent degradation of the edge by daily thermal cycling.

Electrical output leads are brought through the encapsulant and backsheet. The leads go to a junction box mounted on the back of the module. Weather-tight intermodule wire connections are made at the junction box.

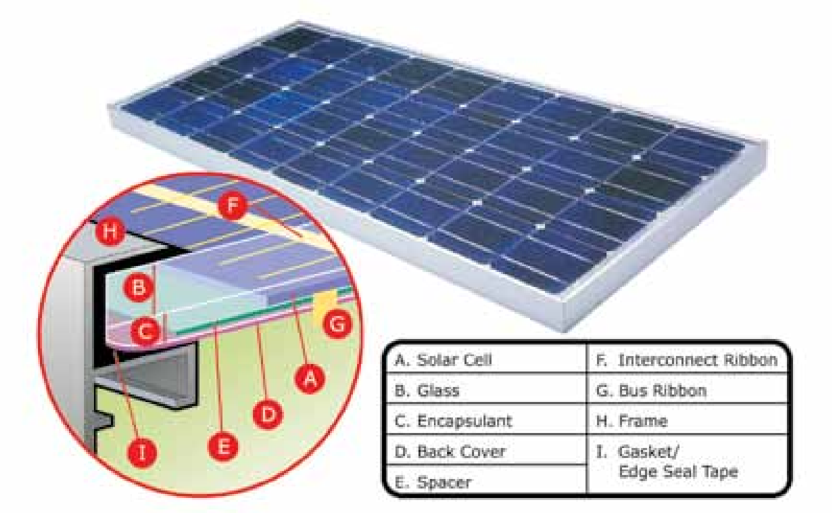

Figure 1. Cutaway view of a standard solar module.

Conventional module process sequence

The manufacturing process uses solar cells and module materials as inputs and produces functional PV modules, ready for use. The process, shown in Fig. 2, consists of the following steps:

- Sorting solar cells into performance groups (current groups at load voltage) using a cell sorter.
- Washing, rinsing, and drying the glass superstrate.
- Cutting EVA and placing it on the glass.
- Assembling and soldering cell strings interconnected with metal ribbons using an assembler/stringer.
- Aligning and placing strings onto the EVA (previously placed on the glass).
- Completing the module circuit by soldering bus ribbons to connect the strings together and provide output leads at a busing station.
- Visually inspecting and electrically testing the module circuit by measuring its dark I-V characteristics at an inspection station.

