A Survey of Thin-Film Solar Photovoltaic Industry & Technologies

by

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Abstract

A new type of solar cell technology using so-called *thin-film solar photovoltaic* material has the potential to make a great impact on our lives. Because it uses very little or no silicon at all, thin-film (TF) solar technology promises to reduce the cost of solar modules to a level where solar power could compete effectively with power generated from fossil fuel alternatives, thus accelerating our society's transition to distributed, renewable forms of energy sources. Furthermore, because thin-film solar PV materials can be applied to surfaces as varied as glass, plastic and flexible metal foils, this emerging technology could open up new range of applications that otherwise would not be possible using traditional solar cells.

The scope of this thesis is to analyze the technical merits of the different thin-film solar technologies, their market and applications, and the dynamics of a growing, new industry. We will compare the different thin-film solar technologies against each other and against the dominant poly-silicon technology. Next, we will take a look at the make up of the thin-film industry and study the different technology strategies employed by players in this industry. We'll highlight a few manufacturers of each type of technology and present a snapshot of the industry in terms of current production and forecasted manufacturing capacity. We'll conclude with a technology outlook and recommend possible technology strategies for firms contemplating entering this industry.

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3 Introduction

For as long as the sun rises, the Earth will have a sustainable source of energy: solar energy. Harvesting this abundant energy source has been a dream of mankind for thousands of years. From Archimedes' experiments with solar concentrators to today's solar cells that quietly convert sunlight to electricity, the science of harvesting sun's power has made huge strides. Yet, despite the lofty dreams and scientific advances, today only 0.04% of world's electricity is generated by solar cells[1]. What makes the power of light so elusive and difficult to capture? The answer lies not only in the scientific quarters, but also in the economic and geo-political arenas. Solar power belongs to a portfolio of energy sources and access to energy is one of our society's greatest needs. As such, solar technology will always be at the whim of political events, dependent on complementary technologies and in competition with conventional sources of energy. Or will it? Has the technology advanced far enough that it could sustain itself without the need for economic subsidies or without the fear that a drop in oil prices would kill an entire industry?

These are all difficult questions, and the search for answers could fill volumes of writings on the subject. The intent of this survey is not to answer these questions directly. Rather, they provided the motivation for a study of renewable energy technologies and, in particular, a new and exciting type of solar cell technology using so-called *thin-film solar photovoltaic* material. Because it uses very little or no silicon at all, thin-film (TF) solar technology promises to reduce the cost of solar modules to a level where solar power could compete effectively with power generated from fossil fuel alternatives. Furthermore, because thin-film solar PV materials can be applied to surfaces as varied as glass, plastic and flexible metal foils, this emerging technology could open up a whole new range of applications that otherwise would not be possible using traditional solar cells. Could thin-film solar technology be disruptive to traditional poly-silicon solar technology that currently dominates the market? Which thin-film technology is likely to survive in the future? These are the types of questions that this thesis will attempt to answer.

The scope of this thesis is to analyze the technical merits of the different thin-film solar technologies, their market and applications, and the dynamics of a growing industry. We begin by comparing the different thin-film solar technologies against each other and against the dominant poly-silicon technology. We'll do so both from a technical as well as a market perspective. Next we will take a look at the make up of this industry and study the different technology strategies employed by players in the industry. We'll highlight a few manufacturers of each type of technology and present a snapshot of the industry in terms of current production and forecasted manufacturing capacity. Finally, we'll take a look at technology strategies employed by firms in this industry and recommend possible strategies for firms contemplating entering this industry.

The research approach includes an extensive interview program of all major firms in the thin-film solar industry. Data collected during these interviews was entered into a database allowing us to perform statistical analysis and graphical presentations. The information extracted from the interview data was augmented with an in-depth research of technical literature, web sites and trade journals and discussions with industry veterans.

The thesis draws from the knowledge and experience of people that have been involved in this field of study for many years. Travis Bradford, the editor of PV News, the industry's oldest newsletter, has provided invaluable insight and feedback for this study. Likewise, Mary Tripsas, Associate Professor in the Entrepreneurial Management Unit at Harvard Business School, has provided the guidance and insight into industry analysis and technology strategies.

This survey will argue that thin-film solar is a viable new solar technology that opens up new markets and applications and, in due course, will begin to displace, though not completely replace traditional solar PV technology.

3.1 Introduction to PV

First used in the 1890s, the term photovoltaic (PV) has come to refer to those materials that convert light energy into electrical energy. PV materials rely on the photo-electric effect to generate an electric current when exposed to electromagnetic radiation such as sunlight. It took a brilliant mind like Albert Einstein, to fully understand and explain this effect (Einstein's explanation of the photo-electric effect won him the Nobel Prize in physics in 1921), but, in principle, a metallic surface exposed to light will absorb the energy of incoming photons and release electrons instead thereby producing a current. Although the photo-electric effect can be observed with a wide range of electromagnetic radiations (x-rays, microwaves, ultraviolet, etc.), sunlight is the most common radiation and the term *photovoltaic cell* or *solar cell* refers to those devices intended to capture energy from sunlight to create electricity.

The amount of current generated depends on the wavelength of light (the color of the incoming light) and the type of material being used. Not all materials are able to release electrons easily. A certain energy threshold, also called *band gap energy*, is required to knock off an electron and release it from the material's crystalline structure to produce a current. Semiconductor materials such as silicon and germanium are ideal for PV devices because they exhibit low band gap energy that matches the energy of incoming photons. Optimizing the material to catch the photon's energy is very important. If the material has too high of a band gap it would not generate any current. Too low of a band gap, and the material would expend the extra amount of energy as heat[2], thus reducing its efficiency.

In addition, a semiconductor's level of conductivity can be modified through a process called *doping* allowing the material to conduct electricity nearly as well as metals[3]. When two types of differently doped semiconductor materials, known as n-type and p-type, are sandwiched together, a so-called *built-in electrical field* is generated which creates the necessary force that could drive the electric current through an external circuit to power a device such as a radio.

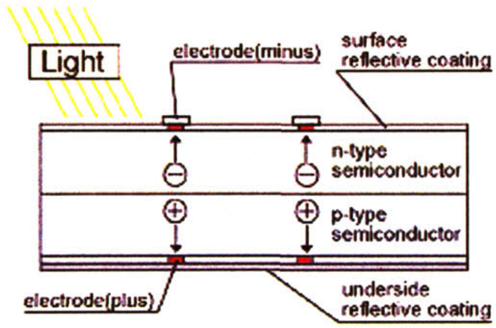

Figure 3-1 - Semiconductor p-n junction (courtesy Kyocera Corp.)

3.2 History of PV Materials

Crystalline silicon has been the material of choice for PV solar cells ever since the first practical solar cell was created in 1950s by physicists at Bell Laboratories[4]. Silicon's application in new electronic devices (transistors, integrated circuits, etc.) ensured constant technical progress that benefited the research into adjacent applications such as solar cells. But while silicon's use in electronic devices proceeded at breakneck speed (prompting Gordon Moore to declare his now-famous law), silicon's application in solar cells was slowed down by the availability of lower cost alternatives for electricity generation. One notable exception was the use in space applications where solar cells were found to be ideal power sources for satellites. With cost not being an issue and given the fact that the only other alternative to solar power was the use of chemical batteries (which are both heavy and could run out of power in a matter of days thereby silencing millions of dollars of equipment), the use of PV in space applications flourished.

Meanwhile, down on Earth, the prohibitive cost of producing solar cells kept the technology out of the electrical power generation market in the first two decades after their discovery. With prices as high as $200 per watt of electricity produced, solar cells could initially be found only in small commercial applications for novelty items such as toys, watches and calculators.

