CdTe PV progresses to mass production

In the past few years, renewable energy sources, particularly solar-based, have become a favorite for news reports and venture capital; as with many 'hot topics', it continues to be difficult to separate fact from the hope and spin. However, it is clear that semiconductor-based solar energy conversion in some form will be a leading contributor to future renewable energy strategies. One company has accelerated its plans for mass production of CdTe thin-film photovoltaic modules and others are following the lead, Dr Mike Cooke reports.

While world photovoltaic (PV) production is dominated by Japan and Germany, the USA has pioneered and leads in many of the lower-cost thin-film techniques just coming into mass production. In 2007, thin film constituted 65% of US PV production (Figure 1) with the top thin-film company being First Solar, according to PV News. First Solar produces solar modules based on cadmium telluride (CdTe) — see Figure 2. According to one top-ten ranking [1], First Solar came fifth globally in terms of production for solar modules of all types, making 200MW out of the world total of ~4300MW. The top four were producers of traditional silicon wafer based modules.

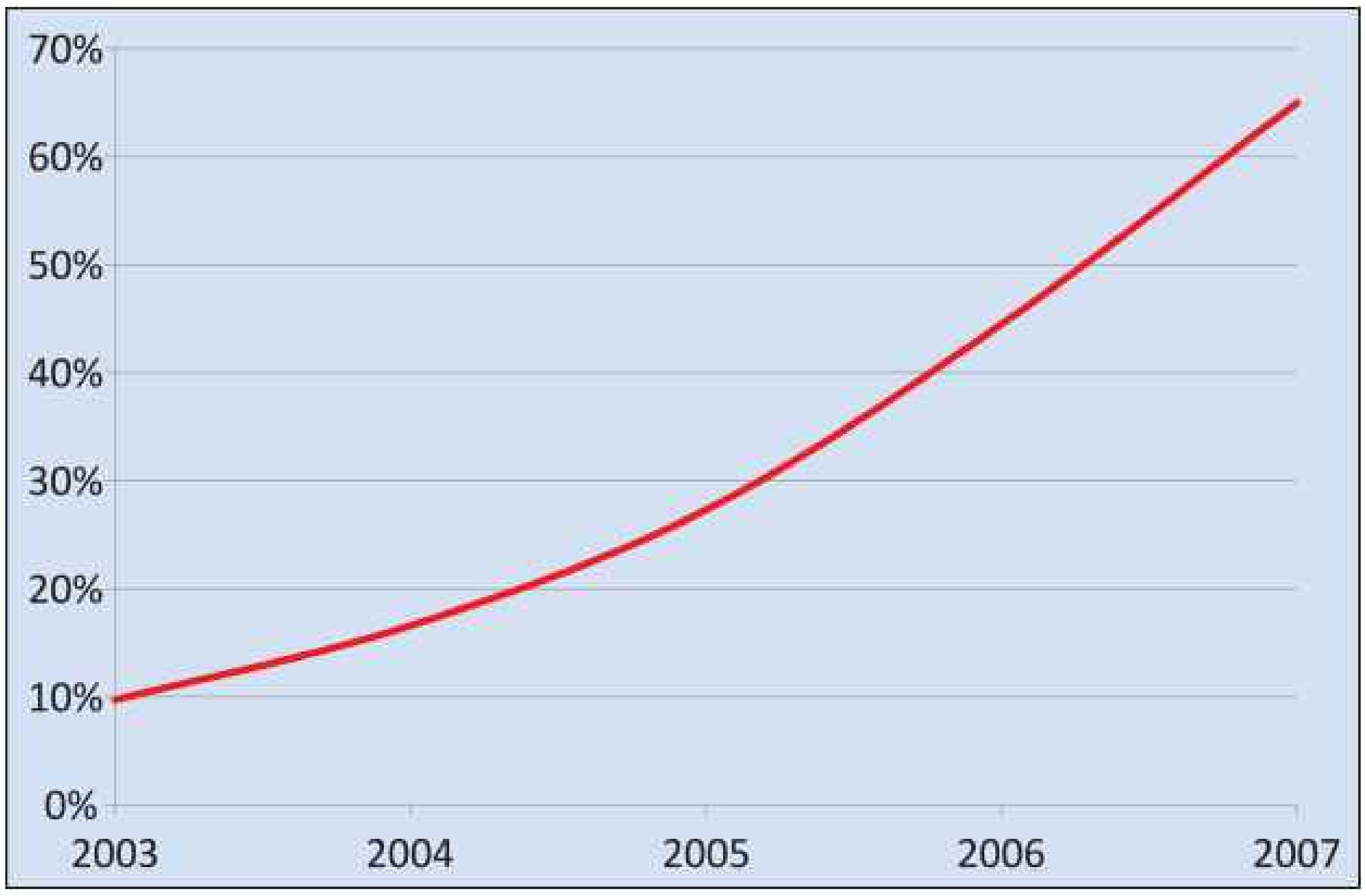

Figure 1. Percentage of US PV module production that is thin-film.

CdTe is a direct-bandgap semiconductor, which enables it to convert solar energy into electricity more efficiently than indirect-bandgap semiconductors such as silicon. The component elements of CdTe are byproducts of the mining and production of metals such as zinc and copper. These materials are present in abundant quantities to support multi-GWs of annual production, according to First Solar. However, others — supporting competing technologies [2] — point to recent increases in the price of tellurium. From averaging $10/pound weight in 2003, the price peaked at $96/pound in 2005 and was $80/pound in 2007, according to the UK-based publication Mining Journal. These price hikes reflect increased use of the element across the electronics industry (e.g. use in rewritable optical storage).