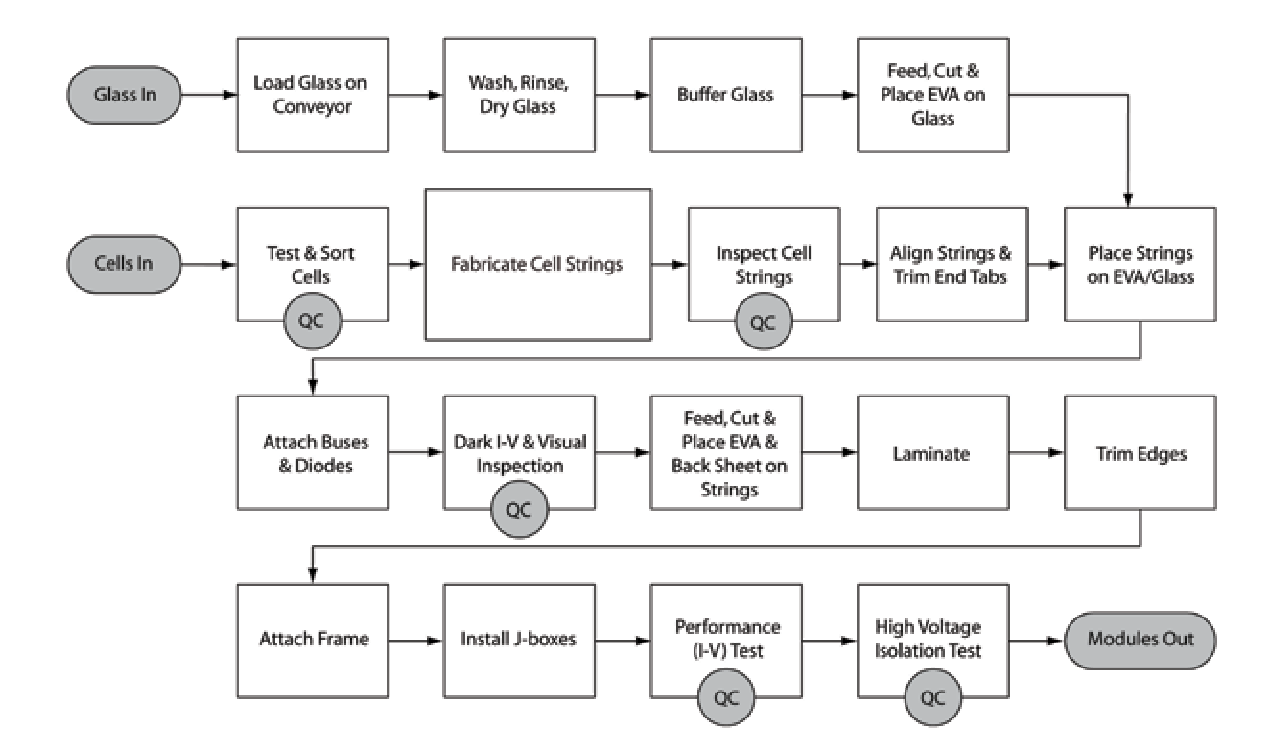

Figure 2. Standard solar module process sequence.

- Cutting EVA, fiberglass, and back sheets to length and assembling them with the glass and module circuit, using an EVA/back sheet layup station, in preparation for encapsulation.
- Laminating the assembly and curing the EVA.
- Completing final assembly, which includes edge trimming, installing an edge gasket and frame, and attaching a junction box.
- Performing a high voltage isolation test to measure the voltage isolation between the cell circuit and the module frame, and testing the frame ground continuity.
- Electrically testing the module under simulated sunlight with a sun simulator to measure its electrical performance.
- Visually inspecting the completed module for quality of materials and workmanship.

New solutions for the utility PV market

The solar utility PV market is experiencing significant growth that will continue through the foreseeable future. Utilities are expected to add at least 20GW of solar PV to their generation portfolios by 2020. The rapid growth in market demand is driving development of utility-scale solar projects such as grid-tied solar farm systems of 25 to 200MW. These farms will consist primarily of crystalline silicon (x-Si) modules, due to utility demands for reliability, high efficiency, a proven track record, and demonstrated 20-year life span, as well as overall cost considerations. Cost remains a major consideration in these growth projections, and further cost reductions will be necessary for additional growth to be achieved.

A new solar cell assembler and associated technology is being developed for the production of supersized 1kW utility PV modules. Such larger modules could provide significant cost savings by lowering materials, balance of system (BOS) and installation expenses. Furthermore, a single, larger panel-integrated microinverter utilized on the 1kW modules will provide cost advantages compared to a larger number of smaller units on conventional modules. Total predicted savings are near US$0.50/watt. This cost reduction would translate into billions of dollars in cost savings over the next decade for this rapidly growing market segment.

The maximum output for a conventional PV module is about 230–245W. Larger modules, up to 400W, have been recently introduced and are targeted specifically at the utility market. Supersized modules, more than double this size, could provide

