

Baseline Evaluation of Thin-Film Amorphous Silicon, Copper Indium Diselenide, and Cadmium Telluride for the 21st Century

Preprint

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BASELINE EVALUATION OF THIN-FILM AMORPHOUS SILICON, COPPER INDIUM DISELENIDE, AND CADMIUM TELLURIDE FOR THE 21ST CENTURY

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ABSTRACT

This paper examines three thin-film PV technologies: amorphous silicon, cadmium telluride, and copper indium selenide. The purpose is to: (1) assess their status and potential; (2) provide an improved set of criteria for comparing these existing thin films against any new PV technological alternatives, and examining the longer-term (c. 2050) potential of thin films to meet cost goals that would be competitive with conventional sources of energy without any added value from the substantial environmental advantages of PV. Among the conclusions are: (1) today's thin films have substantial economic potential, (2) any new approach to PV should be examined against the substantial achievements and potential of today's thin films, (3) the science and technology base of today's thin films needs substantial strengthening, (4) some need for alternative technologies exists, especially as the future PV marketplace expands beyond about 30 GW of annual production.

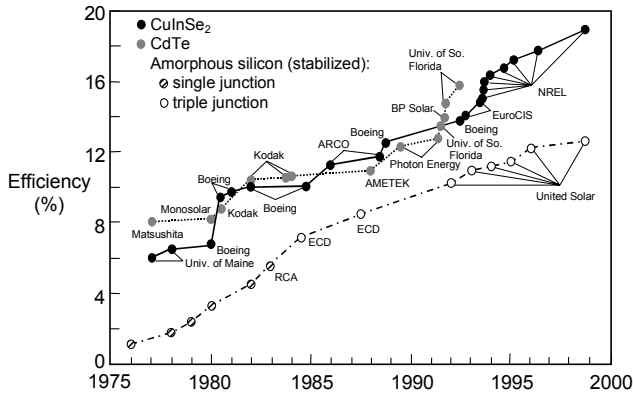
INTRODUCTION

As a concept, thin-film PV modules are regarded as having an excellent chance to reach the very low-cost goals defined by the U.S. Department of Energy (DOE) that would make PV viable for energy-significant markets. This is because of their reduced materials requirements, inexpensive processes, and diminished number of processing and handling steps. Yet thin films have not yet made a major impact in the PV marketplace. For existing thin films, this paper provides insights into: (1) their evolution and present status; (2) issues and challenges facing their near-term, successful entry into the marketplace; and (3) their future prospects in terms of performance, cost, and reliability. The intent is to show the technical progress that has resulted in thin films reaching a level where they are now ready for first-time multi-megawatt production; to define a number of critical challenges; and to portray how thin films may evolve technologically so as to eventually dominate the PV marketplace, perhaps by the second decade of the 21st century.

Another purpose is to provide a baseline against which to reference the potential of new and alternative PV technologies. For example, new, unexplored thin films are sometimes touted as being potentially less expensive, more efficient, having less toxicity, or using more abundant constituents. Which of these criteria really matter? Which are most likely false leads? Clarifying those comparisons by providing a decent baseline is another goal of this paper.

Finally, the paper will examine the long-term prospects of today's thin films in order to propose possible cost and performance goals that are more ambitious than those currently accepted by DOE. By achieving such goals before the middle of the next century, thin-film PV could become a ubiquitous part of the world's energy and environmental infrastructure. Otherwise, future, energy-significant use of PV might depend more on environmental concerns than economic competitiveness.

Record Laboratory Thin-Film Cell Efficiencies



The baseline thin films covered in the paper are those that are now in pilot or commercial production: amorphous silicon, copper indium diselenide, cadmium telluride, and their related alloys. (Thin-film crystalline silicon exists but is not yet in pilot production in a monolithic, large-area form.) By defining a possible path for the evolution of these technologies, less-developed or as yet unknown thin-film alternatives can be measured against them.

One cannot embark on this kind of effort without recognizing the substantial likelihood of being wrong or simply misleading. The purpose here is to add to the body of thought about thin films without reducing the purview of future researchers. It is fairly certain that something new and untried will make a larger than expected impact.