Detractors also point to environmental, safety and health (ES&H) concerns about use of the highly toxic element cadmium. CdTe producers have responded with comprehensive cradle-to-grave care for their product in life-cycle management and take-back recycling schemes to decommission CdTe modules safely and recycle the materials. Supporters also point to numerous safety reports such as [3], which concludes: "Large-scale use of CdTe PV modules does not present any risks to health and the environment, and recycling the modules at the end of their useful life completely resolves any environmental concerns. During their operation, these modules do not produce any pollutants and, furthermore, by displacing fossil fuels, they offer great environmental benefits. CdTe PV modules appear to be more environmentally friendly than all other current uses of Cd." Indeed, the burning of fossil fuels is itself a source of cadmium emissions.

CdTe's energy bandgap of 1.45eV ($\lambda \sim$ 855nm) means that less of the absorbed photon energy is dissipated as heat compared with narrower-bandgap silicon (1.12eV, 1107nm). Many consider 1.36eV (910nm) to be the optimum bandgap for single-junction solar cells. In addition, the fall-off in solar conversion efficiency at increased temperature is less for CdTe compared with silicon. This enables effective use under higher-temperature ambient conditions. CdTe also seems to be better at converting less-than-ideal lighting (cloudy weather, dawn, dusk). Theoretically, CdTe is capable of efficiencies of traditional silicon-based modules using only about 1% of the semiconductor material.

In addition to CdTe, thin-film devices can be based on various competing chemicals such as amorphous or polycrystalline silicon and copper indium (gallium) diselenide (CIS/CIGS). Today, CdTe module installations are predominantly on commercial rooftops and in large-scale utility ground-mounted systems — which is expected to continue up to 2012 [4]. With increasing power efficiency, CdTe manufacturers may begin to move from large-scale projects to devices aimed at the residential mass market.

