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Issues in thin film PV manufacturing cost reduction

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Abstract

Thin film PV technologies face a number of hurdles as they advance towards low-cost goals that are competitive with traditional sources of electricity. The US Department of Energy cost goal for thin films is about \$0.33/W_p, which is based on a module efficiency goal of about 15% and module manufacturing costs of about \$50/m^2. This paper investigates the issues associated with achieving the \$50/m^2 goal based on opportunities for manufacturing cost reductions. Key areas such as capital costs, deposition rates, layer thickness, materials costs, yields, substrates, and front and back end costs will be examined. Several prior studies support the potential of thin films to reach \$50/m^2. This paper will examine the necessary process research improvements needed in amorphous silicon, copper indium diselenide, cadmium telluride, and experimental thin film silicon PV technologies to reach this ambitious goal. One major conclusion is that materials costs must be reduced because they will dominate in mature technologies. Another is that module efficiency could be the overriding parameter if different thin films each optimize their manufacturing to a similar level.

Keywords: Photovoltaics; Thin films; Copper indium diselenide; Cadmium telluride; Amorphous silicon; Thin film silicon; Manufacturing costs

1. Introduction

PV module sales have been growing at an average 20% annually for a number of years. Worldwide module sales in 1998 are estimated to be about 150 MW_p, or about

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\$600M for modules and over a billion dollars for PV systems. However, these sales are for high-value applications that do not directly compete with commodity electricity available from utilities. For PV to become competitive for energy-significant uses, the cost of modules in $\$/W_p$ must fall substantially. Today, PV modules are sold at about $\$3$–$\$5/W_p$. PV systems are priced at about twice this figure. Various studies suggest that system prices near $\$3/W_p$ will be needed to open rooftop and other distributed markets in the United States. Indeed, system prices in the range of about $\$1$-$\$3/W_p$ for PV systems will be a great benefit in the competition for most energy-significant markets. International markets may be less price sensitive. PV sales will continue to grow for high-value markets while new markets will open up as PV module and system prices fall. This continuum of market growth has been an advantage of PV, because it allows substantial business cash flow well before energy significance is reached.

To improve module prices, progress is needed on three fronts: the performance of the modules (efficiency, or W/m^2), their direct manufacturing cost ($\$/m^2$), and increased volume production. It is direct manufacturing cost ($\$/m^2$) and some effects of volume production that are the focus of this paper.

The simple combination of cost per square meter divided by output per square meter yields the key parameter, $\$/W_p$ used as a measure of PV cost-effectiveness. Table 1 shows for thin films some likely future combinations of direct manufacturing cost and efficiency in order to indicate the multiple paths by which low module cost in $\$/W_p$ can be approached. The highest cost ($\$3.3/W_p$) represents about where we are today in commercial thin films. The lowest cost, which is a combination of 15% module efficiency with $\$50/m^2$ direct manufacturing cost, represents the US Department of Energy's long-term goal for thin film modules. It is about a tenfold reduction, which will require substantial progress. Actually, any combination of cost and performance below about $\$0.5/W_p$ would represent a good approximation of this low-cost goal. Despite its importance, the predominant emphasis of this paper will not be on PV module efficiency. That has been covered elsewhere [14]. This paper will be on direct module manufacturing cost, and efficiency will only be of concern in that it must be maintained or enhanced despite strategies that reduce manufacturing cost.

With progress toward low cost, new energy-significant markets should open up for PV. Examples of such markets are: residential and commercial rooftops, building facades, parking lot structures, distributed utility grid support, centralized PV for

Table 1
Direct manufacturing cost ($\$/m^2$) and efficiency determine module cost in $\$/W_p$

	$\$200/m^2$	$\$150/m^2$	$\$100/m^2$	$\$50/m^2$
6%	\$3.3	\$2.5	\$1.7	\$0.8
8%	\$2.5	\$1.9	\$1.35	\$0.63
10%	\$2	\$1.5	\$1	\$0.5
12%	\$1.7	\$1.25	\$0.83	\$0.42
15%	\$1.3	\$1	\$0.67	\$0.33

daytime loads, hybrid systems for decentralized rural electrification, hybrid systems (e.g., with gas-powered fuel cells or microturbines) for distributed power networks, and PV with storage (compressed air) or PV for hydrogen production. By contributing energy on this scale, PV can fulfill its promise to contribute to the betterment of the world's environment (e.g., better air quality and reduced carbon dioxide) while reducing high risks associated with international energy supply tensions resulting from more traditional sources.

