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Toward Low Cost CdTe PV

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"Toward Low Cost CdTe PV"

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Introduction

The development of cadmium telluride (CdTe) photovoltaics has reached a stage where it can be considered a leading candidate for cost-competitive PV electricity generation. Achievements such as high cell efficiencies, good module efficiencies, and the existence of pilot production facilities have placed CdTe in the first rank of thin films alongside $CuInSe_2$. In addition, CdTe technology has an important advantage in that a variety of low cost methods can be used to make quality layers. The low capital costs of these processes make it relatively easy to begin scaling up CdTe manufacturing. We may expect that a number of investors will accept the challenge of beginning serious CdTe manufacture in the near term. Needless to say, they will face issues impeding their success. These issues will be the focus of this paper.

Achievements of CdTe Technology

Before addressing the issues that will form the context for future CdTe progress, we should consider the achievements that have brought CdTe to its current state of development. The importance of these achievements is that they give us confidence that CdTe has the potential to reach truly cost-competitive electricity generation.

Achievements can be categorized in terms of efficiencies, costs, and reliability. These criteria define the technical basis for success in any PV option, because they define the output cost of PV electricity. (See Ref. 1 for PV costing based on module efficiency, system cost, and system reliability.) Table 1 shows electricity cost projections based on Ref. 1. Note that Table 1 assumes low costs for non-module system costs—so-called balance-of-system or BOS costs. See the notes of Table 1 for specifics on these assumptions. The future of CdTe PV could very well fall in the envelope provided by Table 1.

Table 1. CdTe PV System Electricity Costs (Fixed flat plates, average U.S. locations)

Module Efficiency	Module Cost ($/m^2)	Implied Electricity Cost[1,2] (¢/kWh)	
		Near term	Mature
5%	$200	50	41
7%	$200	36	29
7%	$150	31	24
8%	$150	27	21
8%	$100	22	16
10%	$100	18	13
10%	$ 75	16	11
12%	$100	15.5	11
12%	$ 75	14	9
12%	$ 50	12	8
14%	$100	14	10
14%	$ 75	12	8
14%	$ 50	11	7
15%	$ 75	12	8
15%	$ 50	10	6.5
15%	$ 35	9.5	6

[1]Cost calculations based on Reference 1, except that:

a. indirect rate of 25% (not 50%)

b. average U.S. sunlight (1800 kWh/m^2-yr) instead of desert conditions (2400 kWh/m^2-yr)

[2]Area-related balance-of-system (BOS) costs assumed for near term of $100/m^2 and mature of $50/m^2. Power-related BOS costs of $300/kW near term; $150/kW, mature.

Efficiency Achievements

The efficiency achievements of CdTe during the recent past (1991-1992) have been exceptional. Figure 1 shows the history of CdTe laboratory-cell efficiencies. Note that during 1991 the record efficiency was extended four times. Another important aspect of CdTe cell efficiencies is the ease with which they are attained. This is exemplified by Table 2, which shows the multiplicity of groups that have reached 10% efficient cells. Also note that many groups have reached efficiencies in excess of 12%.

Progress in CdTe efficiencies extend beyond the laboratory scale. Table 3 shows the achievement of efficiencies for larger areas, i.e., those of one- and four-square-feet. These trail those for a competing thin film ($CuInSe_2$), which has reached 11.1% on one square-foot and 9.7% on four square-feet, which are also given in Table 3. However, the distinction is not fundamental: (1) The gap is getting smaller, rapidly and (2) the technical potential of CdTe modules is as good or better than $CuInSe_2$.