THE STATUS OF TODAY'S THIN FILMS

The status of a thin film can be defined in terms of a few critical qualities: efficiency, stability, and cost of manufacturing. The latter includes such issues as rates, capital cost, complexity of equipment, downtime, maintenance, ES&H costs, yield, process materials utilization rates, and feedstock costs/availability. A more in-depth perspective on each of these matters is given in references 1,2. The following summarize those findings.

Efficiency

The efficiency of thin films can be understood by observing the efficiency of the best laboratory-made devices (small-area cells) and the best prototype modules. The former show the mid-term potential of thin-film options. The latter indicate progress in the challenges of scale-up: area uniformity and monolithic cell interconnection. A way to quantify scale-up is by ranking modules by output power rather than efficiency because the highest efficiencies are usually on smaller-sized modules.

Figure 1 (previous page) shows the progress and status of the best laboratory cell efficiencies in this films. Table 1 (below) shows the best prototype modules (not commercial samples). Both sets of data are measured under standard conditions: i.e., total area for cells and aperture area for prototype modules (in both cases, stabilized efficiencies for a-Si).

Table 1. Best Large-Area, Thin Film Modules (standard conditions)

Company	Device	Size (cm²)	Efficiency (aperture area)	Power	Date
United Solar	a-Si triple junction	9276	7.6% (stabilized)	70.8 W	9/97
First Solar	CdTe/CdS	6728	9.1%	61.3 W	6/96
Solarex	a-Si dual junction	7417	7.6% (stabilized)	56 W	9/96
Siemens Solar Industries	CdS/CIS-alloy	3651	12.1%	44.3 W	3/99
BP Solar	CdS/CdTe	4540	8.4%	38.2 W	
United Solar	a-Si triple	4519	7.9% (stabilized)	35.7 W	6/97
Golden Photon	CdS/CdTe	3366	9.2%	31 W	4/97
ECD	a-Si triple	3906	7.8% (stabilized)	30.6 W	

How can we summarize the information presented above? Consider Table 2 (next page) that attempts to highlight the differences among the thin films.

It will be important to develop a better measure of performance than efficiency under standard conditions, because such low-temperature (25°C) measurements minimize the differences outdoors at real temperatures and spectra. As an indication, an 11% CIS-based module (standard conditions) performs at about 9% outdoors; an 8% CdTe, at about 7.5%, and a 7% a-Si at about 7%. Thus, the differences in performance among the thin films are a little less than they appear, though still quite important. Based simply on band-gap related issues, all of them are likely to lose less performance under most circumstances outdoors than crystalline silicon modules that have the same efficiency when measured under standard conditions.

Table 2. Efficiency Ranking of Thin Films

Material	Best Cell	Best Module	Most Efficient Module	Comments
CIS-Alloys	18.8%	44 W, 12.1%, 3651 cm ²	12.1% , 3651 cm ²	Highest performance , but most loss at outdoor temperatures (about 15% max)
CdTe	15.8%	61.3 W, 9.1%, 6728 cm ²	9.2%, 3366 cm ²	Modest loss outdoors at peak temperatures (5%-8%)
Amorphous Si multijunctions	12.1%	70.8 W , 7.6%, 9276 cm ²	10.4%, 905 cm ²	Stability issues hold back efficiencies; almost no loss outdoors at operating temperatures due to reverse SWE anneal during summer

Stability

Stability has been a problem for thin films since the beginning. An early technology based on copper sulfide was essentially abandoned because of poor stability. Today, it would not be competitive because of its poor efficiency. Amorphous silicon was nearly abandoned because of a light-induced loss called the Staebler-Wronski effect (SWE). However, tests showed that it saturated at about a 10%-40% loss (depending on device design and materials properties). Now, the SWE is more of a limitation than a fatal flaw for amorphous silicon in that it limits possible designs to those with the smallest losses. But today's best amorphous silicon cells would be 15% efficient without the SWE; better designs would probably make them closer to 17% efficient or more if they could eliminate it. Thus, the SWE is still a major drawback.