2. Today's thin films PV modules

There is little solid information available about thin film manufacturing costs. Three thin films are commercially available, but only in small quantities (less than 10 MW_p/yr of the 150 MW_p/yr market). As such, details of cost status and cost reduction have been based on estimates and models [1–13]. Indeed, no thin film technology is nearly optimized for low cost. Therefore, projections are also needed. Despite this, quite a bit can be understood from previous studies and from some detailed information available from certain manufacturers. Table 2 summarizes the commercial status of three thin film technologies covered in this paper. Thin film silicon is also covered but is in early developmental stages at several companies, including AstroPower.

In addition to previous studies [1–13], the author has used a detailed cost model specifically created for NREL by First Solar (then Solar Cells Inc. of Toledo, OH) to enable a better prediction of manufacturing costs. In cooperation with NREL, First Solar, has provided specific manufacturing information. First Solar currently manufactures small volumes (under 1 MW_p) of CdTe modules. However, they have published plans to increase production to over 20 MW_p in the next several years. The manufacturing model details their projected manufacturing cost for a thin film manufacturing facility based on an existing CdTe sublimation process. The First Solar data is the basis for a baseline thin film manufacturing process that is used throughout this paper. Other technologies are compared using this baseline and data from the public domain, except for Si Film™. AstroPower has supplied the data for their experimental, high-rate, high-temperature process on ceramic substrates, which is

Table 2
Commercial status of thin films (1998)

Technology	Key companies	Status
Amorphous silicon	Solarex, United Solar, Canon, others	Commercial production under 10 MW at several plants
Cadmium telluride	First Solar, BP Solar, Matsushita	First Solar production under 1 MW, others lower
Copper indium diselenide	Siemens Solar Industries (SSI), Global Solar	Initial small quantity manufacture under 100 kW at SSI

being developed in their Thin Film Partnership subcontract with DOE/NREL (as are almost all of the other technologies examined in this paper).

Naturally, the First Solar model is far more representative of their own approach than it is of any other. In addition, the First Solar plant has not yet been scaled-up to the levels implicit in the model, which means that the numbers may underestimate real costs. In fact, since prior projections by some thin film PV companies have seriously underestimated costs, this concern is a valid one, even for this study. In the end, only each company scaling up its own technology can be certain of the real costs of thin film module manufacturing.

Projections concerning the non-first solar technologies (some of which are already commercial) are made merely as guides and in order to establish the potential of thin films in general. The only reason this is a valid activity at this time is that, today, no detailed cost numbers are available concerning any of the basic thin film manufacturing approaches. The model examined here is a substitute for such information. The purpose is to point out obvious, first-order conclusions.

3. The similarities among thin films

A number of substantial, cross-technology similarities exist among thin films. These similarities allow for simplifying the analysis of thin film module manufacturing costs. All thin films have the following similarities:

- A transparent front layer that also protects from the environment;
- A transparent and conductive top layer or grid that carries away current;
- A thin (1–4 μm), central sandwich of semiconductors that form one or more junctions to separate charge;
- A back contact that is often a metal film;
- A back sheet that protects from the environment and that could be supportive (rigid or flexible);
- Various intermediate processing steps: scribes and depositions to interconnect strip cells, annealing steps to activate or complete certain components; lamination to attach encapsulation; buss bar attachment to carry off power; isolation scribes at the borders; glass or other substrate handling, cleaning, and heating.

Even within each of these categories, there are similarities. For example, almost all thin films require transparent, conductive oxides for top contacts. These can be made or purchased pre-deposited by a vender on glass *superstrates* (substrates that end up on top of the module and thus must be transparent to sunlight). In addition, there is also almost always a metal deposition step for the back contact, which is frequently DC magnetron sputtering of a metal like aluminum. Finally, the heart of the module, the formation of the alternating n-type and p-type layers to form a junction, also has overriding similarities such as similar thicknesses, low materials costs when done well, and acceptable energy requirements for manufacture. The great similarities of structure and processing among the various thin films allows us to gain substantial insights into their potential costs and the barriers that they must overcome to reach those costs.