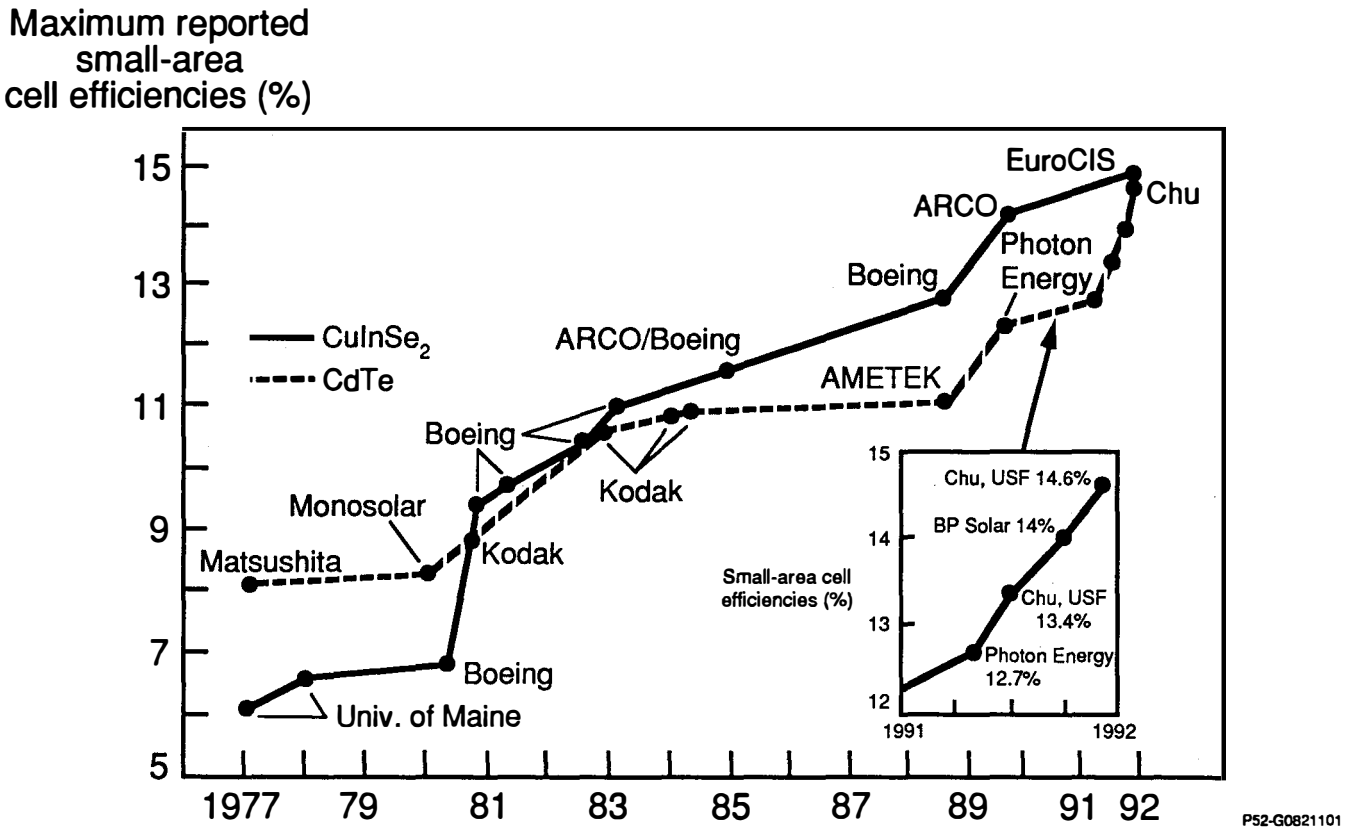

Figure 1. Polycrystalline Thin-Film Cell Efficiencies (Reported; Active Area)