It took an external shock to change all this. With the oil crisis of the early 1970s, the use of solar cells for power generation increased significantly buoyed by advances in manufacturing technologies that reduced the selling price from $100 per watt in 1970 to $20 per watt in 1973. But more importantly, and with great significance to this study, the first oil shock also commenced the search for alternative PV materials that could produce electricity at much lower costs. This is how the field of thin-film PV materials began to take shape and a new industry was born.

Thin-film (TF) PV materials hold the promise of creating electricity from sunlight using only a fraction of semiconductor material and could be deposited on surfaces as varied as glass, plastic or flexible metal foil. TF PV could not only replace silicon-based solar panels, but they could also open up new markets and applications. Because of their low weight, TF PV solar panels can be fully integrated into commercial and residential buildings and because of their low cost and flexibility they could be used for mobile and disposable applications.

4 Thin-Film PV Technologies

The phrase *thin-film PV* describes both the physical property and the manufacturing method used to create a thin-film solar cell. Photovoltaic (PV) material that converts sunlight into electricity is deposited onto a surface in very thin, consecutive layers using a film manufacturing process such as sputtering, deposition or printing. The surface, also called a substrate, could be a material such as glass, plastic or metal and it could be either rigid or flexible. Turning this PV material and corresponding surface into a *solar cell* requires additional processing to protect the material and create the electrical contacts. A collection of solar cells assembled together into a weatherproof enclosure forms a *solar panel* or *module.* The distinction between solar cell and module is important when discussing conversion efficiencies and manufacturing costs later in this survey.

In the two decades since thin-film PV solar has become a reality, an impressive array of materials, substrates and manufacturing methods have been employed to produce thin-film solar panels. An in-depth discussion of thin-film PV technology must address topics such as PV material type, substrate type, manufacturing process & equipment.

Thin-film technology is generally classified by the type of PV material being used. We identify four broad categories of thin-film technologies:

1. **Amorphous Silicon (a-Si)**

2. **Cadmium Telluride (CdTe)**

3. **Copper Indium (Gallium) di-Selenide (CIS/CIGS)**

4. **Emerging (Dye-sensitized, Organic or Nano-materials)**

A question that is often asked in this industry is: "Which thin-film technology is better?" All thin-film technologies listed above are economically viable and have demonstrated the ability of ramping up into large-scale manufacturing. A more appropriate question for the future is "Which thin-film technology will dominate?" In addition, thin-film technologies considered as a whole could potentially be disruptive to traditional silicon-based PV technology. Therefore another important question is "Will thin-film PV technology replace traditional PV technology?"

In the next section we will analyze the merits of these four technologies and compare them against each other. To explore the theory that thin-film PV solar could be a disruptive technology to traditional PV solar, we will also compare thin-film technology with traditional poly-silicon technology.

4.1 Traditional PV Solar

Traditional PV solar technology uses pure silicon in the form of wafers sliced directly from a silicon ingot. The ingot is a silicon crystal grown in a high-temperature quartz crucible inside an atmosphere of inert gas. Today's silicon PV material could be either single crystal or multi-crystalline material hence the term *poly-silicon PV* is often used in the industry for solar PV technology which uses silicon as both PV material and substrate.

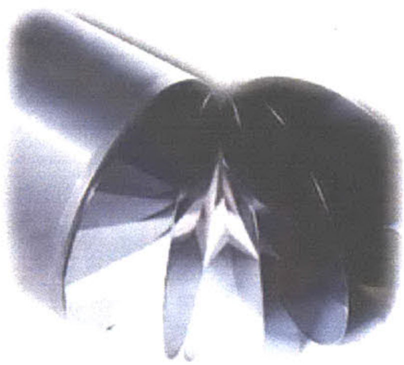

Figure 4-1 – Traditional PV uses wafers sliced from an ingot (courtesy www.svmi.com)

Manufacturing process of crystalline silicon-based PV cells uses 10-11 grams of silicon per Watt of output power[5]. With silicon prices as high as $300/kg (spot market price), an increase of over 65% in the last 3 years due to a shortage of silicon raw material, the traditional solar PV industry is experiencing a serious bottleneck in its upstream manufacturing process. Most experts agree, however, that this is a short-term situation which will be remedied by new silicon manufacturing plants that are coming on line. Regardless of this, to reduce the price of solar cells to the magic $1/W level, the solar industry must develop new ways to reduce the cost of silicon manufacturing or reduce the amount of silicon used in solar cells.

In recent years, various manufacturing processes have been devised that significantly reduce the amount of silicon used in creating a solar cell. Ribbon silicon is one such manufacturing process that promises to overcome the bottleneck by using as little as 6-7 grams per Watt with the potential to reach 4-5 grams per Watt in the near future. Despite improvements in the manufacturing process of traditional PV technology, thin-film PV technology could claim to use only a tiny fraction of the silicon used in traditional PV technology and, in some cases, no silicon at all. Because of this, and in conjunction with the renewed interest in solar technology as a clean source of energy, thin-film solar technology has taken off recently.

The solar power marketplace is currently dominated by traditional PV technology. As the figure below shows, traditional PV solar technology is still the basis for a majority of the total worldwide PV solar cells and modules produced in 2006.

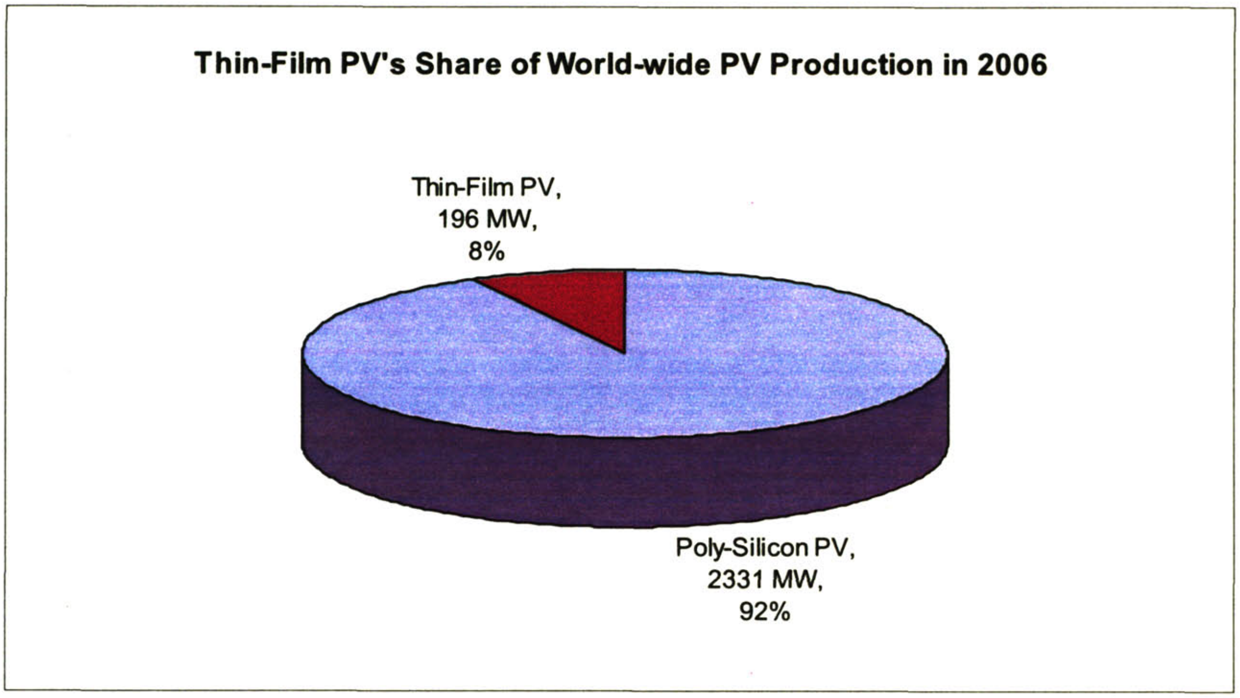

Figure 4-2 – Thin-film PV's share of world-wide solar PV production

In 2006, thin-film PV's share of total production was 8% compared with 5.8% in 2005, 5.3% in 2004 and 4.3% in 2003[6]. Whereas the compound annual growth (GAGR) of the entire industry was 49.5% since 2003, the growth in the thin-film sub-segment was 79% during the same period of time. The high growth rate coupled with the recent jump in market share suggests that thin-film PV technology is gaining acceptance in a rapidly growing energy sector.