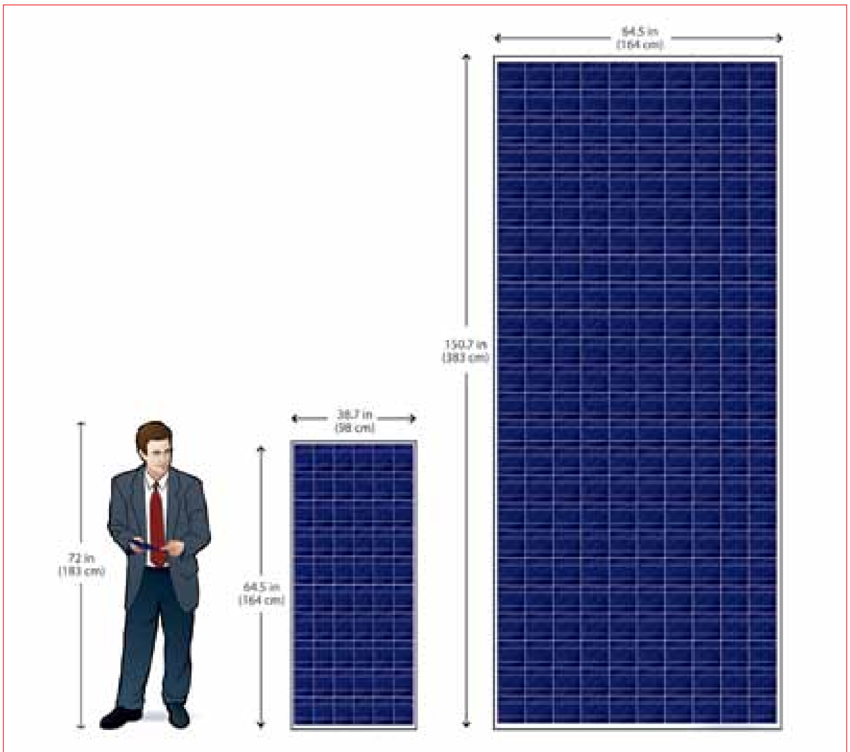

Figure 3. Comparison of standard (230W) and supersized (1kW) modules.

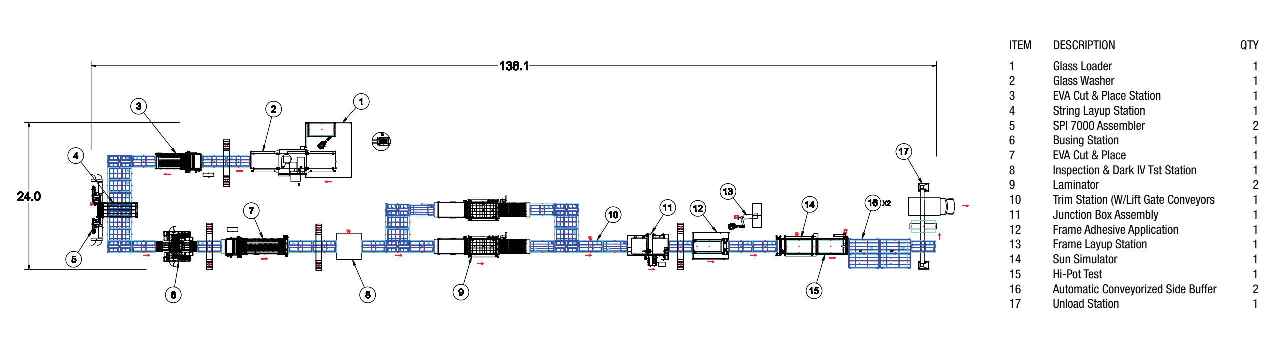

Figure 4. Layout of a 40MW module production line for 1kW supersized panels.

even greater benefit for PV utilities. But very large modules are impractical if they require transportation over significant distances. Importantly, the transportation constraint does not apply to the key materials that go into a module – the solar cells, which are small and light, and can be tightly packed. The transportation complexities for the supersized module provide an incentive for local module manufacturing at the solar farm site or at centralized locations with multiple customers nearby. The expenses associated with building a local factory would be quickly offset by savings realized from the larger module design.

An important consideration in the rethinking is how to address a factory designed to service a very limited, exclusively local customer base. Simply put, the production plant can be moved every few years. At the completion of the project, the factory can be decommissioned and the equipment relocated to another solar farm site to continue manufacturing.

Supersized PV modules

A preliminary design has been created for the supersized module, which will be nominally 5.5-ft × 12.5-ft (1.6m × 3.8m) and made with 240 standard 156mm crystalline silicon solar cells connected in 10-cell strings. Using cells with a nominal output of 4.19W/cell (with 17.2% cell efficiency) will produce a module power of 1kW (see Fig. 3).

Supersized module process sequence

The major steps required in the supersized module process sequence are very similar to those used in a standard module production line. As currently planned, the major differences between the two production lines are as follows:

- Size of production equipment. Producing modules that are four times the size of a standard module requires larger assembler and string layup, laminator, sun simulator, and conveyor stations.
- Increased automation. Expected to weigh approximately 330lb (150kg), the production line for the supersize module requires a high degree of automation.