Table 2. Performance of Thin Film CdTe Solar Cells

Type	Process	Area (cm^2)	Eff. (%)	J_{sc} (mA/cm^2)	V_{oc} (mV)	FF	Group
Glass/TO/CdS/CdTe	CSS	1.08	14.6*	24.4	850	0.704	Chu, USF
Glass/TO/CdS/CdTe	Electrodeposition	0.02	14.2	23.5	819	0.74	BP Solar
Glass/TO/CdS/CdTe	ALE	0.12	14.0	23.8	804	0.73	Microchemistry
Glass/TO/CdS/CdTe	CSS	1.08	13.6*	23.12	846	0.696	Chu, USF
Glass/ITO/CdS/CdTe	Electrodeposition	0.02	13.1	27.9	720	0.65	Univ. of Queensland
Glass/TO/CdS/CdTe	Spray	0.30	12.7*	26.21	799	0.605	Photon Energy
Glass/TO/CdS/CdTe	Electrodeposition	1.0	12.7	23.8	807	0.68	BP Solar
Glass/TO/CdS/CdTe	CSS	1.125	12.6*	20.16	836	0.746	Chu, USF
Glass/CdZn/CdTe	Screen Printing	0.3	12.5	23.6	870	0.61	KAIST
Glass/CdS/CdTe	Screen Printing	1.02	11.3	21.1	797	0.67	Matsushita
Glass/ITO/CdS/CdTe/ZnTe	Electrodeposition	1.068	11.2*	22.36	767	0.696	AMETEK
Glass/TO/CdS/CdTe	Spray	0.296	11.2*	23.08	838	0.578	Photon Energy
Glass/ITO/CdS/CdTe	Evaporation	0.191	11.0*	20.09	789	0.692	IEC
Glass/ITO/TO/CdS/CdTe	CSS	0.38	11.0	22.8	750	0.65	Battelle Europe
Glass/TO/CdS/CdTe	MOCVD	0.08	10.9*	22.10	745	0.66	Georgia Tech
Glass/TO/CdS/CdTe/HgTe	CSS	1.112	10.6*	21.62	745	0.658	Chu, SMU
Glass/ITO/CdS/CdHgTe	Electrodeposition	1.48	10.6	27.0	620	0.63	ISET/Monosolar
Glass/IO/CdS/CdTe	CSVT	0.1	10.5	17.0	750	0.62	Kodak (75 mW/cm^2)
Glass/TO/CdTe	CSVT	4.0	10.5	28.1	663	0.56	ARCO Solar
Glass/TO/CdS/CdTe	MOCVD	1.34	9.9	19.58	812	0.62	Chu, USF

Note: Active area = total area for superstrate cells, IO = indium oxide, ITO = indium tin oxide, TO = tin oxide
*NREL Measurements

Table 3. Performance of Polycrystalline Thin Film Photovoltaic Modules

Group	Material	Area (cm^2)	Eff. (%)	Power (W)
Siemens Solar	$CuInSe_2$	3883	9.7*	37.8*
AstroPower	Si-Films**	3984	9.5	34.2
Photon Energy	CdTe	3323	6.4*	21.3*
Siemens Solar	$CuInSe_2$	938	11.1*	10.4*
Matsushita Battery	CdTe	1200	8.1	9.7
BP Solar	CdTe	706	10.1	7.1
Photon Energy	CdTe	832	8.1*	6.8*

*NREL Measurements
**Non-monolithic integration

Cost Achievements

Unlike efficiencies, PV module costs cannot be measured independently. Thus, we must content ourselves with gross evaluations of costs based on categories such as capital costs, material costs, utility costs, and labor costs. Various estimates exist of PV costs (Refs. 2-7). Perhaps the most important conclusions to be drawn from these studies are the following:

1. Thin films have cost advantages based on reduced materials, handling (large modules instead of single cells), and utilities costs (energy inputs).

2. All thin films have relatively similar materials costs if feedstock materials are used well, i.e., if utilization rates are reasonable (above about 70%). When this is the case, materials costs are actually dominated by front and back covers, e.g., by glass, metal, and plastics. Ultimately, materials costs should be below $\$25/m^2$ for modules to meet low cost goals.

3. Capital costs are not dominant, but they are important for a variety of reasons:

   a. They define up-front capital risks; i.e., it may take anywhere from \$0.5-5 million to pay for each MW of production capacity.

   b. High capital costs can mean more risk because technical failures are more costly (replacing a segment of the line) and can also imply lower yield and more downtime and maintenance.

   c. Ultimately, to meet truly low costs (near $\$50/m^2$), low-cost, high-throughput processes are critical. Capital costs near $\$10/m^2$ will be appropriate.

4. Perhaps the most important conclusion about cost is that module efficiencies are the most powerful determinant of final thin film costs. This is because all thin films should ultimately be made for $\$50$-$\$100/m^2$. Given this fact, the practical efficiency of different thin films (e.g., $CuInSe_2$, a-Si, CdTe) becomes the crucial determinant of their competitive potential.

The CdTe technology has a number of advantages relative to these factors. Table 2 showed the variety of processes by which 10% CdTe cells have been made. The implications of the table are: (1) CdTe can be made by a greater variety of methods than any thin film absorber for solar cells, and (2) several relatively inexpensive methods (including nonvacuum methods) exist for making high-quality CdTe. This implies that it will be easier for investors to start CdTe manufacturing facilities (i.e., with less capital risk), and individual companies should be able to choose unique CdTe deposition techniques and establish advantageous proprietary positions.