4.2 Thin-Film PV Solar

Amorphous Silicon (a-Si)

Amorphous silicon technology is the most mature thin-film technology and was the first technology to be available commercially in large volumes. Research into this technology began as far as 1975 when Sanyo produced the first hybrid amorphous-Si on crystalline silicon cell. Since then, many thin-film companies have adopted this technology pushing the boundaries of its conversion efficiency and helping it achieve the largest production volume amongst all thin-film technologies. The evolution of this technology is illustrated in the number of different configurations available. Single junction configuration (a-Si) is the oldest, but has the lowest conversion efficiency. Double junction, a-Si (2), and triple-junction, a-Si (3), configurations have followed with increased conversion efficiency and stability over time. In addition, a new type of a-Si technology, called micromorph (µcSi/a-Si), has recently emerged, breathing new life into this mature technology.

Company	Country	Thin-Film Technology	Production Efficiency (%)	Substrate Type	Manufacturing Process
United Solar	US	a-Si (3)	7.9	stainless steel	vapor-deposition, roll-to-roll
Kaneka Silicon PV	Japan	a-Si	6.3	glass	chemical vapor deposition
Shenzhen Topray Solar	China	a-Si (2)	7	glass	chemical vapor deposition
Mitsubishi Heavy Industries	Japan	a-Si, μc/a-Si(2)	7.3	glass	plasma chemical vapor deposition
Bangkok Solar	Thailand	a-Si (2)	5.1	glass	chemical vapor deposition
Ersol Thin Film GmbH	Germany	a-Si	6	glass	chemical vapor deposition
Fuji Electric	Japan	a-Si		plastic film	roll-to-roll
CSG Solar AG (Pacific Solar)	Germany	c-Si	7	glass	deposition, laser printing, sputtering
SCHOTT Solar GmbH	Germany	a-Si (2)	5.3	glass	plasma deposition
Sharp	Japan	μcSi/a-Si	8.1	glass	dual layer deposition
PowerFilm Solar (Iowa Thin Films)	US	a-Si	5	flexible polymer	printing, roll-to-roll & monolithic integr.
Energy Photovoltaics (EPV)	US	a-Si (2)	5.5	glass	chemical vapor deposition
Terra Solar	US	a-Si	6	glass	plasma chemical vapor deposition
Sanyo Solar	Japan	a-Si (HIT)		various	plasma chemical vapor deposition
Heliodomi S.A.	Greece	a-Si		glass	chemical vapor deposition
Sinonar	Taiwan	a-Si		glass	chemical vapor deposition
Tianjin Jinneng Solar Cell Co.	China	a-Si		glass	chemical vapor deposition
ICP Solar (Intersolar)	Canada	a-Si	4.5	various	deposition & laser scribing
Flexcell (VHF Technologies SA)	Switzerland	a-Si	5.5	plastic	plasma deposition, low temperature
Free Energy Europe	France	a-Si	5	glass	chemical vapor deposition
API GmbH	Germany	a-Si		glass	chemical vapor deposition
Brilliant 234 GmbH	Germany	μcSi/a-Si	8	glass	chemical vapor deposition
Moser Baer	India	μcSi/a-Si	8	glass	chemical vapor deposition
NexPower Technology	Japan	a-Si (2)		glass	chemical vapor deposition
Solems	France	a-Si		glass	chemical vapor deposition
Gen3 Solar	US	a-Si		glass	chemical vapor deposition
XsunX	US	a-Si		glass	plasma chemical vapor deposition
Solar Cells (Koncar)	Croatia	a-Si	4.9	glass	chemical vapor deposition
Calyxo GmbH	Germany	a-Si		glass	chemical vapor deposition
HelioGrid	Hungary	a-Si		glass	chemical vapor deposition
T-Solar	Spain	μcSi/a-Si	8	glass	chemical vapor deposition
Sunfilm AG	Germany	μcSi/a-Si	8	glass	chemical vapor deposition

Figure 4-3 – Industry players in the amorphous Silicon category

Amorphous silicon solar cells are produced using a variety of deposition techniques at relatively low temperatures (< 300 degC)[7] using either a rigid or flexible substrate. Unlike in crystalline Si cells, the silicon used in a-Si cells is amorphous (has no shape) and can be deposited in thin layers from gaseous chemical compounds such as silane (SiH_4) or other hydrogenated silicon alloys.

A few companies have developed roll-to-roll manufacturing techniques using flexible substrates such as stainless steel or plastic film. United Solar, the largest manufacturer in this segment produces modules on flexible stainless steel, but the flexibility is limited due to the substrate thickness. One company, PowerFilm Solar, produces an a-Si cell on a paper-thin (0.025 mm) plastic foil[8]. Most other manufacturers use glass as the substrate.

A-Si solar cells are well suited to multi-junction layers which enable optimum utilization of the solar spectrum. As shown in the figure below, multiple layers of PV material tuned to specific spectral bands are deposited on a substrate and between two layers of electrical contacts to form the back and front contacts. Traditionally, though, a-Si solar cells consist of a single layer of PV material (a single-junction configuration).

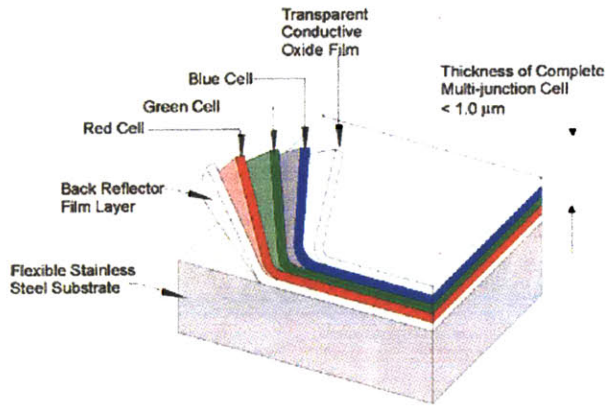

Figure 4-4 – Multi-junction amorphous Silicon (a-Si) cell structure (courtesy United Solar)

The efficiency of single-junction a-Si cells can be rather low (less than 5%) and because of this, the technology has evolved over the years into so-called double-junction (two layers) and triple-junction (three layers) cells with efficiencies as high as 8%. A major drawback of a-Si cells is the degradation of cell efficiency over time due to the so-called Staebler-Wronski (S-W) effect. Although this effect can be minimized through various manufacturing processes, it is nonetheless present and must be accounted for. On the other hand, despite the low conversion efficiency, a-Si cells tend to work better in low-light conditions and, therefore, are well-suited to indoor applications.