A layout schematic (with dimensional units in meters) for an automated 40MW line capable of producing 1kW modules is shown in Fig. 4.

Case study

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

Cost and resource modelling history

Cost and resource modelling is a comprehensive approach to understanding a wide variety of factory-level issues. The methodology was originally pioneered by semiconductor consortium Sematech in the 1990s and then adapted and extended by Sandia National Laboratories. The concept was developed to initially assist two capital-intensive industries – integrated circuits and then flat panel displays (FPDs) – 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.

> "Cost and resource modelling is a comprehensive approach to understanding a wide variety of factory-level issues."

Factory Commander is a commercialization of the factory cost model (FCM) developed at Sandia in the mid-1990s. The model was expressly developed for the U.S. display industry for making cost-competitive decisions regarding new FPD manufacturing initiatives. FCM was one of several cost modelling tools and projects developed under the National Center for Advanced Information Components Manufacturing

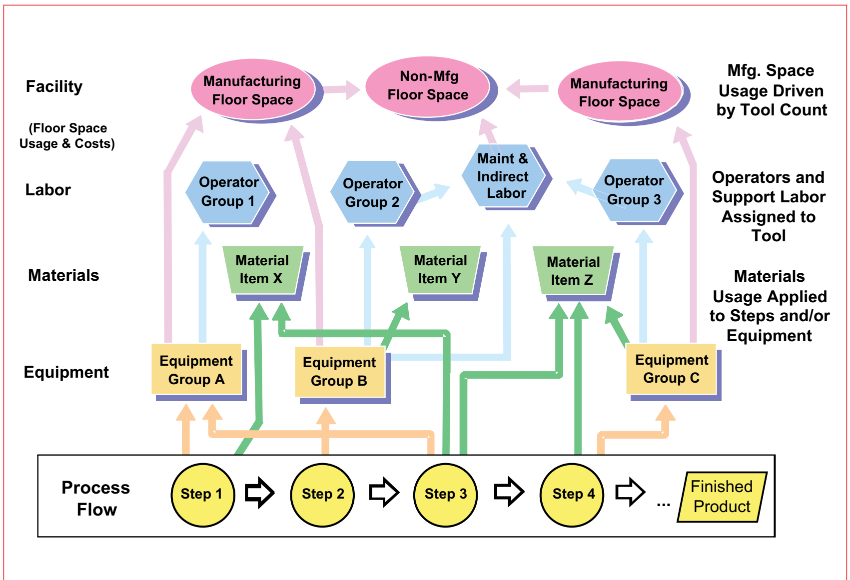

Figure 5. Chart of activity-based resource relationships.

Parameter	1kW Module	SAI Public Model (NREL)
Factory size	40MW	100MW scaled to 40MW
Production demand/year	40,000 modules	163,265 modules
Module size	1kW	245W (mean)
Cell cost	US$5.03	US$5.82 (US$6.67 when scaled)
Cell size	156mm	156mm
Yield loss	4%	4%

Table 1. Major cost and resource model inputs. (Cell costs were assumed to be equal between the two scenarios at US$5.03.)

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

Table 2. Process routes for two module production models.

Product cost summary, year 3

Model name: SAI public model 40MW, v101910
Model start date: 01/01/2010
Product: Module) PV module
Process: Module) PV module

Evaluation date: 11/10/2010 11:20 AM
Modeling timeframe: Uniform annual
Annual units out : 163,265 modules

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 and 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
Labour	**2,106**	**12.897**	**2.9%**	**0.053**	**12**
Direct labour	1,436	8.798	2.0%	0.036	7
Indirect labour	669	4.099	0.9%	0.017	6
Materials and 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 and 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**

Table 3. Cost summary for 245W module.

(NCAICM) program. The NCAICM initiative was located at Sandia and was a collaboration with members of the United States Display Consortium (USDC).

The NCAICM cost modelling project originally planned to adapt the Sematech cost and resource model (CR/M) for application in the FPD industry. The model's main purpose was to assist in 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 modelling to the U.S. FPD industry.