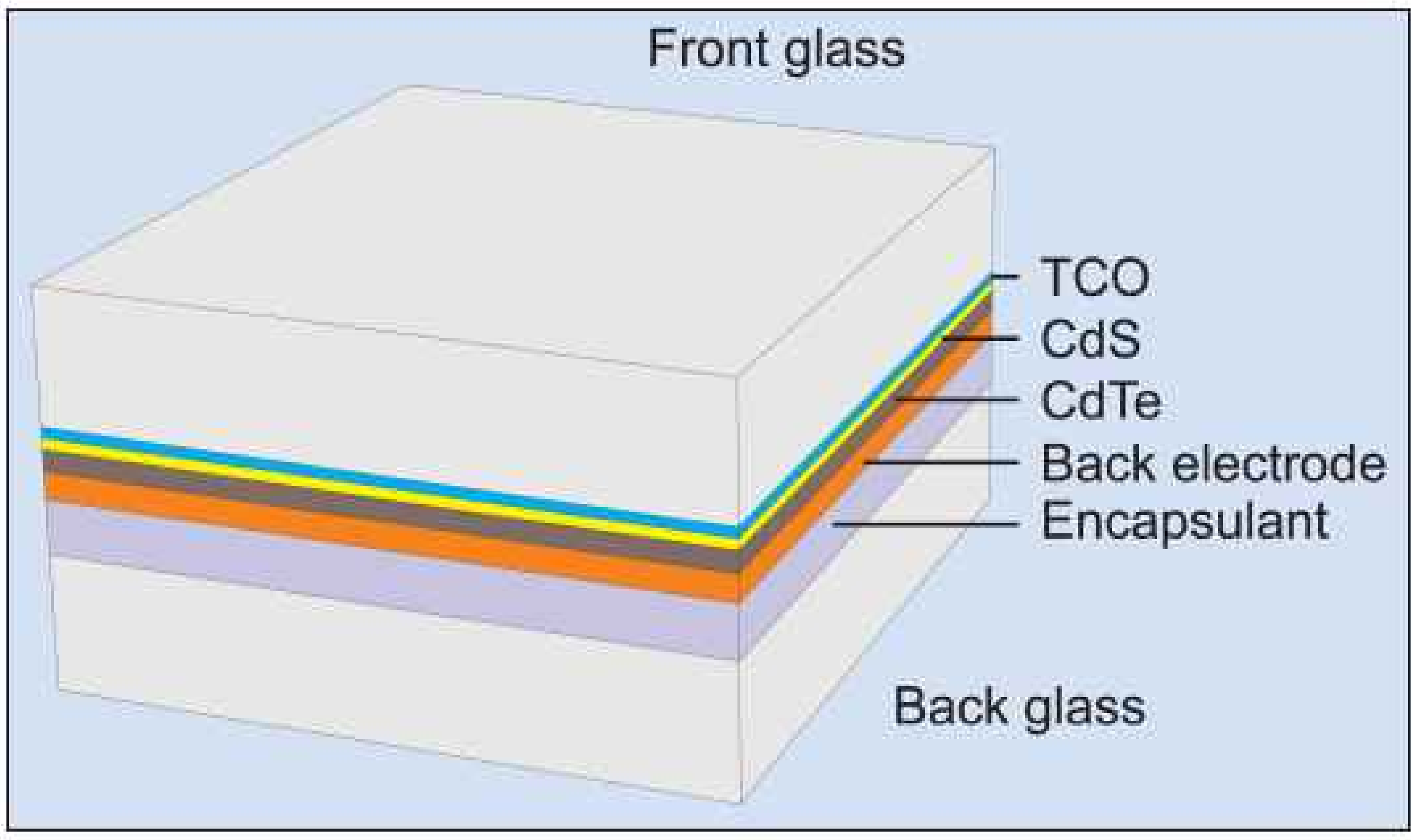

Figure 2. Typical layer structure for single-junction CdTe PV module. TCO = transparent conductive oxide.

Potential for thin-film PVs

Specialists at the US National Renewable Energy Laboratory (NREL) [5] have assessed the potential capabilities of various thin-film technologies based on present day 'champion cell performance' in each technology class as well as the expectations of this performance feeding through to mass-manufactured modules.

These authors cite First Solar's FS-275 CdTe-based module as having an efficiency of 10.4%, which attains 63% of the performance of champion cells. This compares with the leading monocrystalline silicon wafer product using a special junction formation from SunPower (315), which has 19.3% efficiency (78% that of a champion cell). CIGS products come in at 11% (WürthSolar WS11007/80) and 8.1% (GSE Solar GSE 120-W), or 55% and 41% that of the CIGS champion cell, respectively.

A somewhat crude model where manufacturing achieves 80% of current champion cell attainments — along with a factor of two to express the production cost advantage of thin-film technologies over monocrystalline silicon wafer devices — leads to CIGS and CdTe being classed as 'highly competitive' (Table 1). The lower cost of thin-film PVs is related to the reduced amount of semiconductor material that is used. Silicon wafer-based production in recent years has shifted from relatively low-grade to premium-grade Si, increasing costs and thus boosting the thin-film advantage.