An important new developing in a-Si technology is the combination of an amorphous-Si layer with a microcrystalline silicon layer to form a tandem cell structure called a micromorph cell. The microcrystalline layer exhibits both enhanced optical absorption and stability under extended light-soaking conditions, thereby resulting in higher efficiency, stable cells. A number of established companies such as Sharp and Mitsubishi have migrated to this new technology and a majority of the new firms entering the industry in this technology sub-segment such as the new spin-off from Q-Cells (Brilliant 234) and Moser Baer (in partnership with Applied Materials) are adopting this new technology suggesting that there's still plenty of growth in this mature thin-film industry segment.

a-Si Technology		
Category	**Pros**	**Cons**
Materials	• Does not use expensive crystalline silicon only silicon alloys such as silane (SiH_4) • No feedstock limitation as silicon is one of the most common materials on Earth • Multiple materials can be deposited to capture wider spectrum of light • Reliable output even at low light levels	• Low efficiency • Exhibits efficiency degradation over time • Requires multiple layers of semiconductor material to achieve higher efficiencies and increased photo-stability
Surface	• Could use rigid or flexible substrates • Glass and stainless steel substrate-based modules can be warranted for 20 years • Can be deposited as both superstrate and substrate configurations	• Generally does not use very thin substrates so the flexibility is limited • Plastic-based modules have shorter lifetime
Manufacturing	• Uses proven manufacturing processes that have evolved over the years • Can be manufactured in countries with low-cost manufacturing labor • Supported by large companies with deep R&D pockets and manufacturing expertise	• Manufacturing of high-efficiency (triple-junction) cells can be expensive • Minimizing efficiency degradation adds manufacturing complexity

Cadmium Telluride (CdTe)

Next to amorphous-silicon, cadmium telluride (CdTe), is the other mature and well-understood thin-film technology. CdTe technology has been around nearly as long as amorphous silicon with the research beginning in early 1970s. The largest thin-film PV manufacturer in the world at this moment is First Solar, a company that produces CdTe-based solar panels. First Solar's 2006 production of 60 MW accounts for 32% of the worldwide thin-film PV market.

CdTe technology has two strong advantages. First, it uses a semiconductor material whose band-gap is perfectly matched with the solar spectrum thereby providing the potential for high-efficiency modules. Secondly, it has the lowest cost large-scale manufacturing process at the moment, and therefore the lowest price, making it an attractive option for large scale solar farm applications.

Company	Country	Thin-Film Technology	Production Efficiency (%)	Substrate Type	Manufacturing Process
First Solar	US	CdTe	9.5	glass	high-rate vapor deposition
Antec Solar Energy GmbH	Germany	CdTe	6.9	glass	chemical deposition & sputtering
Solar Fields. LLC	US	CdTe	9.5	glass	atmospheric pressure deposition
Primestar Solar	US	CdTe		glass	
AVA Technologies LLC	US	CdTe		glass	Air-to-Vacuum-to-Air (AVA) belt transport
Canrom	US	CdTe		glass	
Matsushita Battery	Japan	CdTe		glass	printing & sintering or CVD
Golden Photon	US	CdTe			

Figure 4-5 – Industry players in the CdTe technology category

CdTe-based solar cells are produced by depositing four layers of material: a tin oxide (TCO) layer used as the front electrical contact, followed by a layer of n-type CdS, followed by a layer of p-type CdTe and finally a layer of conducting material as the back electrical contact. Typical substrate used in CdTe technology is glass (soda lime or borosilicate glass). To be more precise, CdTe cells use a *superstrate* configuration, rather than a substrate configuration; the layers are deposited on the backside of a glass material as shown below and the light strikes the thin-film material through the deposition surface. Because of this, the superstrate configuration can only use transparent glass as the thin-film deposition surface.

Production module efficiency for CdTe is in the order of 9% with the highest conversion efficiency, in laboratory conditions, demonstrated to be 15.8%.

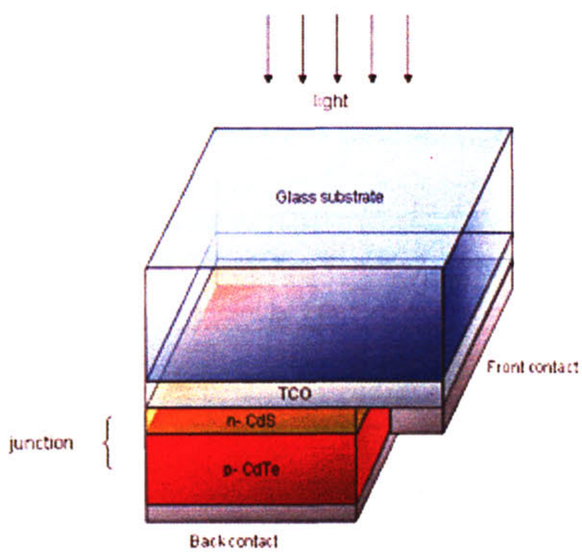

Figure 4-6 – Composition of a CdTe cell (courtesy www.pv21.org)

Only a few companies are involved in the development of CdTe-based devices. In all cases, they use a deposition process (chemical-bath or vapor deposition process) in conjunction with a sputtering process. Since the superstrate needs to be a glass surface, this limits the manufacturing process to a batch-type process, as opposed to a continuous, roll-to-roll process.

Matsushita Battery is one company experimenting with a radical new process of screen printing CdTe PV materials, however it does not have any large-scale manufacturing at the moment. In fact, only two companies, First Solar and Antec Solar, have large-scale manufacturing plants and are currently shipping CdTe-based solar modules.

CdTe Technology		
Category	**Pros**	**Cons**
Materials	• CdTe is an excellent PV material for converting sunlight to electricity • Uses very little Cadmium material (one 8-square-foot module contains less cadmium than one size-C NiCd flashlight battery[9]) • Research on CdTe as PV materials started in the early 1970s	• Uses cadmium (Cd) which, in elemental form, poses a health risk • Uses telluride (Te) which is a rare-earth material that could cause a supply bottleneck • Manufacturing facilities need to control worker's exposure to CdTe compound • Modules need to be properly recycled at the end of their lifetime to minimize environmental impact of CdTe compound
Surface	• Uses glass as a superstrate which is ideal for thin-film deposition • Lifetime of a glass-based module can reach 20 years	• Can <u>only</u> use glass as a deposition surface • If the glass breaks or cracks, the module can be rendered useless
Manufacturing	• largest thin-film PV manufacturing production in 2006 • presence of strong leader in the industry sub-segment (First Solar) • It's been shown that it could be produced efficiently in high-volumes • at $1.40/Watt it is the lowest cost large-scale manufacturing process at the moment	• CdTe technology cannot be manufactured on flexible substrates thus limiting the types of applications • Manufacturing process must contain evaporative, water and solid wastes • Can only be produced in batch-process as opposed to roll-to-roll process

Copper Indium (Gallium) Di-Selenide (CIS/CIGS)

CIGS technology holds the distinction of being the highest performance thin-film technology with record cell efficiency, in laboratory conditions, of 19.2%. Because of this, CIGS technology is being hailed as one of the most promising solar power technologies and the companies that have adopted CIGS technology have been the focus of much media and investor attention in recent months.

Although only two companies reported any significant production in 2006 (Global Solar in US and Wuerth Solar in Germany), 2007 could be breakout year for CIGS technology. Companies such as Miasole in US and Johanna Solar in Germany are quickly ramping up manufacturing capacity. Total CIGS manufacturing capacity could rival a-Si capacity by 2008.

Company	Country	Thin-Film Technology	Production Efficiency (%)	Substrate Type	Manufacturing Process
Miasole	US	CIGS	10	stainless steel foil	sputtering & roll-to-roll
Johanna Solar (Aleo Solar)	Germany	CIGS		glass	sputtering & chemical bath deposition
Honda Soltec	Japan	CIS			
Showa Shell Sekiyu	Japan	CIGS			
Wuerth Solar GmbH	Germany	CIS	11.5	glass	multi-source evaporation
DayStar Technologies	US	CIGS	10	flexible metal	sputtering & batch (gen2) or roll-to-roll (gen3)
Global Solar	US	CIGS	10.9	flexible steel foil	deposition & roll-to-roll
Sulfurcell	Germany	CI Sulfide	6.1	glass	deposition
Odersun	Germany	CIS	10	glass	roll-to-roll
Ascent Solar	US	CIGS	9.5	plastic	roll-to-roll & monolithic integration process
Avancis	Germany	CIS	9.4	glass	deposition
HelioVolt	US	CIGS	12	glass or metal	rapid, low temp process w/ monolithic integr.
Nanosolar	US	CIGS	10	flexible metal	printing & rapid thermal processing
Solibro GmbH	Germany	CIGS		glass	
Solarion GmbH	Germany	CIGS		flexible polymer	roll-to-roll process
International Solar Electric (ISET)	US	CIS		glass	non-vacuum approach
Flisom	Switzerland	CIGS		plastic	roll-to-roll & deposition
SoloPower	US	CIGS			electrochemical process
Solyndra	US	CIGS			sputtering
InterPhases Research	US	nCIS		flexible metal	roll-to-roll electroplating process
ITN Energy Systems	US	CIS		various	
Scheuten Solar	Netherlands	CIS		glass	