However, as a result of 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. Items such as detailed material tracking/costing, modelling of rework loops, mergers of multiple process flows, and better output reporting capabilities would have required significant changes to the model. As a result, the NCAICM cost modelling project set out to develop its own application called FCM.

WWK acquired the intellectual property rights to Sandia's work in 1996 and commercialized FCM. With nearly 15 years of further enhancements, cost and resource modelling has been rendered technology neutral and applicable to all discrete manufacturing and assembly operations, including photovoltaics.

Cost and resource models

Cost and resource models assess the resources needed – people, equipment, materials, etc. – to complete a process or task, which in turn 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 modelling are activities. Each activity requires resources, and 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, tool counts, etc.). Four common business practices are subsets of cost and resource modelling.

- Cost of ownership (COO) is essentially the cost of an individual activity [1].

Product cost summary, year 3

Model name: Breeder module rev c - 40MW adjusted cell cost 101910
Model start date: 01/01/2010
Product: 2) PV module 1005W, 240 156mm cells, 40 MW
Process: 2) PV module 1005W, 240 156mm cells, 40 MW

Evaluation date: 10/20/2010 04:49 PM
Modeling timeframe: 8 quarters + 8 years
Annual units out : 41,571 modules

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 and 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 labour	1,329	31.96	1.8%	0.032	36
Indirect labour	720	17.31	1.0%	0.017	21
Materials and 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 and 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**

Table 4. Cost summary for 1kW module.

- 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.
- Budgeting, including capital budgets, is a function of the capacity needs and the costs associated with meeting them.
- 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 modelling had been done previously with spreadsheets, this approach was akin to taking a two-dimensional approach to a four-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.

Factories are dynamic, with near-constant change in product volumes, product mix, yields, productivity rates (cycles of learning), process flows, material costs, labour efficiency, product value and other factors. There are non-products run in the factory, such as R&D, engineering evaluations and monitor units, as well as 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; labour requirements can change; and the price paid for any of these items can change with inflation and volume pricing contracts. Outside factors, such as licensing IP, overheads, and currency rates, all have an impact on product cost.

Once these factors are identified, the cost and resource model quantifies resource requirements and allocates those resources to individual products (see

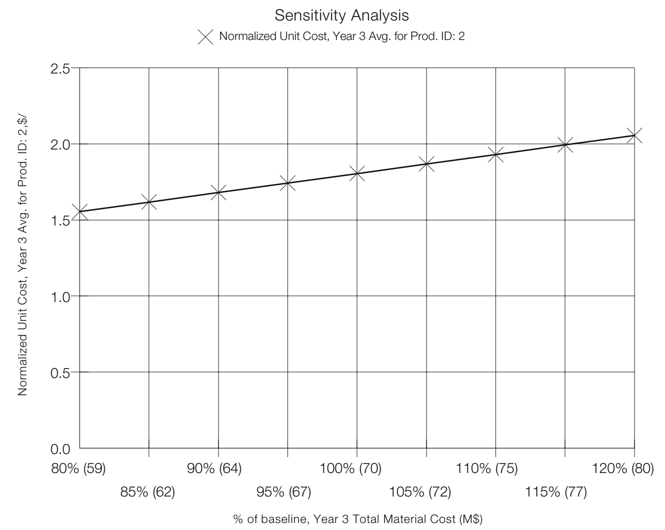

Figure 6. Sensitivity analysis of cell costs.

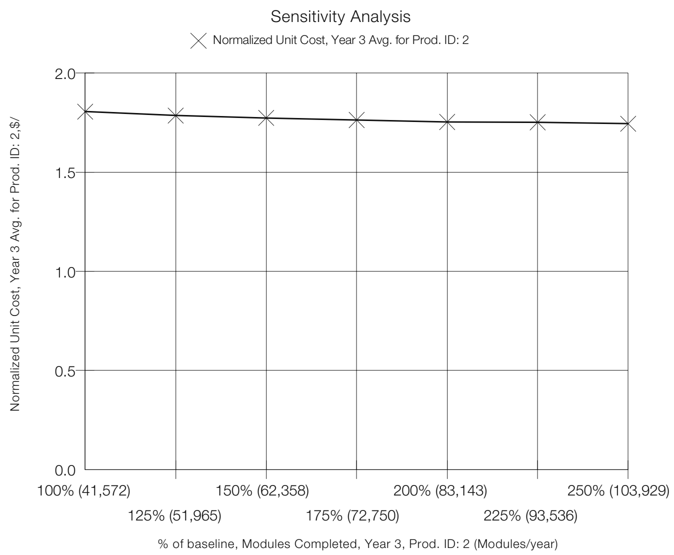

Figure 7. Sensitivity analysis of production demand.