In this evaluation, CIS/CIGS technology has some advantage over CdTe but, with such crude assumptions, actual manufacturing details and developments could change the cost/benefit equation. In addition, CdTe is clearly closer to the 80% of champion performance assumed in the analysis. This is the result of impressive progress by First Solar in recent years (Figure 3).

Expanding volumes

In first-quarter 2008, First Solar reported production costs of $1.14/W, which the company compared with silicon wafer modules at $3.00–3.25/W. As CdTe production-line volumes expand, further cost reductions are to be expected from the economies of scale.

By 2015, boosting yields (from ~90% to 95%) and efficiencies (from ~9% now up to 13%) could reduce production costs to $0.70/W (Table 2). First Solar has set $0.70/W as its target for 2012, a figure that is seen as being price competitive with grid-parity electricity.

First Solar's modules use polycrystalline CdTe in a simple single-junction formation. The firm says that its high-throughput automated operation does not need expensive cleanroom arrangements or other specialty equipment. Up to the end of 2007, First Solar had installed some 300MW of solar modules globally.

The company is now building a production facility in Malaysia that is due to be fully operational in the

Table 1. Anticipated future module efficiency and relative cost based on demonstrated champion cell performance from [5]. Future commercial module performance is estimated at 80% of current record cell efficiency. The column of future relative cost gives a 50% advantage to thin-film PV.

Technology	Future commercial module performance	Future relative performance	Future relative cost	Assessment
Si (non-standard)	19.8%	1.18	0.85	competitive
Si (standard)	17.0%	1.00	1.00	reference
CIS/CIGS	15.9%	0.92	0.54	highly competitive
CdTe	13.2%	0.78	0.64	highly competitive
a-Si (1-j)	8.0%	0.47	1.06	about the same
a-Si (3-j), (or a-Si/nc-Si)	9.7%	0.57	0.88	competitive