Given these similarities, where do the cost differences among the thin films come from? First, thin film modules differ in performance. Though this is important and sometimes crucial, it is not the subject of this paper. (But see Ref. [14].) In terms of *manufacturing cost* (*cost per unit area*), the most substantial factors are:

- Some cell structures are more complex than others (multijunction amorphous silicon versus single junction CIS and CdTe);
- Some key semiconductors are more difficult to make while maintaining performance (graded layers such as $Cu(In,Ga)(S,Se)_2$);
- Some processes are more capital intensive than others;
- Some processes waste expensive material feedstocks;
- Some processes require more environmental controls;
- Some processes have lower yields at adequate module performance;
- Some processes require greater feedback control and more cleaning and maintenance or result in more downtime;
- Some technologies require added annealing or chemical treatments to finish processing steps;
- Some module designs can be made with less expensive encapsulation steps/materials.

Given the similarities among thin films, *which essentially determine that all of them will have order-of-magnitude similarities in direct manufacturing costs*, these differences provide the most substantial causes for the costs to differ from some typical value among different materials, device, and processing options. For example, the baseline First Solar thin film technology uses only a few dollars of semiconductor material, requires very little capital cost, has a low-cost glass substrate, and sustains some added cost for encapsulation. In their model, these costs sum to a cost per square meter of less than $100 at the 20 MW/yr production level, and they will trend down towards some lower cost (perhaps about $50) as their technology is optimized for larger volumes (see below). Other technologies vary from this baseline because of the differences stated above. Table 3 gives a summary of the costs of the First Solar CdTe manufacturing process used as a baseline in this paper. The costs were taken from the First Solar-supplied model. The data can provide rough comparisons with other technologies.

4. Capital costs

Although initial capital costs for PV manufacturing can be large (from $0.5M–$5M for each megawatt of annual module production capacity, based on current costs and module efficiencies), the impact of these costs on module costs is greatly reduced by the length of the equipment depreciation period. For example, if a typical seven-year depreciation period is chosen, the annualized cost of the equipment is about one seventh of the initial cost. To find the cost per square meter, this is then spread over the total annual output of the plant. For example, if the capital equipment in a 10 MW plant costs $28M, the annualized cost is $4M (one seventh), and this is spread over

Table 3
Summary of the First Solar CdTe manufacturing model at 20 MW/yr

Component	Direct manufacturing cost ($/m^2)	Comments
Materials (all)	$48	Semiconductors only about $5; mostly encapsulation, substrate, and modularization
Capital (all)	$10	Semiconductors only about $5
Heat, electricity, water	$3	Energy payback < 3 months for energy added during manufacturing
Labor	$12	Plant labor and operations management
Maintenance of Equipment	$3	4% of initial capital cost
R&D	$4	Must maintain technical lead
Warranty	$5	3% of sales (very high for early high prices)
Rent and factory overhead	$5	Factory overhead at 1.5% sales
Total direct manufacturing	$90/m^2	Projected from existing technology, not yet optimized

10 MW of production (i.e., it costs \$0.4/W_p). Assuming that module efficiency is 8%, the capital cost per square meter would be \$32/m^2. This cost may be appropriate for certain of today's technologies; e.g., low-volume, in-line amorphous silicon plants. The baseline First Solar model is quite different. In their model, they require only about \$15M for a 20 MW plant, or \$0.11/W_p (\$9/m^2 at 8%). Of this amount, about half is for depositing the key semiconductors (CdS/CdTe). High-rate deposition is the key strength of the First Solar approach. Future capital costs for thin films should be reduced to about this level for thin films to compete successfully against conventional sources of commodity electricity.

The simplest comparisons of the capital costs of different PV technologies compare dollars per installed megawatt of annual capacity. However, this can be misleading, because two parameters are varying: cost per square meter and module wattage per square meter (efficiency). To get a true picture of *manufacturing costs*, analysis must be based on cost per square meter. Performance can be folded in later to get \$/W_p comparisons. It is possible to come to a better understanding of the direct manufacturing cost per square meter of different thin film approaches if one breaks process costs into components. *However, such insights depend on making simplifying assumptions that have substantial uncertainties. With this in mind, the estimates presented below must be viewed as merely heuristic assistance in comparing different thin film approaches*.