Fig. 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).

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

Cost and resource modelling software inputs

The following are the results of the cost and resource analysis run on the 1kW and 245W lines. Table 1 details the high-level input parameters. While the data available from the SAI Public Model suggest a cell cost of US$5.82, both scenarios were evaluated using a cell market price of US$5.03/cell (or US$1.20/W). In addition to the Table 1 parameters, there are highly detailed inputs for both models including process routes, equipment performance and costs, labour requirements, facilities costs and utilities. 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

An examination of the product summary outputs in Tables 3 and 4 highlights the

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 : 11/10/2010 11:20 AM — Unit costing method : Total cost per completed units at end of process

Process step	Tool group ID	Total unit cost ($/module): All categories	Cumulative production cost	Cost categories ($/module): Equipment depreciation	Building depreciation	Operation and maintenance	Direct labour	Indirect labour	Materials	Supplies	Overhead and non-production	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 and 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 and 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	

Table 5. Unit cost per process step for 245W module.

product cost differences between the two models. One difference between the models is that the SAI line specifies the raw wafer as a starting material since it is an integrated cell and module line, while the 1kW line has modelled it 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 US$1.809 and US$1.805 for the SAI and 1kW models, respectively – identical for all practical purposes.

A deeper look at the data provides insight into which process steps are the main cost drivers and which components of cost are the most important. Tables 5 and 6 show this comparison in terms of the unit cost per process step, which is the equivalent of the COO for each step [1]. Both models share the layup station as a top cost driver. The extremely high cost of this step in the 1kW model results from the cost of finished cells being introduced at this step, as opposed to this cost being categorized as a starting material in the SAI model. Also among the top three cost

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

Process step	Tool group ID	Total unit cost ($/module): All categories	Cumulative production cost	Cost categories ($/module): Equipment depreciation	Building depreciation	Operation and maintenance.	Direct labour	Indirect labour	Materials	Supplies	Overhead and non-production	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	

Table 6. Unit cost per step for 1kW module.

drivers is framing, which has a higher cost in the 1kW model as would be expected with a larger module size.

Cost driver sensitivities

This section focuses on two sensitivity analyses based on the 1kW model. The first analysis 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%. Fig. 6 compares 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, the normalized cost per watt as a function of production demand was also examined. The start rate was varied from the initial 40MW plan to a +250%. In this case, a 250% increase in starts only reduces the finished module cost per watt by 3.3%. This indicates that the 40MW supersized-module line design has been appropriately balanced and the individual equipment throughputs well matched, as illustrated in Fig. 7.

Installation

As shown in Tables 3 and 4, the production of a supersized module matches 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 reasonable to assume that there is greater room for improvement in the long-term manufacturing costs for the supersized module. In addition, current estimates indicate that savings of US$0.30 to US$0.55 per watt can be achieved through the installation of PV systems greater than 20MW [4]. 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.

Conclusion

The photovoltaics industry has gone through immense changes in recent years, and continues to rapidly develop in many ways. While previous papers in this series focused on process step improvements in cell manufacturing using COO and overall equipment efficiency (OEE) measures, this paper examined a method of leveraging innovation in module assembly. These improvements required a more holistic approach to financial analysis as represented by cost and resource modelling, which allowed us to examine differences in process routes, equipment sets and materials.

One such innovation is the development of a supersized 1kW PV module with integrated microinverters, which has been shown to have a nearly identical cost compared to conventional 245W modules. Once the differences in installation costs are factored in, the modelled advantage for 1kW modules in utility-scale solar farms, in excess of 20MW, is approximately US$0.30 to US$0.55/watt.

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