Figure 4-7 – Industry players in the CIGS technology category

CIGS technology uses a rigid or flexible substrate coated with multiple layers of materials beginning with a molybdenum (Mo) layer, followed by the CIGS absorber layer (the main layer that absorbs the photons; also the thickest layer), followed by a cadmium sulfide (CdS) buffer layer and then a zinc oxide (ZnO) layer. The device is completed by adding a top grid layer of aluminum or nickel and an antireflective coating. CIGS manufacturing process includes a variety of processes such as sputtering, electro-deposition and vapor deposition. In the assembly process, laser scribing is often used to connect the front and back sides of adjacent cells to create a CIGS module. Some companies use a so-called monolithic integration process to automatically build the connections between solar cells during the deposition process rather than using a separate assembly process. Monolithic integration can lead to significant manufacturing cost savings.

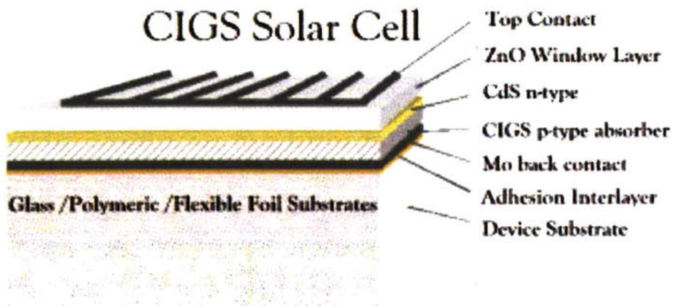

Figure 4-8 - CIGS solar cell structure (courtesy International Solar Electric, Inc)

Typical production efficiency of CIGS-based module is around 10%. In addition to high efficiency, CIGS-based solar cells also exhibit excellent stability over an extended period of time. Modules tested outdoors at NREL over a period of 10 years have shown no significant degradation in performance[10]. In addition, the CIGS material itself is very robust and defect tolerant.

CIGS Technology		
Category	**Pros**	**Cons**
Materials	• Highest efficiency at converting sunlight to electricity among thin-films technologies) • CIGS compound is robust and defect tolerant • Does not exhibit efficiency degradation over time	• Uses a rare-earth element (Indium) which could cause a supply bottleneck • Uses trace amounts of cadmium (Cd), a rare and toxic material
Surface	• Could use rigid or flexible substrates • Can be deposited on very thin plastic substrates using low-temperature processes • Glass and stainless steel substrate-based modules can be warranted for 20 years	• Only substrate configuration • Flexible substrates are less durable
Manufacturing	• Uses manufacturing processes developed and proven in other industries • Potential to have the lowest cost manufacturing because of roll-to-roll capability • Potential to offer the lowest capital expenditure cost (in $/W)	• No large-scale manufacturing yet • Complex manufacturing process requires the deposition of many thin-film layers

Emerging

Next generation thin-film technologies are still in the research phase, but a few companies are starting to move into pilot production phase and planning large-scale manufacturing using novel PV materials. Emerging thin-film PV cells (often called 3[rd] generation cells) use materials ranging from organic materials, to nano-based materials and dye-sensitized titanium oxide (DSC). The conversion of light to electricity in these materials occurs through a process of photo-synthesis similar to the one observed in biological materials. Emerging thin-film PV cells can be manufactured at very low cost because of relatively inexpensive materials and simple processing. Information about materials and manufacturing processes used in this field is scarce as many companies prefer to keep details of their technology secret while still conducting research.

In this category, the dye-sensitized solar cells (DSC) seem to have the biggest lead at the moment. Research into DSC technology has been going on for almost 20 years. One of the lead researchers in this field, Dr. Michael Graetzel, has helped bring this technology from laboratory into production. One company, G24 Innovations, is building a 30 MW pilot facility using a technology license from Konarka, an early pioneer in this field. Efficiency of DSC cells has been observed to be as high as 11% with production modules expected to reach an efficiency of about 5-6%.

Company	Country	Thin-Film Technology	Production Efficiency (%)	Substrate Type	Manufacturing Process
G24 Innovations	Wales	DSC	5	plastic	roll-to-roll
Dyesol	Australia	DSC		glass	roll-to-roll
Konarka	US	organic	target 5%	plastic	roll-to-roll, low-temperature
Innovalight	US	nano			
Stion	US	nano			
Global Photonic	US	organic			
Plextronics	US	organic		plastic	
Octillion	Canada	nano		glass	
SCHOTT Solar	Germany	DSC			
Solaris Nanoscience	US	DSC		plastic	roll-to-roll
AISIN Seiki	Japan	DSC		plastic	

Figure 4-9 – Industry players in the Emerging technology category

4.3 Equipment Suppliers

Most companies in this industry tend to develop manufacturing equipment in-house. A few firms offer both finished solar modules as well as processing equipment for other manufacturers. Energy Photovoltaics (EPV) is one company that has assisted in the adoption of amorphous Si technology by launching joint-ventures (Heliodomi in Greece and Tianjin Jinneng Solar in China) and providing manufacturing equipment and expertise to other manufacturers.

Most recently, a number of firms have entered this industry as equipment suppliers realizing that the same equipment used to make semiconductor electronic equipment can be used to make solar cells. Oerlikon Solar is a division of Oerlikon, a large equipment manufacturer that has traditionally made coating and vacuum equipment for high-technology products such as disk drives. Similarly, Applied Materials, the global leader in semiconductor equipment manufacturer for the electronic industry, recently entered the solar industry and is aggressively signing new deals to provide equipment for companies planning to introduce solar PV products using amorphous-Si technology.

For the most part, however, thin-film PV manufacturers develop their own technology in-house. Manufacturing expertise is one reason why many new firms are entering this industry. Deposition and sputtering technology is well understood from its use in industries such as disk-drive, optical media or flat panel displays. It is no surprise to see that thin-film PV technology adoption is boosted by the manufacturing experience available from other industries. Miasole, a start-up company with deep engineering expertise in disk-drive equipment manufacturing, used its manufacturing expertise as an important factor when deciding to enter the solar market.

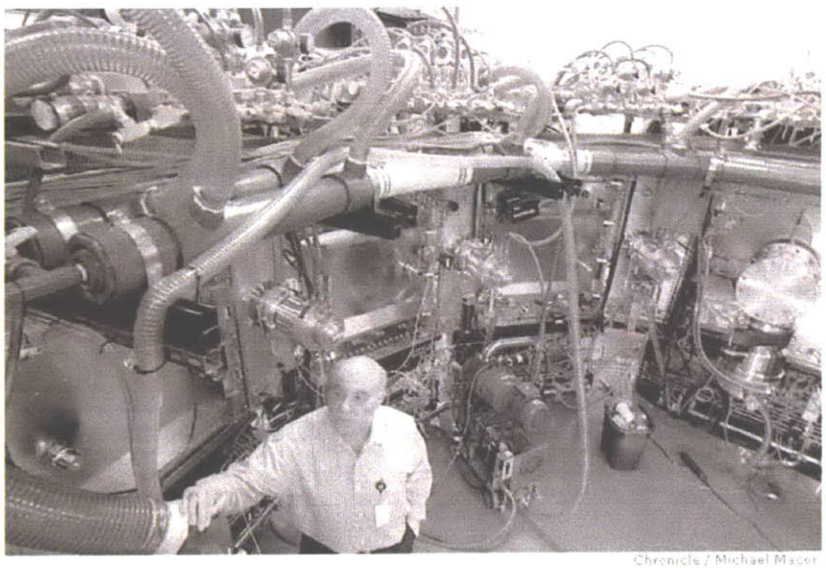

Figure 4-10 – Equipment used to manufacture CIGS solar cells[11]

4.4 Feedstock Issues

Unlike poly-silicon PV technology, thin-film PV technology is not affected by the world-wide shortage of crystalline silicon that is currently limiting the growth of traditional solar PV industry. Thin-film PV technology, however, has its own shortages to worry about because it relies on exotic materials such as tellurium and indium.