Two major categories of capital cost are: (1) the equipment used to make the active semiconductor layers; and (2) the equipment used to make the rest of the module (e.g., metal contacts, lamination, scribing, annealing). The most critical aspect of capital cost is the first: equipment to make the semiconductors. The rest of the capital costs will be very similar for all thin films and can be minimized separately (e.g., by doing away with a second piece of glass in encapsulation). For the purpose of this study, I will assume that the non-semiconductor capital cost is the same for all approaches and equals $5/m^2. This is the amount in the First Solar baseline. This assumption helps in the examination of differences in the semiconductor aspect of manufacturing.

Based on the baseline case and a seven-year depreciation, the total capital cost (C) can be parameterized by the *ratios of three properties to the baseline*. The three properties are: the semiconductor deposition rates (R), the semiconductor thicknesses (T), and some measure of the relative complexity of the equipment (E). This latter is needed because equipment costs vary per deposition zone area. Vacuum equipment is more expensive than a simple annealing oven. For an in-line process, this parameter can be calculated by dividing the equipment cost by the area of the deposition zone. For a batch process, it is the equipment cost divided by the deposition zone area and then divided by the number of plates being simultaneously processed. This points out that batch processing has an inherent advantage over in-line processing, *if it can be done while maintaining module performance and production throughput.*

Based on these assumptions, and using the baseline data from First Solar, the formula for *semiconductor deposition* capital cost (\$/m^2) is

$$C = 80\text{W m}^{-2} \times (\$8\text{M} + (E \times T/R) \times \$7\text{M})/(7 \times 18\text{MW})$$
$$= 0.63 \times (\$8 + (E \times T/R) \times \$7)\$/\text{m}^2.$$

The figure of 80 Wm^{-2} comes from the assumed baseline efficiency; the 7 comes from the depreciation period, and the 18 MW comes from the plant's designed throughput. For the semiconductor deposition alone, this reduces to semiconductor equipment (SE) costs of:

$$\text{SE} = (E \times T/R) \times \$4.4.$$

Recall that these parameters (E, T, R) are ratios to the baseline. If all the ratios are 1 (i.e., we are using the baseline), C reduces to about \$9.4/m^2. SE reduces to \$4.4/m^2. These are the First Solar values of total capital equipment cost and semiconductor capital equipment cost; and the difference is the 'front and back end' capital equipment cost. An interesting comparative number is the ratio of capital cost for just the semiconductor layers (compared against the First Solar baseline), which can be defined as $\text{SR} = E \times T/R$. This figure shows the relative contribution of that equipment as compared to the baseline value of 1. Most ratios are higher than one, with a few exceptions.

Table 4 gives the set of assumptions used in comparing various approaches to thin film manufacturing for amorphous silicon, cadmium telluride, copper indium diselenide, and Si-Film$^{\text{TM}}$. I have chosen these because I was able to make reasonable estimates of the parameters. One process not examined is CIGS fabrication using a two-step sputtering and selenization process. Although this is a mainstream process in CIGS, the batch process parameters are difficult to estimate without company input. Also, I have assumed that the semiconductor layers already include secondary, very thin layers such as buffers, windows, heterojunction partners; and these are all done by the selected process and are included in its thickness. This assumption is clearly an oversimplification but is probably not a major source of error.

Table 4
Assumptions used for semiconductor capital cost estimates

Process (status)	Deposition rate(μm/min)	Equipment cost per deposition zone area (M/m^2)	Semiconductor thickness (μm)	Companies	Comments
Sublimation of CdTe (commercial)	6	8	4	First Solar	Fast in-line
Electrodeposition CdTe (pilot line)	0.006	0.005	2	BP Solar	Slow batch
In-line a-Si glow discharge (commercial)	0.02	0.7	1	Solarex, USSC	Slow in-line
Box carrier (Batch) a-Si (commercial)	0.02	0.1	1	EPV	Slow batch
High-rate a-Si (experimental)	0.1	1.8	1		Moderate in-line
High-rate CIGS evaporation (experimental)	0.3	5	2	Global Solar	Moderate in-line
Silicon-film™ (experimental)	500	30	50	AstroPower	Fast in-line

Table 5 is a compilation of various SE and SR values for different semiconductor options. Recall, however, that these are very sensitive to assumptions. *This is especially true for the unknown value of the equipment ratio* (*E*), *which could vary over a large range*. Unlike rate and thickness, *E* can only be estimated. For example, a rough estimate of the baseline value would be: $7M/0.9 m^2 = $8 M/$m^2$. For in-line glow discharge, a rough estimate would be: $7M/10 m^2 = $0.7M/$m^2$. Then the *ratio*, *E*, for in-line glow discharge would be 0.09 (as in Table 5). *Since these are only rough estimates, the uncertainties in Table 5 are quite large*. Table 5 should only be used to give a sense of magnitude differences between semiconductor deposition processes.