Because several modules tested at NREL have been stable since 1988, CIS-based devices have long had a reputation for perfect outdoor stability. However, recent accelerated tests have shown some sensitivity to water vapor. CdTe cells and modules are subject to various instabilities. These range from contact issues likely related to the movement of copper or other contact dopants, to encapsulation issues such as preventing water vapor damage.

Most thin films have gone through an early period of module "infant mortality". That is, the earliest encapsulation schemes, based on the least outdoor experience, have had stability problems. The amorphous silicon technology went through serious issues, especially because module encapsulation issues were often confused with the SWE. Today, amorphous silicon modules have an excellent reputation for outdoor stability once the initial 20% or so loss of performance has taken place. Perhaps they have solved their non-SWE encapsulation issues. The other thin films have not yet passed through this "trial-by-fire" period.

A subtle form of instability is performance transients. These transients go beyond the universal effects of changing temperatures and spectra outdoors. All PV technologies have some electronic hysteresis. This means that their sunlight exposure and electronic history

influence performance. Flash simulators measure different efficiencies than continuous simulators or measurements taken outdoors. For those modules with significant hysteresis, reproducible measurements are difficult, and misleading artifacts are maximized. *Fortunately, conditions change more slowly outdoors, and hysteresis effects have minimal to no impact on real-world performance.* The extent of transients is quite technology-specific, even to the level of how the modules are made and sealed. The cause of fully reversible light- and current-induced transients is usually trapping (or de-trapping) in the active semiconductors influencing the junction properties. Often, these actually increase efficiencies (but make reproducible measurements difficult!). Again, real-world performance almost always takes place under nearly transient-free conditions.

Table 3. Stability Status of Thin Films

Material	Intrinsic Issues	Encapsulation Issues	Transients
CIS-alloys		Water vapor	Lamination and Trapping
CdTe	Contact changes, especially at high temperatures	Water vapor	Trapping
Amorphous Si	SWE	Minimized or eliminated by field experience	Spectral sensitivity due to multijunctions; reverse SWE anneal during summer

Amorphous silicon has proven itself in commercial systems to be quite robust after the initial SWE degradation. CIS-alloy modules have been remarkably stable at NREL for 10 years and under other outdoor tests. Encapsulation issues to prevent water vapor ingress remain but will likely be resolved shortly. CdTe modules have also shown near-perfect stability outdoors at NREL, but have some in-progress issues associated with very high temperatures, water vapor, and contacting. It is yet marginally possible that one or more of these CdTe- or even CIS-related stability issues will have the impact on them that the SWE had on a-Si. If so, that would bring into question whether this current set of thin films would be as successful as they now appear likely to become (see below). Further outdoor experience and volume production will be needed to resolve this challenge. But this "hidden" problem of long-term outdoor stability remains a subtle challenge to the future of baseline thin films.

Manufacturing

Manufacturing issues are fairly subtle and much harder to characterize because they do not depend on one universally measurable quantity such as efficiency. Also, companies maintain their competitive advantage in proprietary processing matters, and details are rarely forthcoming from them. However, reference 2 summarizes today's knowledge of thin-film manufacturing and allows us to develop several important insights.

Table 4. Manufacturing Status of Thin Films

Material	Equipment Complexity	Equipment Rates	Materials Utilization	Yield
CdTe	Medium for vapor transport; small for electrodeposition	Very rapid in-line processing; high-throughput batch processing	Good for vapor transport; very good for electrodeposition	Unproven in real manufacturing
A-Si	Large for in-line glow discharge; less, for batch processing	In-line processing slow, but may be increased; high-throughput batch processing	Poor	Good to excellent
CIS	Large for all methods	Slow, but may be increased	Mediocre but acceptable	Has been a serious issue but is being overcome

Table 4's characterizations are still preliminary because the thin films have not been made in sufficient volume. But one "lessons learned" from developing thin films is that each of them takes much more money and time to reach manufacturing than expected. Not only is the obvious issue of area-uniformity a challenge, but the less obvious issue of process reproducibility tends to cause serious technical challenges leading to downtime and yield falloff. The missing link is a substantial scientific and technical base for the transition to manufacturing. Not enough is known about these materials to easily head off problems that naturally arise prior to and even during the start of first-time manufacturing.