Martin Green, one of the leading physicists and thinkers in the solar PV arena, has formulated a simple set of criteria for PV materials. If PV is expected to play a major role in the future of our energy supply, the materials for solar cells need to be "inexpensive, nontoxic and readily available"[12].

CdTe technology uses both a rare material, tellurium (Te), and a toxic material, cadmium (Cd), as primary components. The issue of cadmium as a toxic element has been mentioned as a drawback for this technology. However, when considering this issue, it's important to put it in perspective. The majority of cadmium use is in re-chargeable batteries and only a small fraction is used in solar panels. Furthermore, the cadmium material is derived from zinc smelting waste and its use in solar panels actually prevents this toxic material from entering the environment[13] Regarding its availability, most people agree that, at the current rate, only a small percentage of the US consumption of cadmium will be required in the manufacture of CdTe solar cells[14]. On the other hand, tellurium could present much more of a limiting factor. Tellurium is used in very small quantities, approximately 10g of tellurium for a module surface area of 1 square meter (with a realistic potential to decrease this amount to about 3.5 g per square meter in the future). Experts generally agree that the forecasted production of tellurium could limit the expansion of CdTe module production to about 20 GW per year by 2030[15]. Compared with current production of 0.068 GW in 2006, this is by no means a limiting factor for the growth of this technology in the near future.

CIGS technology uses indium (In) a rare material that has to be purified to very high levels before it can be used in thin-film PV applications. Like tellurium, indium is a by-product of zinc manufacturing. Indium's rarity in conjunction with the fact that manufacturers of screen monitors and mobile phone displays are competing aggressively for the same raw material, has made indium a prized commodity with a highly volatile price. Whereas at the end of 2002 a kilogram of indium went for about $70, today that figure is almost $900 per kilogram, an increase by a factor of almost 13 times[16]. Despite the price volatility and after taking into consideration the amount needed by the other industries, there's plenty of indium available on the market today to sustain an annual production of 4 GW of CIGS modules. Considering that CIGS technology is only in its infancy and the fact that the supply of indium can easily increase if the market demands it, there appears to be no immediate limit in the growth of CIGS technology. If the mine operators double their annual production (which some of them admit it's easily possible), and the majority of this new increase goes towards CIGS PV applications, then the CIGS module production could start to run into feedstock issues at around the 20 GW production level[17].

In contrast with CdTe and CIGS, traditional silicon PV technology doesn't have to worry about such limitations in the supply of raw material. As the second most abundant element in earth's crust, silicon is an almost unlimited resource. Despite this fact, silicon is not inexpensive and is not readily available as demonstrated by the recent increase in price (65% increase in the last 3 years). With millions of dollars going into manufacturing plants for processing and producing pure silicon, the current shortage of silicon will be alleviated in the near future and the traditional PV technology will continue to grow as it makes its own progress in reducing the amount of material it needs for each Watt of power it generates.

What does this all mean? Traditional silicon-based PV will continue to dominate the PV industry as it sorts out its own feedstock issues. Thin-film PV technologies such as CdTe and CIGS will grow uninhibited by feedstock issues for the time being and will find niche applications and markets where they will dominate.

Where does this leave the amorphous silicon technology? A-Si thin-film technology uses the same raw material (silicon) as traditional PV technology, but does not have the feedstock limitations and can be manufactured at a lower cost. Therefore, since a-Si technology competes in the same markets with traditional PV technology, it has the chance to disrupt traditional PV technology. The only thing that holds back a-Si technology is its low electrical conversion efficiency and a manufacturing process that relies primarily on batch processing rather than a high-speed, roll-to-roll processing.

4.5 Thin-Film Efficiency

Efficiency is an important parameter that provides a figure of merit for a solar conversion device. Efficiency numbers are often misreported and can vary depending on the conditions under which the measurement was made. For example, the efficiency of a module is generally lower than the efficiency of a cell because the module efficiency must be averaged over the cells that comprise the module and not all cells have the same efficiency. Also, cells produced in large-scale manufacturing tend to have lower efficiency than the cells produced in laboratory conditions. Best efficiency numbers tend to be reported for small batches of carefully manufactured cells. In this survey we've tried to capture the module or cell production efficiency data rather than the best efficiency data that is often reported. To keep everything consistent, if a company did not have a pilot or large-scale manufacturing plant, we did not record the efficiency number in our database.

The best-research cell efficiencies are captured by a graph published regularly by NREL (Figure 4-11)[18]. Efficiency of solar PV technologies increases at a linearized rate of about 0.5% per year due to incremental improvements in materials and manufacturing processes. Technological breakthroughs which allow the efficiency to increase dramatically are often observed in each technology category.

In the thin-film PV category, CIGS technology is the most dynamic at the moment with recent breakthroughs around 1994. Coincidently, this also corresponds with a spike in the number of firms entering the market in the CIGS category a couple of years later. Although the NREL graph does not show it, the organic or so-called emerging PV technologies have also experienced recent breakthroughs.

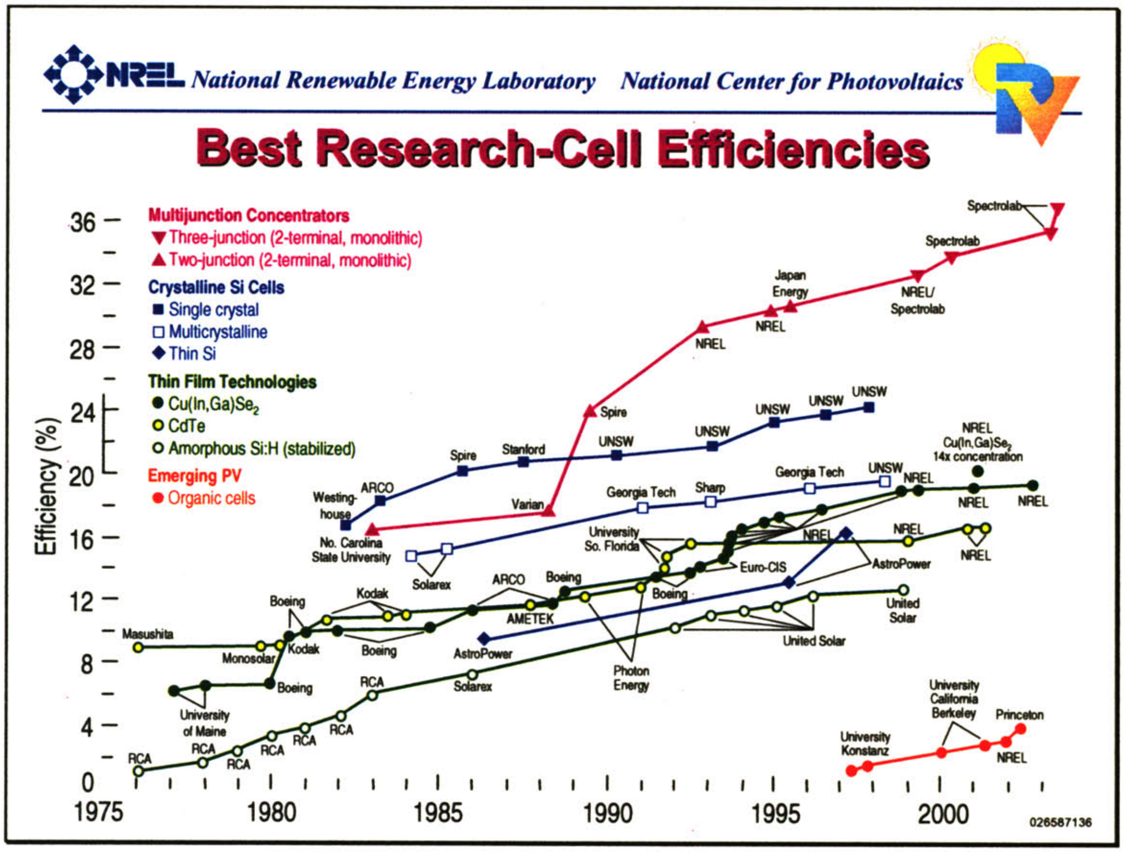

Figure 4-11 - Historical Best Research-Cell Efficiencies by Technology (courtesy NREL)