The last column in Table 5 gives a rough approximation of the capital cost of a 100 MW plant for each semiconductor deposition process (it does not include back end costs). Note that the uncertainty of this number is very large and should only be used to indicate trends. This is because the equipment ratio (*E*) is quite uncertain (as explained above). The value of the semiconductor capital equipment cost for a 100 MW plant shown in Table 5 is *calculated* from the other assumptions by multiplying the baseline cost for the First Solar approach ($31 million) by the ratio SR, as defined above. Thus these are derived values, and are not independently verified. Again, they are estimates useful for understanding trends.

In addition to the previously mentioned uncertainties, other caveats are necessary. For example, the above comparisons cannot be made assuming the same module efficiency. In fact, it is because efficiency does vary substantially (from about 5% on the low end, to almost 12% on the high end) that companies may make decisions based on this factor rather than manufacturing cost, especially for initial manufacturing plants. At costs of $\$1/W_p$, a change of about 1% in module efficiency is worth about $\$9/m^2$ in cost (although this factor changes at different cost/performance levels), and about double that at the system level.

Similarly, manufacturability, uptime, and yield vary for different processes, and they can be overwhelmingly critical in making choices among competing technologies.

In the future, most processes will be optimized for higher rates than those given in Table 4. In addition, most absorber layer thicknesses will be 1 μm or less, since that is all that is needed to absorb over 90% of the incident sunlight. Today's greater thicknesses reflect technical compromises needed to achieve high-yield in early manufacturing. Clearly, there are options for improving most of the approaches given in Table 5, even in-line GD (through higher rates) and CIGS evaporation (through higher rates, thinner layers).

An important aspect of capital cost is that it can be a very high initial hurdle for new manufacturing. Not only are the up-front costs high in terms of financing a new factory, they have serious impact on the first few years of production. Like any form of capacity costs, if the factory does not operate at full capacity, capital costs are multiplied. In other words, if module production yields are lower than expected and downtime stretches out production volumes, capital costs can balloon. Low initial capital costs have substantial value.

5. Maintenance costs

Many industries estimate maintenance costs using a fixed percentage (about 4%) of initial capital cost as the expected annual maintenance cost of equipment. This may appear small, but since it is not reduced by dividing by a depreciation period, it is actually quite similar to the amortized capital cost. Using the 4% factor on the processes in Table 5 yields Table 6. This increases the impact of high capital costs and emphasizes the difficulty of some approaches.

Since the estimates given in Tables 5 and 6 have a great deal of uncertainty, especially in the E value, we must take these estimates with substantial caution. However, based on very large observable differences, some hypotheses are:

1. Several processes appear to be inexpensive enough to consider for very large scale manufacturing. Until PV module costs fall below \$1/W, the differences among these low-cost processes will not be drivers. However, below this level, even small capital cost differences will be magnified and will matter in final decisions.
2. Only CIGS evaporation and in-line glow-discharge of amorphous silicon appear to be too expensive to be used for large-scale manufacturing. These should be greatly improved or replaced by cheaper processes before going to the next level of manufacturing. In both cases, other processes (higher rate a-Si or batch processing; sputtering and selenization of CIGS) exist or are being developed.

Table 5
Estimated capital costs for various thin film semiconductor deposition processes

Process (status)	Rate ratio (R)	Equipment ratio (E)	Thickness ratio (T)	SE ($\$/m^2$)	SR	Companies	Initial cost ($M) for 100 MW @ 10% efficiency
Sublimation of CdTe (com mercial)	1	1	1	$4.4	1	First Solar	$31M
Electrodeposition CdTe (pilot line)	0.001	0.006	0.5	$1.8	0.3	BP Solar	$10M*
In-Line a-Si GD (commercial)	0.0033	0.09	0.25	$30	6.8	Solarex, USSC	$210M
Box Carrier (Batch) a-Si (commercial)	0.0033	0.012	0.25	$4	0.9	EPV	$28M
High-Rate a-Si (experimental)	0.017	0.22	0.25	$14	3.2		$99M
High-Rate CIGS Evaporation (experimental)	0.05	0.625	0.5	$26	6	Global solar	$186M
Silicon-Film™ (experimental)	83	3.63	12.5	$2.4	0.55	AstroPower	$16M

*In this case, the secondary processing steps may contribute almost as much as the batch electrodeposition process (which is very small), raising total capital costs for the semiconductor deposition by 50% or more.