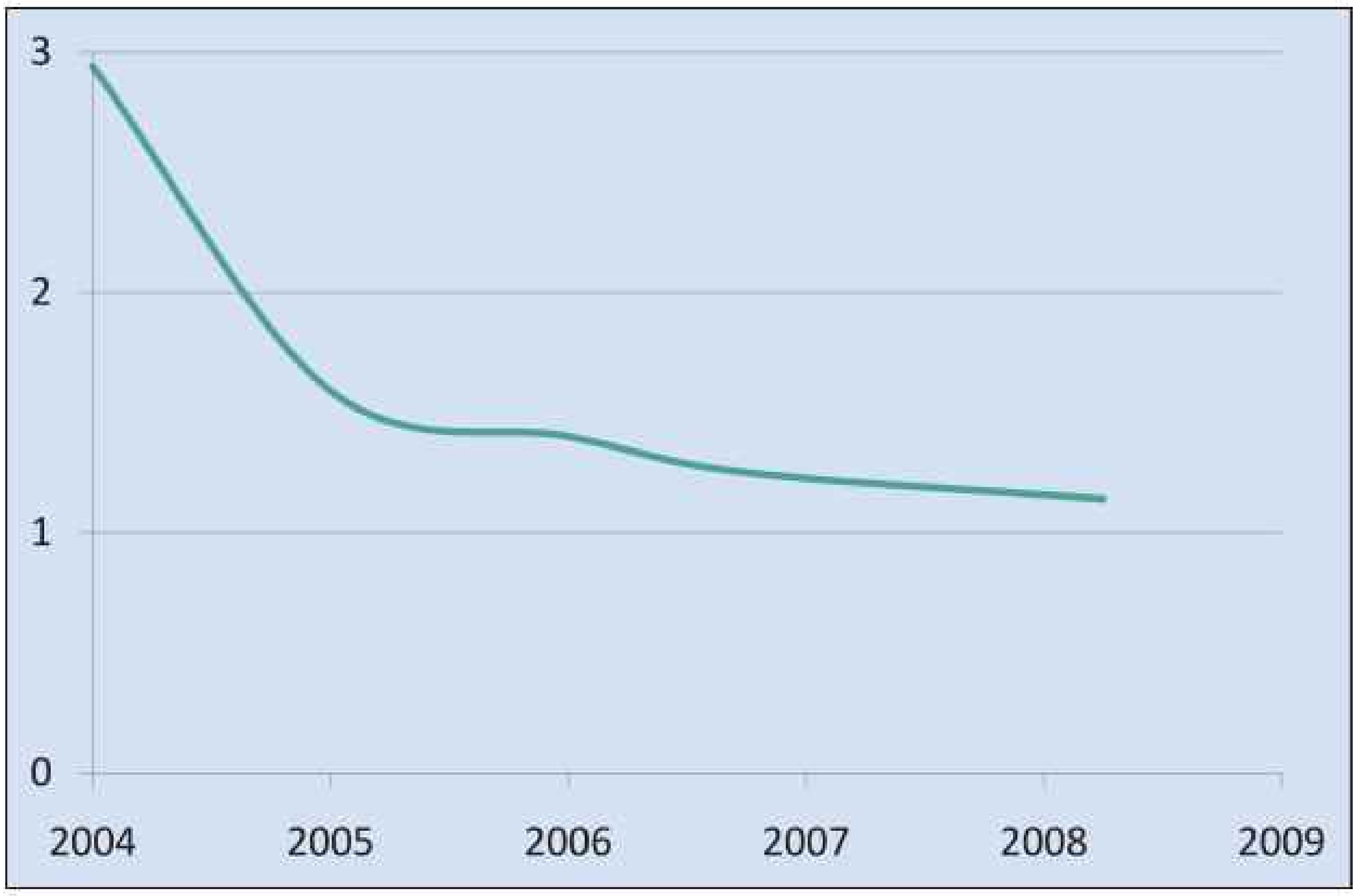

Figure 3. Efficiency of First Solar modules ($/W) 2004–2008.

second-half of 2009 at an expected cost of $680m. The site will consist of four plants capable of producing 720MW of solar modules annually, employing 2000 staff. The first plant at the facility was formally inaugurated this July. The firm is also due to add to its facilities at its Ohio base, moving up to 192MW (due to be completed in second-quarter 2010). This adds to some 120MW at its German operation. Further development facilities are also to be added at Ohio. First Solar has the stated aim of having more than 1GW in capacity by the end of 2009, which is more than double 2008's expected 495MW (Figure 4).

First Solar has built on the work of its predecessor, Solar Cells Inc, which carried out NREL-funded research from 1991. First Solar itself was founded in 1999, and commercial products became available in 2002. For 2008–2012, the firm has 3.4GW of long-term supply agreements in place. Among the projects for which First Solar is supplying and installing modules is a 40MW plant in Brandis, Germany, which is billed as the world's biggest photovoltaic power plant, being constructed in conjunction with Juwi Solar for EUR130m. In February 2008, some 12.7MW of this 40MW total was connected to the German grid. The project is due for completion at the end of 2009.

Southern California Edison is also to install First Solar panels in a project involving about 150 commercial rooftops covering two square miles. Indeed, First Solar's devices are to be used at the first site that covers 600,000 square feet. The potential power output is rated at 2MW. This site is due to be plumbed into the grid this September. The full five-year project is due to use 250MW of solar cells.

First Solar is not the only company producing CdTe modules. Calyxo GmbH (which was established in 2005 as a 100% subsidiary of leading PV maker Q-Cells) set up an 8MW CdTe pilot line in summer 2007, based on a worldwide exclusive technology license from US-based Solar Fields LLC. In October 2007, Solar Fields and Calyxo were merged into a new company, with 93% of shares going to former Calyxo and 7% to Solar Fields. The firm now has full rights over the technology and a 100% subsidiary in the USA. Calyxo USA will focus on CdTe R&D, while Calyxo GmbH in Germany is now completing its pilot facility with a production capacity of 25 MW. A further 60MW of capacity is to be added at a site next to the present production facility in Germany. Another German company, Antec Solar, also has some CdTe thin-film production.

AVA Solar is a further CdTe solar module manufacturer that is planning large-scale facilities with technology that was developed and incubated (with NREL support) at Colorado State University. The firm says that the fully automated, dry, in-line, continuous, single-pass system that it uses has very high throughput and yield. Pilot production is due in second-half 2008 and a large-scale 200MW manufacturing facility is to be completed in early 2009. The company reports testing that validates a 30+ year product life, and initial device efficiencies ranging from 11% to 13%.

"We are very happy with our initial pre-production runs and have decided to move up production plans on our existing manufacturing line," said AVA's president & CEO Pascal Noronha earlier this year. "Although this will be relatively limited production, we intend to accelerate our production learning curve and get our products into the market faster than we thought possible last year."