Making square miles of thin films annually remains a big technical and financial challenge. The transition to a money-making, commercial success has still not been accomplished. In the future, as the PV market generates enough cash-flow to support a reasonable technical base for the transition from the lab to manufacturing, the risks of manufacturing new technologies will likely diminish. Until that happens, stunning failures still remain possible.

It is important to observe that despite their great attainments, today's thin films still require support for fairly basic research. This is demonstrated in the challenges of continued efficiency improvements; continued work on unresolved stability issues; continued need to transform small-area cell results to large-area modules; and the most challenging thing of all, making square miles of modules with little yield falloff. The baseline thin films are not mature technologies needing little ongoing research focus. Quite the opposite. By some measures, today's mainstream thin films still qualify as innovative concepts or similar terms usually applied to long-term research programs.

THE POTENTIAL OF TODAY'S THIN FILMS

What is the potential of today's thin-film options?

Table 5. Potential of Today's Thin-Film Options (ultimate, practical, and probable)

Option	Efficiency (commercial module)	Manufacturing Cost (\$/m ²)	Loss Outdoors	Cost per Operating Watt (\$/W _{op})
CdTe	14%	\$45	5%	\$0.34
CIS-alloys	17%	\$60	12%	\$0.4
a-Si Multijunctions	11% (stabilized)	\$55	1%	\$0.5

What are these aggressive projections based on? Table 5 assumes that each thin film can come fully to grips with its stability issues and overcome them (except the SWE). It also assumes that manufacturing challenges will be met.

The efficiency projections are based on assumptions about the best lab *cells*. For CIS-alloys, the future best lab cell is assumed to be 21%; for CdTe, 18%; and for a-Si, 14% (i.e., only about 2% higher than today's). Table 6 shows today's status that has been used to make the projection:

Table 6. Comparison of Today's Best Cells, Prototype Modules, and Commercial Modules

Option	Best Cell Today and Assumed	Best Module Prototype Today	Ratio of Prototype/Cell	Future Best Commercial Module (0.8 * Ultimate Lab Cell)
CdTe	16% (18%)	9%	0.6	14%
CIS-alloys	19% (21%)	12%	0.63	16%
a-Si Multijunctions	12% (14%)	10%	0.83	11%

We have used a factor of 0.8 to estimate the difference between the future "ultimate cell" and the future "ultimate commercial module". Clearly, the "ultimate" cells and modules are a fiction, as they will never be synchronous. But they provide a logical basis for the estimates used in Table 5 (above). The use of a factor of 0.8 (rather than lower figures) indicates that the a-Si number is more telling, since a-Si has been designed for product sizes longer than the others. Its factor of 0.83 is a leading indicator for the others. Few if any physical differences among the module designs would affect it.

The manufacturing cost projections are based on information given in reference 2. There, it is established that if the active semiconductors of thin film modules can be made using

inexpensive processes, costs will be under \$100/m² and trend down towards a common level of about \$50/m². This assumes substantial progress in both a-Si and CIS manufacturing. (CdTe deposition is already inexpensive.) Amorphous silicon multijunctions are today made in slow, in-line processes. The deposition rates are 1-3 angstroms/s. By raising these rates to 10 angstroms/s or more, capital costs for a-Si will become similar to those for CdTe, which are already low. Other items such as materials use will also have to be addressed. Given the current ranking, with CdTe the least expensive to manufacture, a-Si next, and CIS the most costly, we have chosen a small range in Table 5 around \$50/m² that reflects this.

Given the obvious uncertainties, it would be hard to distinguish between the three thin-film options, except in terms of the potential module efficiency of amorphous silicon, which is on the low side. Still, there are approaches for reducing the SWE, and even advanced theories of its nature [3] that might lead to even further amelioration or elimination. Given the number of uncertainties among the thin films, only one conclusion is important:

The cost potential of thin film modules under *operating* conditions is below \$0.5/W_{op}, and could trend down below that towards \$0.3/W_{op}.