It is important to note that efficiency alone is not enough to judge the merits of a solar PV technology. A low-efficiency module that is also low-cost can be quite economical and competitive.

Comparison

Category	Technology	Record Cell Laboratory Efficiency (%)[19]	Average Module Production Efficiency (%)	Substrate Type	Manufacturing Process
Traditional PV	Mono-crystalline Si	24.7	14	rigid (silicon)	Crystal growth
Traditional PV	Multi-crystalline Si	20.3	11	rigid (silicon)	Crystal growth
2nd Generation TF	CIGS	19.2	10	Mostly flexible	Deposition, sputtering or printing
1st Generation TF	CdTe	16.5	9	glass	Deposition
1st Generation TF	a-Si	12.7	6	glass or flexible	Deposition
3rd Generation TF	Emerging (DSC, organic)	11.1	5	Mostly flexible	Mostly printing

A side-by-side comparison of the different PV technologies offers an illuminating picture. Average production efficiencies tend to be around half of the record cell efficiency measured in laboratory conditions. As a mature technology, traditional silicon is closest to reaching its record efficiency in production cells (one company, SunPower, makes a module with 18% production efficiency[20]).

In terms of efficiency, thin-film CIGS technology, a second generation thin-film PV technology, has leapfrogged first generation thin-film technologies such as a-Si and CdTe. High-efficiency and ability to be deposited on flexible substrates could lead to explosive growth for CIGS technology.

But amorphous-Si and CdTe technologies are not giving up yet. Although their efficiencies are lower, these first-generation thin-film technologies have found many new uses in building-integrated and solar farm applications where technology maturity expressed in durability and manufacturing volumes is more important than efficiency.

Emerging thin-film PV technologies such as DSC are quickly coming up from underneath. This will be a technology to watch in the next few years to see if it will compete effectively with the other thin-film technologies.

5 Thin-Film PV Manufacturers

In 2006, the world-wide thin-film PV production was 196 MW, nearly double the 2005 thin-film PV production. Despite the increase, thin-film PV production is still dwarfed by traditional poly-silicon production which was 2.3GW in 2006[21]. Thin-film's share of the total world-wide production in 2006 is 7.5% up from 5.8% in 2005. Top producers in this field are First Solar and United Solar in US, Kaneka in Japan and Shenzen Topray Solar in China.

Manufacturer	Thin-Film Technology	2006 Production (MW)	Market Share (%)
First Solar	CdTe	60	30.6%
Kaneka Silicon PV	a-Si	30	15.3%
United Solar	a-Si (3)	28	14.3%
Shenzhen Topray Solar	a-Si (2)	20	10.2%
Mitsubishi Heavy Industries	a-Si, µc/a-Si(2)	13	6.6%
Sharp	µcSi/a-Si	8.2	4.2%
Antec Solar Energy GmbH	CdTe	8	4.1%
Bangkok Solar	a-Si (2)	5	2.5%
Sanyo Solar	a-Si (HIT)	5	2.5%
Sinonar	a-Si	4	2.0%
SCHOTT Solar GmbH	a-Si (2)	3	1.5%
Global Solar	CIGS	2.5	1.3%
ICP Solar (Intersolar)	a-Si	2.5	1.3%
Wuerth Solar GmbH	CIS	2.4	1.2%
Energy Photovoltaics (EPV)	a-Si (2)	1.5	0.8%
Tianjin Jinneng Solar Cell Co.	a-Si	1.5	0.8%
	Total	**194.6**	**99.2%**

Figure 5-1 – Top Thin-Film PV manufacturers in the world

The majority of top producers are using updated amorphous-Si technology (tandem, triple-junction or micromorph) illustrating the resilience and innovating potential of this mature thin-film technology. Only two companies produced any significant amount of CIGS modules in 2006, Global Solar and Wuerth Solar. The production numbers for CIGS will change significantly in 2007 as new entrants plan to begin or ramp up production. Overall, the top producer in 2006 was First Solar which uses CdTe technology. Their production was twice the production of the nearest competitor, Kaneka Silicon PV.

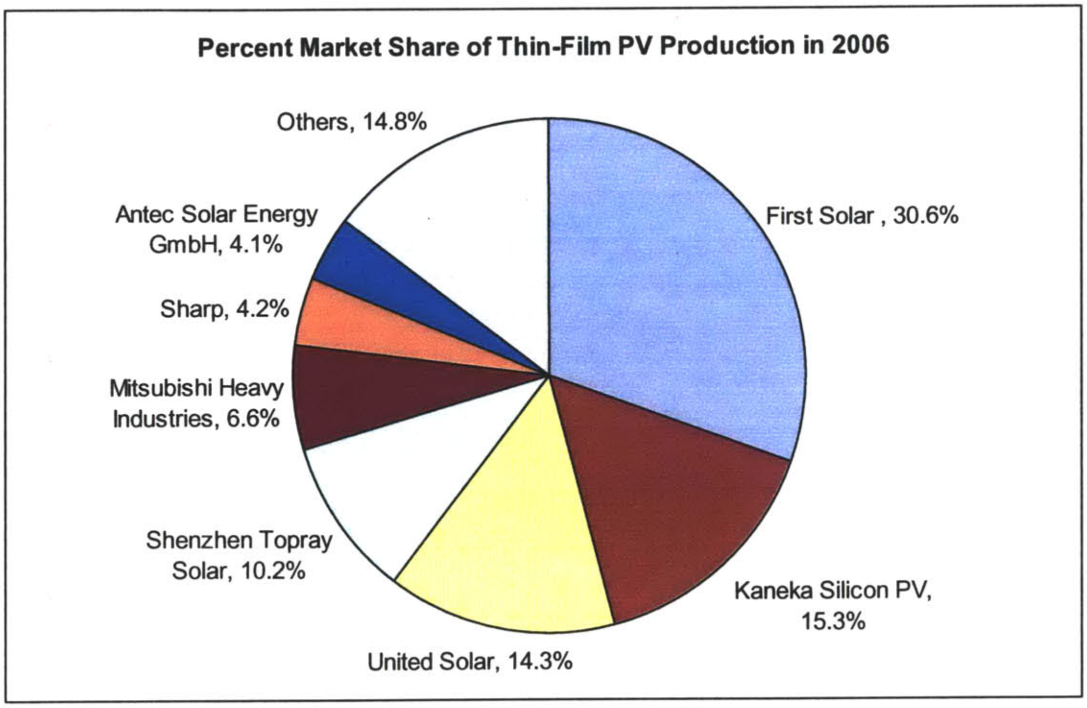

Figure 5-2 – Thin-film PV market share

Production vs. Capacity

In comparing the different thin-film PV technologies we distinguish between annual manufacturing production versus manufacturing capacity. Manufacturing capacity (also called nameplate capacity) is the minimum rated output of the manufacturing line(s) expressed in MW. Most firms in the industry will announce their new manufacturing capacity plans years in advance, thus we could judge the projected growth of the industry by tracking the announced capacities.