Another advantage of CdTe is its potential efficiency. For example, amorphous silicon thin films appear to have a relatively limited efficiency potential. This is partially because of the known light-induced degradation, but also because of the poor electronic quality of a-Si materials. The comparison with $CuInSe_2$ is less obvious. CdTe has a band gap closer to the theoretically optimum for simple PV devices (single-junction cells). Thus, it has a somewhat higher efficiency potential (about 10% higher) than $CuInSe_2$. Both should be able to make 15% efficiency for manufactured modules. Because CdTe cells have higher voltages, they will retain their efficiencies better at operating temperatures.

Reliability Achievements

The reliability of CdTe devices is as yet a cause for concern. Until recently, few CdTe modules were available for testing and even fewer were available for independent (nonproducer) testing. Thus, most data are either from NREL testing of one producer (Photon Energy) or from reports by Matsushita and BP Solar.

The context for CdTe reliability tests is based on the following:

1. CdTe cells and modules are known to degrade if they are well encapsulated.

2. Some CdTe contacts (e.g., gold and gold/copper) are known to be unstable.

3. It is unknown whether CdTe-based devices are intrinsically stable. This is because it is hard to deconvolute intrinsic device degradations from those caused by environmental exposure, e.g., by water vapor.

4. Evidence exists that at least some CdTe modules are stable over extended periods (up to 3 years).

Table 4 exhibits the corporations that are presently developing CdTe PV.

Table 4. CdTe Corporate Participants

Company	Country	Status
Photon Energy	US	Prototype production, at 4 ft^2
BP Solar	UK	10% 1 ft^2 modules
Matsushita	Japan	8% 1 ft^2 modules; cells in calculators
Solar Cells Inc.	US	Experimental module production
Martin Marietta	US	Startup
Microchemistry	Finland	Cell technology

Strategies for the Future

Two sets of issues are important for the future of CdTe: ongoing technical issues and those associated with initial product entry.

The key ongoing technical issues are:

1. Reliability
2. Manufacturability
3. Efficiency

The key issues associated with new product entry are:

1. Perceived cadmium risks
2. Skepticism of new, unproven module reliability
3. Lower-efficiency, but lower-cost, modules

The technical issues are interrelated. Laboratory work must continue in order to maximize cell efficiencies. The theoretical efficiency of CdTe cells is above 27%. Practical cell efficiencies should be 18%-20%. Such efficiencies would imply modules of 15%-17%.

However, translating cell efficiencies into commercial module efficiencies requires numerous steps that relate to manufacturability. The first level of manufacturability is large-area fabrication—achieving uniformity over areas of 10^3-10^5 cm^2. But it is not enough to make one-of-a-kind, large area modules. Products must be made in huge numbers, which means that manufacturing yields must be high and equipment downtimes must be low. These are challenges well beyond the laboratory level. It is important to acknowledge (at least for planning purposes) that the transition to true manufacturing will take several years and an order-of-magnitude more investment. Murphy's Law ("anything that can go wrong, will") is likely to hold, and numerous problems that are as yet unknown will cause delays and unexpected expenses.

Fortunately, a number of processes and device designs exist. No new process for any of the layers must be developed (although several probably will be). But some critical decisions will be made, such as whether to use solution growth to make thin CdS or to use some other method. Thin layers, reproducibility, area uniformity, and waste handling will all require attention as areas and volumes increase.

Reliability issues will be intimately related to manufacturing issues. This is because the quality and reproducibility of optimal encapsulation will need time to evolve. No potential issue is of greater significance than the need to develop the best encapsulation of CdTe modules. In parallel, we may expect that reliability issues internal to modules may arise; i.e., some junction instability, contact instability, or design-related issues such as scribing may cause new problems. Until the CdTe community can segregate degradation mechanisms into different technical categories, we will be at risk of enormous and costly delays if these issues arise in CdTe products.