Any new PV technology must take this kind of potential into account. If a new technology cannot exceed this mark, it should not be considered unless there are special reasons to do so (see below).

Today's thin-film technologies could be used in the future to develop several hybrid, multijunction options that would increase performance and reduce cost per operating watt. Consider the following combinations:

Table 7. Future Two-Junction Module Options with Today's Thin Films (estimated)

Two-Junction Option	Best Future Cell ³	Best Commercial Module ²	Cost/m ²	Cost per Operating Watt (\$/W _{op}) ¹
CIS-alloy/CIS	30%	24%	\$70	\$0.26
CdTe/CIS	27%	21%	\$55	\$0.29
CdTe-alloy/CIGS	28%	22%	\$60	\$0.3

Notes:

1. 10% Reduction for outdoor performance losses, probably an overestimate.
2. 80% factor used to estimate "commercial module" from "best cell," as before.
3. Formula for estimation is the ultimate top cell efficiency plus 90% of the ultimate bottom cell efficiency, reduced by spectral losses by another 60% (loss of higher energy photons and other transmission losses due to top cell).

Notice how close all these options are. Considering the substantial uncertainties, there is really not much difference among them—and not that much improvement from the simpler, single-junction alternatives. However, since the module efficiencies would be higher, *the system costs would be proportionally lower*. That makes these options worthy of attention.

Clearly, there are major uncertainties in the assumptions of Table 7 that could still make the hybrid two-junction cells valueless. For example, even if all the processes for making the cells could become compatible (they are *incompatible*, now), the top-cell subgap transmission losses might be too substantial to make the combined cell more efficient than the separated cells.

It is important to realize that the heart of thin-film cells—making the active semiconductors—only costs about \$10/m². Thus, fabricating a multijunction only adds this approximate amount to the cost of the single-junction on a per-square-meter basis. This fact is important for understanding the cost estimates of Table 7. If, instead, manufacturing costs doubled, such cost increases would obviate any advantages from the expected performance enhancements. Note also that thin-film amorphous silicon is unlikely to be an important hybrid option due to its low efficiencies (unless the SWE can be eliminated).

Although each of these options would likely require substantial research to be successful, they provide obvious paths for improvements based on today's thin films, without beginning research on entirely new semiconductor options.

CHALLENGES AND QUESTIONS

Table 8. Major Technical Challenges

Technology	Efficiency	Manufacturing Cost	Comments
CdTe	Needs innovative cell designs and improved materials options, especially doping		Contact stability unproven
CIS-alloys		Reproducibility; alternatives to selenization	Manufacturability unproven
a-Si	SWE and possible redesign of multijunctions after SWE is reduced	Higher rates; better use of gases like germane	SWE limits potential
Hybrid Multijunctions	Process incompatibilities and new, different-band gap CIS and CdTe alloys/cells	Same as above for CIS-alloys	Serious process incompatibilities (temperature, chemistry)

We have tried to state some of the caveats and uncertainties about today's thin films. In no case is achieving the existing, aggressive goals a "slam dunk". Further work to improve performance, reduce manufacturing costs, and assure stability will be crucial. Table 8 summarizes the major challenges facing each thin film (previous page).

There is a common thread in all of these problems: lack of a sufficient science/technology base for these materials, devices, and processes. Due to limited cash flow in PV, only federal support provides the resources for this at present. In this case, the cart has come before the horse because it must. In the future, if and when commercial demand for PV is substantial, the PV science and technology base may become robust.

SPECIAL REASONS TO CONSIDER NEW OR ALTERNATIVE PV TECHNOLOGIES

What are the characteristics that might make a novel PV technology worth addressing?

1. The potential to approach or actually exceed the goals outlined in this paper.

If a new technology can meet the same goals, it would provide a potential competitor for today's thin films, which would naturally provide benefits (reduced costs due to competition, less stress on certain materials availability). Indeed, because we cannot yet be certain that current thin films will meet stability requirements outdoors, we need some alternatives that are "merely" just as good. High-efficiency concentrators for desert applications are one possibility. Thin-film crystalline silicon, if it can overcome deposition rate and efficiency issues, could be an alternative, too.