AVA is a recipient of a US Department of Energy Solar America Initiative (SAI) PV Incubator Award. Primestar Solar is another firm receiving incubator funds from SAI. General Electric Energy (GE Energy) has recently become a majority shareholder. The firm has yet to make a concrete announcement concerning pro-

Table 2. A view of prospects for CdTe development to 2015 [4].

Parameter	2007 status	Goal for 2015
Commercial module efficiency	>9%	13%
Champion device efficiency	16.5%	18%–20%
Module cost ($/W)	1.21	0.70
$/watt installed system cost	$4–5/W	$2/W
Levelized cost of electricity (LCOE)	18–22 ¢/kWh	7–8 ¢/kWh
Overall process yield	90%	95%
Identify relevant degradation mechanisms & develop appropriate accelerated lifetime tests (ALTs) for device and mini-modules	1.2%/year	0.75%/year

duction facilities, and its first product is described in the future tense on the firm's website.

On the development side, Sunovia and EPIR Technologies see CdTe as part of a multi-junction solar cell approach (using ZnTe and Si components) that is hoped will reach efficiencies of about 32%. These firms believe that, since CdTe is more abundant and affordable than other compound semiconductors such as InGaAs/InP/Ge, efficient multi-junction solar cell performance can be produced at significantly lower cost. InGaAs/InP/Ge cells can produce efficiencies only slightly better (~34%) than that expected for ZnTe/CdTe/Si. Whereas the Ge substrate makes up 65% of the cost of the III–V structure, Sunovia/EPIR believe that the use of silicon substrates will make the substrate cost factor almost disappear, particularly with larger-diameter wafers. Sunovia representative Don Sipes sees production on silicon wafers of 200mm or larger as being possible.

More than $25m has been invested into the firms' core CdTe research, development and design for a high-throughput CdTe-based manufacturing facility. The firms say that advanced manufacturing concepts should allow the production of more than 100MW of high-efficiency CdTe solar cells within a 10,000ft^2 area. The first manufacturing system is to be operational in less than two years time and will have the capacity to produce more than 10MW of CdTe-based solar cells during the first year. The initial target market will be the commercial and utility sectors. Manufacturing is designed to be 'scalable', meaning that additional capacity can be added quickly, as required.

Single-crystal material grown by high-throughput MBE deposition methods could reach 24%... above 30% is achievable for optimized two-junction CdTe/Si solar cells in which both the CdTe and the silicon act as solar energy absorbers

The basis for the high-throughput manufacturing technologies for growing single-crystal CdTe on silicon substrates was first demonstrated at the University of Illinois at Chicago and transferred by EPIR into night-vision infrared (IR) sensors for military application over the past decade. While amorphous or polycrystalline CdTe is thought to offer an upper limit of 16% efficiency, EPIR calculates that the single-crystal material grown by its high-throughput molecular beam epitaxial (MBE) deposition methods could reach 24%.

This efficiency was calculated assuming no antireflection coating and no back mirroring under a terrestrial solar spectrum with the standard global tilt of 37° (AM1.5G).