CdTe product introduction will raise a new set of issues. The main one may be the perceived risks of cadmium. Technical issues of cadmium are already being addressed; i.e., we are able to manufacture CdTe modules, use them, and dispose of or recycle them and their associated wastes (Ref. 8). However, the consumer may or may not react to Cd-based PV. The relatively small quantity of cadmium in CdTe modules will probably obviate a "chemophobic" reaction, as will the perceived environmental value of PV (versus conventional energy). But non-CdTe PV manufacturers as well as those advocating other (non-PV) energy sources are likely to pressure CdTe-PV on this issue, as will fringe environmental groups. Others will look more closely and note that CdTe modules are nearly risk-free and replace energy production that has far greater environmental impact. No resolution of this issue is to be expected any time soon.

Clearly, until module reliability tests and product warranties are convincing, consumers will mistrust CdTe products. This issue will take patience to resolve, as well as technical progress needed to solve encapsulation problems. Finally, CdTe products during this century are likely to be less efficient than existing silicon modules. We may expect products to be 5%-10% efficient in the 1990s. Thus, consumers will be faced with the issue of buying more modules to meet the same power needs. This will mean that array sizes will increase, with implications for siting and for area-related BOS costs. Lower efficiency affects the value of CdTe PV modules, implying that the costs (and prices) of these modules ($\$/W_p$) must be significantly lower than silicon module prices to be marketable. Fortunately, this is expected to be the case (but it will reduce CdTe profit margins).

One of the attractions of CdTe technology is its potential for significantly lower module costs. This should imply the development of significant new markets. In other words, CdTe product issues will extend beyond those associated with competing with efficient silicon modules. As CdTe module costs drop below \$2/W and \$1/W, major new markets will develop. These will require substantial technical product development and infrastructural support (e.g., distribution and recycling infrastructures). For any large-scale markets, including utilities or distributed applications, truly low cost BOS components will

have to be manufactured. The potential of low cost CdTe to catalyze the development of large-scale, worldwide PV markets during the 1995-2005 period will depend on parallel development in systems and applications.

Conclusions

The CdTe PV technology may be regarded as one of the strongest candidates for low cost PV. Among the thin films, only $CuInSe_2$ seems to have equal promise. Most issues are no longer at the laboratory cell level, with the caveat that ongoing progress in cell efficiencies is needed to reach the technology's ultimate promise. Secondly, some technical reliability must be sorted out, especially an understanding of possibly different degradation mechanisms.

But the technical emphasis has shifted to manufacturing issues. Laboratory successes must be translated into module and product successes. The relatively lower cost of CdTe manufacturing equipment, and the implied reduced capital risks, should help the CdTe technology make this important transition successfully.

References

1. National PV Program, May 1987, *Five Year Research Plan, Photovoltaics: USA's Energy Opportunity,* DOE/CH 10093-7.

2. K. Zweibel, A.M. Barnett, 1992, "Polycrystalline Thin Film PV," in *Fuels and Electricity from Renewable Sources of Electricity,* R. Williams, editor, Island Press, Washington, D.C. (in press).

3. T.W.F. Russell, B.N. Baron, R.E. Rocheleau, 1984, "Economics of Processing Thin Film Solar Cells," *J. Vac. Sci. Technology* B2(4):840-844 (October-December 1984).

4. B. Jackson, September 1985, CdZnS/$CuInSe_2$ Module Design and Cost Assessment, SERI/TP-216-2633, Solar Energy Research Institute, Golden, Colorado.

5. D. Carlson, 1990, "Low Cost Power from Thin Film Photovoltaics," *Electricity: Efficient End-Use and New Generation Technologies, and Their Planning Implications,"* T.B. Johansson, B. Bodlund, R.H. Williams, eds., Lund University Press.

6. V.K. Kapur and B. Basol, 1990, "Key Issues and Cost Estimates for the Fabrication of CIS PV Modules by the Two-State Process," *Proceedings of the 21st IEEE PV Specialists Conference,* 1:467-470.

7. P.V. Meyers, March 1990, Polycrystalline Cadmium Telluride n-i-p Solar Cells, SERI Subcontract ZL-7-06031-2, Final Report, Solar Energy Research Institute.

8. P. Moskowitz, K. Zweibel, 1992, *Recycling of Cd and Se Bearing Materials from PV Module Production and Use: A Workshop Report,* March 11-12, 1992, Golden, Colorado (in press).