Table 6
Maintenance costs based on Table 5 at 4% of initial capital investment for semiconductor deposition (28% of annual capital cost/m^2, assuming 7 yr depreciation)

Process (status)	Capital Cost (\$/m^2)	Maintenance \$/m^2 (28% of capital cost)	Total (*capital plus maintenance*) (\$/m^2)	Companies
Sublimation of CdTe (commercial)	\$4.4	\$1.2	\$5.6	First solar
Electrodeposition CdTe (pilot line)	\$2	\$0.6	\$2.5	BP Solar
In-Line a-Si GD (commercial)	\$30	\$8	\$38	Solarex, USSC
Box carrier (Batch) a-Si (commercial)	\$4	\$1.1	\$5.1	EPV
High-rate a-Si (experimental)	\$14	\$3.9	\$18	
High-rate CIGS evaporation (experimental)	\$26	\$7	\$33	Global Solar
Silicon-Film™ (experimental)	\$2.4	\$0.67	\$3.1	AstroPower

3. Since so much depends on E, in other words, since the complexity of equipment (and therefore, its cost) can vary so substantially, simpler or faster processes, or batch processes in which a large number of substrates can be processed, should be seriously considered if module performance and yield can be maintained.

Note that the above estimates are without the contribution of non-semiconductor depositions. However, these are very similar among the different options, usually consisting of scribing, laminating, and contact sputtering. They contribute about another \$5/m^2 in capital and maintenance costs (and these are already included in Table 3 for the first solar case).

6. Material costs

The First Solar baseline for material costs is about \$48/m^2, which is a very large cost, especially in comparison to the other component costs listed in Table 3. An important point about these costs is that only about \$5/m^2 is for active materials (semiconductors and contacts). The rest is mostly encapsulation, substrates, and modularization (e.g., mounts and j boxes). Thus about \$43/m^2 of thin film module costs will be almost the same across technologies. Only the remainder may vary, depending on the materials utilization rates of different processes, the cost of specific materials, and the thicknesses of different devices. Table 7 shows a summary of the cost of active materials in the First Solar baseline.

Table 7
Cost of active materials in first solar baseline

Material	Amount (g) @ 75% utilization and 4 μm thickness	Cost per kg	Cost/m^2
Cd	13 g	$90	$1.2
Te	13 g	$270	$3.5
S, Al, etc.	2 g	$100	$0.2

Active material cost is dominated by one component, the tellurium, which is the most costly feedstock. Notice also that these costs are for 4 μm CdTe films. In the future, these numbers will be reduced as CdTe thickness approaches 1 μm.

The amounts for other technologies are fairly similar. Table 8 gives some estimates for these other technologies, based on reasonable assumptions. *Only the most costly element is given*, and this is usually the one that dominates such costs. If a technology has more than one costly element that is used poorly, it will have problems. None of the ones examined have this problem.

Note that these costs are fairly reasonable for all approaches with the possible exception of germane for amorphous silicon multijunctions made in an in-line system. Substantial R&D is being done to improve germane utilization in order to cut these costs for in-line systems; they are already low for batch processing.

Of the non-semiconductor costs (about $43/m^2 in the baseline), substrates are one of the most important and best understood. Table 9 gives a list of common substrates and their approximate costs. One key question is whether to make or buy tin oxide-coated glass for those technologies (CdTe and a-Si) that have this option. It is quite likely that the price of tin oxide-coated glass will drop substantially as volumes increase, since the *cost* to the glass maker for large pieces is only about $4/m^2 (with transportation). Rough estimates of future costs are also given in the table.

The costs in Table 9 are all similar with the possible exceptions of ceramic and polyimide. However, choices are also made based on the thermal stability needed for high-temperature processes, or on product design, such as the need for flexibility or light weight. Some substrates require extra processing (e.g., conductive stainless steel has extra handling/processing steps as compared to nonconductive glass) and other minor differences (breakage, rolls versus stacks, packaging, etc.). These can alter costs. In the future, new glass superstrates may be chosen if they maximize transmission while maintaining low cost (e.g., borosilicate glass made on a float line); and new ceramic or high-temperature plastic substrates may become available.