2. A device option free of toxic elements, compounds, and processing steps would be attractive.

Today's thin films each have some concern in this realm. None of the concerns are considered to be overwhelmingly serious, but each raises costs (in-plant ES&H, recycling, biomonitoring, etc.) or might raise market resistance. However, it is very difficult to find an advanced PV technology that has none of these ES&H concerns, even including silicon (e.g., toxic or explosive feedstock gases).

3. A technology based on materials that are highly available.

CIS-alloy PV uses indium, which is rare, and selenium and gallium, which are somewhat rare. CdTe uses tellurium, which is rare. Production of these technologies beyond some level (perhaps 3 - 60 GW/year, depending on assumptions of layer thickness, recycling, and availability) [4] would cause supply issues and substantially increased materials costs. Thin-film, silicon-based PV is an obvious alternative for this long-term issue.

4. Greater potential and flexibility for making hybrid multijunctions, possibly in combination with today's thin films.

Making multijunctions with today's options presents substantial challenges, even the development of new alloys based on higher band-gap CIS alloys and CdTe alloys, neither of which can be made into cells anywhere near today's state-of-the-art efficiencies. If other semiconductors

can be found that would also be useful in top or bottom cells, they could provide some value. Perhaps the crystalline thin-film silicon technology could be an alternative to CIS as a bottom cell, if it can overcome previously stated issues.

5. Materials/devices that have significantly simpler processing and can thus achieve higher yields.

In the end, all thin films will be produced by simple, robust processes with high yields and high performance. But in most cases, serious processing impediments must be overcome for today's thin films to reach this desired outcome. If a new material can be made by a process that is inherently simpler and thus more reproducible than those available today, it may become successful. However, each of today's thin films has one or more processing options for reduced complexity in manufacturing (and CdTe may have already achieved it). Dye-sensitized cells, if they can reach high enough efficiency, might fit this description.

One or more alternatives to today's thin films is likely to be developed to supplement or replace them, either because of materials availability issues, chronic stability or manufacturing issues, or simply because something better can be done. But any new option must have some clear basis for development, such as those given above.

THE QUESTION OF GOALS FOR ACHIEVING ENERGY SIGNIFICANCE BASED ONLY ON ECONOMIC COMPETITIVENESS (NOT ENVIRONMENTAL DRIVERS)

It is possible that PV will reach energy significance worldwide based on environmental drivers such as the greenhouse effect. This may happen even without progress in reducing PV cost! However, based on purely economic factors, such as competing in the US against the utility grid or worldwide against other options such as local power from gas turbines, PV would need to meet very ambitious cost goals. Today's DOE cost goals are for systems that can produce electricity in average US locations at 6 cents/kWh. This translates to approximate installed PV system costs of about $\$1/W_p$ (watt peak). If non-module costs total about $\$0.7/W_p$, the PV modules would have to cost the utility about $\$0.3/W_p$ (from an economic standpoint, equivalent to about $\$0.36 W_{op}$). This is already a very ambitious goal when compared to today's wafer-Si PV costs of about $\$3-\$5/W_p$ for modules. Yet today's thin-film options (see Table 4) appear to have this long-term potential.

Even in developed countries, there are many uses for PV that do not require 6 cents/kWh electricity. Commercial and residential consumers could avoid retail electricity costs closer to 8 or 10 cents/kWh in many regions. But because they would depend on the grid for backup to their PV, one could not reach ultra-large-scale use in this manner. In fact, some costs for back-up or storage have to be added to basic PV costs in uses where dispatchability is assumed. Developing countries may have less restrictive needs.

In terms of true, economic competitiveness, the question remains: How low should cost goals for PV be; and how low can thin-film PV costs go? Let's look at the latter. Two

avenues exist for PV module cost improvements: performance enhancements and manufacturing cost reductions. The hybrid multijunctions would improve efficiencies at some marginal costs. By doing so, the overall system costs would be reduced perhaps by 25% or so. Reducing the module manufacturing costs beyond the assumptions made using today's module technologies would reduce costs by a smaller amount, perhaps 10%. One might estimate that the $\$1/W_p$ ($\$1.2/W_{op}$) system goal could be reduced by 35%, to about $\$0.65/W_p$ ($\$0.8/W_{op}$) by these means. Such reductions could have a profound effect on the usefulness of PV in the middle of the 21st century. And it is always easier to rationalize energy production changes done for environmental reasons if the economics are not too far out of line.