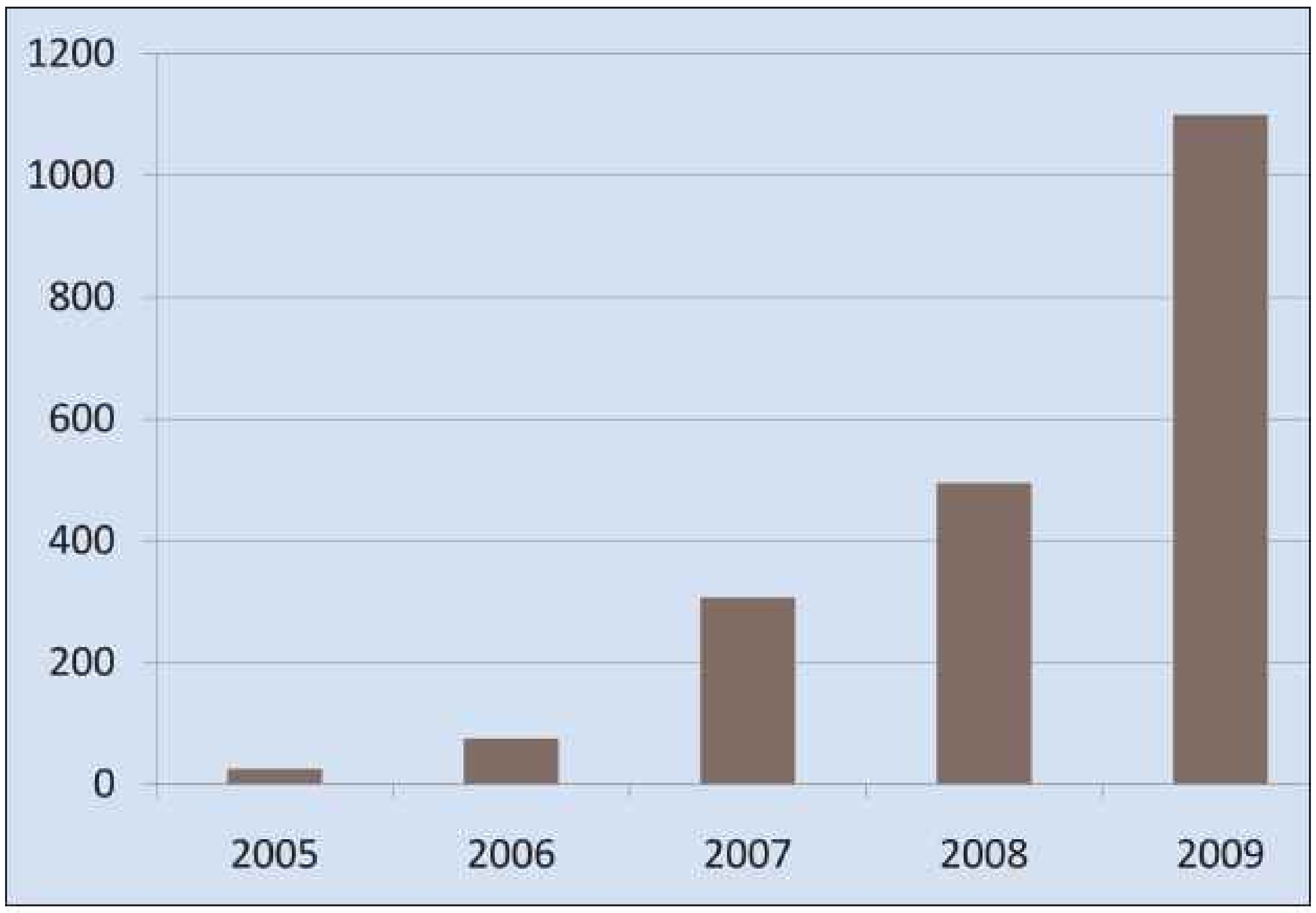

Figure 4. First Solar's capacity (MW): 2008–2009 projected.

The calculation was performed for a cell having a thin top layer of n-type cadmium sulfide on 4µm of p-type CdTe (the most common CdTe solar cell configuration). For a CdTe solar cell of a proprietary design, EPIR calculated an efficiency that is above 26%. It believes that a maximum efficiency above 30% is achievable for optimized two-junction CdTe/Si solar cells in which both the CdTe and the silicon act as solar energy absorbers.

This May, the firms announced that they had created improvements in the crystal quality of 3-inch CdTe wafers more than twice as great as all of the improvements achieved over the last decade. The companies also claim that the improvement in across-the-wafer uniformity is even more striking than the great improvement in crystal quality at the center. This gives a high likelihood for rapid progress to commercial large-scale manufacturing of even larger-area CdTe/Si wafers, for even lower costs and faster production.

Finally, silicon solar cell manufacturer Xunlight is also exploring CdTe by, in April, establishing the subsidiary Xunlight 26 Solar (X26) to develop and commercialize lightweight and flexible solar cells based on CdTe and other II–VI compound semiconductors. Presently, CdTe solar cells are produced on rigid soda-lime glass. X26 has received a $997,000 grant from the State of Ohio under the Alternative Energy Program to continue development of flexible CdTe solar cells. The project will be carried out in collaboration with the University of Toledo and Akron Polymer Systems of Cleveland, OH. ■

References

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