7. Warranty cost

A 3% warranty cost represents a reasonable accounting practice for initial manufacturing. One would expect it to fall to much lower levels as a technology matures (and there are fewer returns). Indeed, as sales price falls, this cost falls on a per square

Table 8
Estimated semiconductor materials costs for the most expensive material

Process (status)	Material	Utilization rate	Cost ($/kg)	Thickness (μm)	Amount (g) per μm-m^2	Approximate cost ($/$m^2$)
Sublimation of CdTe (commercial)	Te	75%	275	4	3.2	$3.5
Electrodeposition CdTe (pilot line)	Te	95%	275	1.5	3.2	$1.3
In-line a-Si GD (commercial)	Ge	10%	3000	1	0.4	$12
Box carrier (Batch) a-Si (commercial)	Ge	25%	3000	1	0.4	$5
High-rate a-Si (experimental)	Ge	10%	3000	1	0.4	$12
High-rate CIGS evaporation (experimental)	In	50%	400	2	2	$3
Silicon-film™ (experimental)	Si	75%	20	50	2.3	$3

Table 9
Substrate costs ($\$/m^2$)

Material	Now	Projection based on large volume	Comments
Float glass	$4	$3	Requires making own TCO or metal contact
Float glass/tin oxide	$10	$4	Baseline for First Solar and Solarex
Stainless steel foil	$4	$3	USSC
Polyimide roll	$10	$5	Global Solar and others (temperature limited)
Ceramic	$9	$5	Device-design driven, AstroPower

meter basis. At a sales price of $3.5/W, at 3%, it costs about $0.1/W, or $\$10/m^2$. In the future, at a sales price of $1/W, 3% would be $0.03/W (or less), or $\$3/m^2$. It will be more or less the same for all successful technologies and should fall as low as 1% for mature PV.

8. R&D cost

Like other semiconductor technologies, PV is scientifically driven. For a company to maintain its profitability, it will have to be a technical leader. Staying ahead in PV device design and module manufacturing requires this technical leadership. The baseline estimate of R&D cost for First Solar is $\$4/m^2$. This is about $1M for a 20 MW plant. It is actually similar to the cost of labor for the manufacturing plant. However, in the future, as volumes increase, R&D costs will not rise at the same rate and should become a manageable part of the total cost. For example, if R&D costs maintained the same *percentage* of module price in dollars per watt, at a price of $1/W R&D cost would be an affordable $\$1–\$2/m^2$. Clearly, as volumes increase, R&D costs will not rise at the same pace.

9. Smaller cost components

Other costs that play a much smaller role include: utilities, labor, rent, and factory overhead. However, these costs do not vary much by technology. They vary more by plant capacity. They are given for the First Solar baseline in Table 3. One could imagine them varying by a factor of 50% in either direction. That would give a range of costs of from $10 to $\$26/m^2$. As the technologies mature, automation is improved, and volumes go up, they are very likely to fall substantially.

10. Future progress in manufacturing cost reduction

Three major avenues will result in the biggest cost savings: continued process and device optimization, minimization of materials costs for encapsulation/modularization,

Table 10
Reasonable, long-term goals for thin film manufacturing

Component	Direct manufacturing cost ($/m^2)	Comments
Materials (all)	$28	Volume purchases reduce all costs, especially substrates; lower-cost encapsulation
Capital (all)	$5	All process can be optimized, rates increased, layers thinner
Heat, electricity, water	$2	Larger volumes, thinner layers
Labor	$6	Full automation
Maintenance of equipment	$2	4% of lower capital cost
R&D	$1	Rising sales, lower prices
Warranty	$1	Lower prices, greater product reliability
Rent and factory overhead	$5	Larger volumes
Total direct manufacturing	$50	Optimization, R&D, and higher volumes

and volume purchases and manufacturing. Of these, R&D has the greater impact on the first two costs. However, large volume production will be essential to leverage the last few dollars out of module costs, and will have an even greater impact on the *sale price* of modules. This is because sale price depends strongly on marketing and distribution costs and other indirect costs, which are highly dependent on volumes. R&D and volume production work together to reduce costs/prices, but their specific effects are quite different.