SUMMARY OF VIEWPOINTS

1. Today's mainstream, direct-band-gap thin films still face major technical challenges associated with stability, efficiency, and manufacturing. This reflects the shaky scientific and technological base upon which today's thin films are built. Only continued focus and sufficient resources can provide good confidence that these issues will be overcome.

2. During the near-term (before 2010) thin films will face major technical and market challenges and will compete against each other and crystalline silicon for leadership in the PV marketplace.

3. With continued success, thin films may surpass crystalline silicon in the marketplace by about 2010 and begin to make serious inroads in electricity markets.

4. At least one or more thin-film technologies is likely to achieve the current DOE performance goal of 15% module efficiency by about 2010. (CIG(S) is already at 12%.)

5. At least one or more thin films is likely to achieve the cost goal near $\$50/m^2$ (CdTe is quite close).

6. As thin films become mainstream in the PV marketplace, innovations in cell designs, including multijunctions, should allow best cell efficiencies to surpass 20% (single-junction CIG(S) is already 19%).

7. The potential of thin films, including hybrid multijunctions, based on extrapolations from existing technologies, surpasses the current DOE goals, allowing for the definition of more ambitious system cost goals about 35% below today's $\$1/W_{op}$; achieving such goals would help make PV attractive for energy-significant use on a purely cost-effective basis.

8. The most serious unknown that could impact the future of existing thin films is outdoor stability. Until long-term stability is proven, we must continue to hedge our bets.

9. The most serious threat to the *large-scale* deployment of existing thin films (beyond about 30 $GW_p/year$, each) is materials availability (and cost implications)

concerning key elements such as indium, tellurium, and germanium. Substantial improvements in process materials utilization efficiencies, layer thickness reduction, light trapping, process control and uniformity, materials substitution (e.g., gallium for indium), and other technical and infrastructure achievements (such as recycling) can ameliorate this problem. At market levels above about 30 GW_p per year (for each successful thin film), new thin films made of more available materials will be needed to raise the use of PV another order of magnitude. *That is why, in the long run, the silicon-based technologies must never be abandoned, and some new, high-risk technologies might be worth investigation.*

Conclusions on research priorities:

- 1. Unless a new technology can meet criteria stated above, it should not be investigated at the expense of ongoing or increased research in today's thin film options. Red-herring PV technologies should be avoided!**
- 2. Work to improve the scientific and technological underpinnings of today's thin films needs greater emphasis.**
- 3. An area for somewhat increased focus should be development of hybrid multijunctions based on today's thin films.**
- 4. Nontoxic and highly available materials should receive attention for the long term, even if they have some drawbacks in terms of other criteria.**

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REFERENCES

1. K. Zweibel, "Thin Films: Past, Present, Future," *Progress in Photovoltaics*, V. 3, No. 5, Sept/Oct 1995; also available in revised form at the NREL web site: <http://www.nrel.gov/>.
2. K. Zweibel, "Issues in Thin Film PV Manufacturing Cost Reductions," *Solar Energy and Solar Cells*, 1999 (in press); also available in revised form at the NREL web site: <http://www.nrel.gov/>.
3. H. Branz, "Hydrogen Collision Model of Light-Induced Metastability in Hydrogenated Amorphous Silicon," *Solid-State Communications*, V. 105 # 6, pp. 387-391, 1998; and "Hydrogen Collision Model: Quantitative Description of Metastability in Amorphous Silicon," *Physical Review B*, V. 59 # 8, 15 Feb. 1999 (II).
4. B. Andersson, "Materials Availability and Waste Streams for Large-Scale PV," *PV and the Environment 1998*, V. Fthenakis, K. Zweibel, P. Moskowitz (eds.), Brookhaven National Laboratory, Feb. 1999 (BNL-52557).