The value of R&D includes:

- Improved performance (toward 15% modules producing 150 W/m^2);
- Higher deposition rates;
- Thinner layers;
- Better materials use;
- Lower temperatures (less energy input, simpler processes);
- Simpler processes that cost less initially and to maintain, and reduce downtime;
- Higher yields;
- Improved scribing, lamination, encapsulation, and modularization options;
- New transparent conductive oxide options;
- Innovative substrates.

The value of increased volume manufacturing include:

- Cheaper volume purchases of materials (unless availability shrinks);
- Lower percentage contribution from overheads on production, management, and sales;
- Some decrease in unit capital cost for larger equipment (and larger substrates);
- Less cost for larger sized modules (j boxes, frames or struts, edges);
- Better optimization of manufacturing product flows;
- Better make/buy choices (e.g., TCO/glass);

- Lower warranty cost as price drops;
- Increased automation.

Table 10 gives a summary of reasonable goals for cost reductions by category based on R&D and volume production improvements.

Of these various cost reductions, perhaps the most difficult will be materials cost reductions. However, today's PV R&D has focused on module efficiency and semiconductor process development. In the future, increased resources will be devoted to improving encapsulation methods and other similar processes and their costs. Simpler designs (e.g., eliminating either front or back glass; substituting other materials for current EVA pottants; and avoiding the costs of lamination) should provide avenues for improvement.

11. Other thin films

There are other thin films being developed in addition to those examined here. More will be added in the future. The others (especially dye-sensitized cells) are not included because data about scale-up is relatively harder to find. But, in the broad sense, the general conclusions of this paper also apply to these and any new thin films in the future. Their costs will be similar to the costs discussed here, and variations will depend on process and design specifics.

12. Summary and conclusions

The availability of a detailed First Solar model provides a basis for a substantially greater understanding of thin film PV manufacturing costs. Previous studies have had to depend exclusively upon projections. Despite this limitation, those prior studies yielded very similar results to this one: *the* $50/m^2 *goal for the direct manufacturing cost of thin film PV is reasonable and could be achievable.*

In addition to this fundamental observation, a number of other key findings can be made:

- Existing capital and maintenance costs for some semiconductor processes are quite high (over $50/m^2 by themselves), leading to a substantial barrier (1) to initial investment, (2) to the success of early manufacturing, due to high start-up costs from running at below-capacity first and second year volumes, and (3) to poor product cost-competitiveness.
- The development of reasonable-cost semiconductor manufacturing processes is essential to achieving a low cost technology.
- Even the highest cost approaches to making thin films have technical avenues for substantial cost reductions, and this study is too limited by uncertainties to eliminate any of them from consideration.
- Once a viable semiconductor processing approach is achieved, materials costs dominate total cost.

- Semiconductor costs can be a small portion of materials costs if processes are optimized for reasonable (over 50%) feedstock utilization rates and/or for thin layers.
- If semiconductor costs are optimized, costs for other materials (substrates, encapsulants, pottants, mounts, electrical connections) dominate material costs. These costs are large but can be reduced by redesigning modules to minimize them (e..g, replacing expensive materials with cheaper ones), making larger modules (so that one-of-a-kind items like j-boxes are minimized per unit area), and by volume purchases and better make/buy decisions.
- Special items such as warranty and R&D costs per square meter will drop as volumes increase and prices decrease.
- Other, minor costs exist and can be individually optimized.
- Process improvements must be weighed against any potential efficiency or yield losses, since these will be especially important at low module costs and at the PV system level.
- Although not covered here, it is obvious that module efficiency could be the most critical distinguishing parameter among the various thin films as module costs become more similar.

It is interesting to speculate about the ultimate cost of thin films. It could be lower than the $\$50/m^2$ goal, since achieving that goal can be visualized with current knowledge. Since thin film PV is a scientifically based technology that will eventually be produced in ultra-large volumes, it should ultimately cost the sum total of the materials costs of its elemental constituents processed and transported with the greatest efficiencies. This cost could be lower than $\$50/m^2$. Efficiencies will also improve beyond the 15% performance goal (but that is not the subject of this paper). Thus the module cost per watt goal of $\$0.33/W_p$ could also be surpassed as the stimulus of positive cash flow allows the thin film PV technologies to mature and blossom during the 21st century.

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