Manufacturing production is the actual annual amount (in MW) produced by the manufacturer. If the manufacturing line produced at maximum capacity, the production number would be equal to the capacity number. In reality, a manufacturing line is not used at maximum capacity. Production numbers depend on market demand, production forecasts and the productivity of the workforce.

Manufacturing production that is greater than 5 MW is generally considered to be volume manufacturing production. Anything below 1 MW is considered to be a pilot production, although some firms, such as Free Energy Europe, have produced less than 1 MW in a manufacturing environment for many years.

5.2 World-wide Manufacturing Production

It's not surprising to see that current world-wide manufacturing production is concentrated in amorphous-Si technology, a mature technology that has been adopted by many firms in this industry. CdTe technology has the next largest manufacturing production while CIGS is barely registering on the scale.

Technology	2000	2001	2002	2003	2004	2005	2006
a-Si	11.0	15.3	17.3	32.5	52.0	74.7	123.2
CdTe	0.0	0.0	0.0	0.0	7.0	28.0	68.0
CIGS	0.0	0.0	0.0	0.0	0.0	0.0	4.9
Emerging	0.0	0.0	0.0	0.0	0.0	0.0	0.0

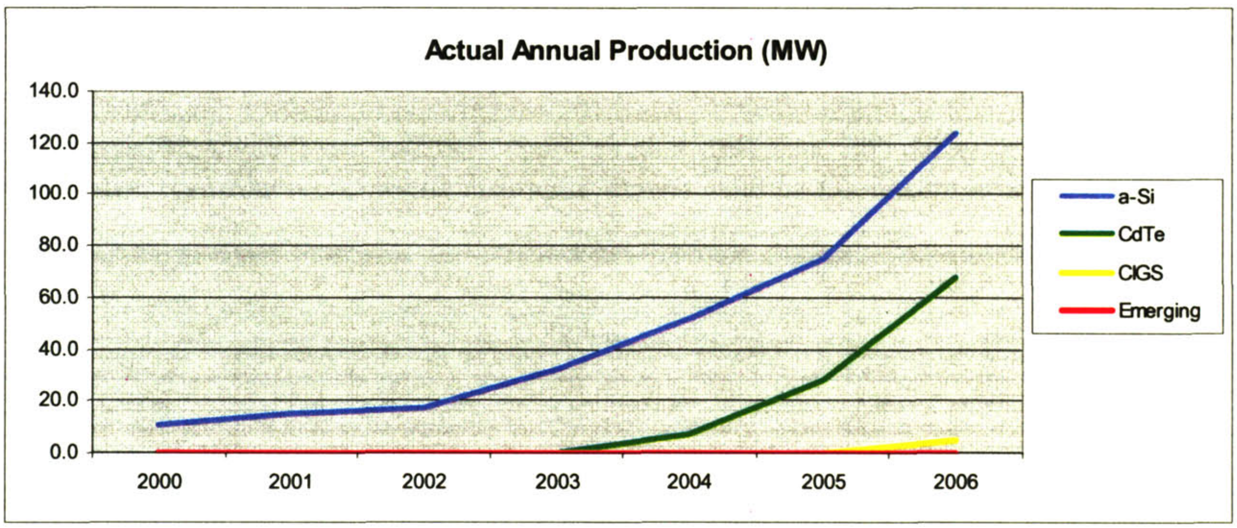

Figure 5-3 – Actual thin-film PV production in 2006

Production numbers show that thin-film technology has been buoyed by the increased awareness and demand for renewable energy products sparked by government subsidies in countries like Germany, US and Japan. As a rising tide that floats all boats, all thin-film technologies are showing increasing production numbers in the last few years.

5.3 World-wide Manufacturing Capacity

The picture is slightly different when looking at the manufacturing capacities planned through 2008, the year for which most capacity numbers have been announced at the time this thesis was written.

Technology	2000	2001	2002	2003	2004	2005	2006	2007E	2008E
a-Si	13.7	16.7	17.7	54.7	73.2	97.2	208.8	449.5	949.2
CdTe	0.0	0.0	0.0	0.0	0.0	60.0	85.0	225.0	300.0
CIGS	0.0	0.0	0.0	0.0	5.0	7.0	43.9	328.3	632.0
Emerging	0.0	0.0	0.0	0.0	0.0	0.0	0.0	30.0	200.0

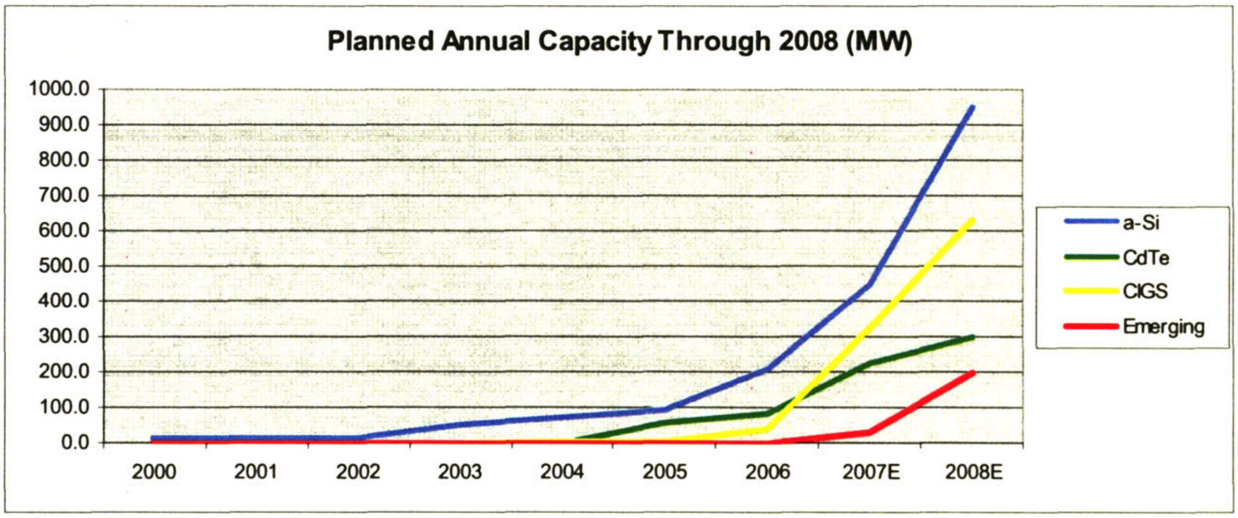

Figure 5-4 – Planned thin-film PV production up to 2008

Capacity of CdTe will level off as most entrants in the industry tend to adopt the newer CIGS technology. CIGS will experience tremendous growth. But this growth also comes with a lot of hype. One firm, Nanosolar, has announced a 430 MW plant capacity to be available by 2008. At this capacity, the Nanosolar plant would account for half of all CIGS capacity in 2008 (to be more realistic and to account for the possibility that this manufacturing capacity will not be fully available by the end of 2008, we've reduced Nanosolar's capacity contribution from 430 to 200 MW for 2008).

Although CIGS will experience tremendous growth through industry players with strong venture capital backing such as Miasole and Nanosolar, amorphous-Si will still dominate the thin-film PV industry through 2008 with almost 1 GW of planned capacity. Also, for the first time in 2008, we could see significant production of 3rd generation DSC cells through a company in Wales, G24 Innovations, which is planning to expand its production to 200 MW.

In 2007, the estimated thin-film world-wide manufacturing capacity will reach 1 GW, an increase of over 200% compared with 2006 when the manufacturing capacity was only 327 MW. From a geographical perspective, US-based firms will lead the way. Almost half of this capacity is planned in the United States or by US-based firms, but many of the manufacturing plants will be located overseas in regions such as Germany and Asia.

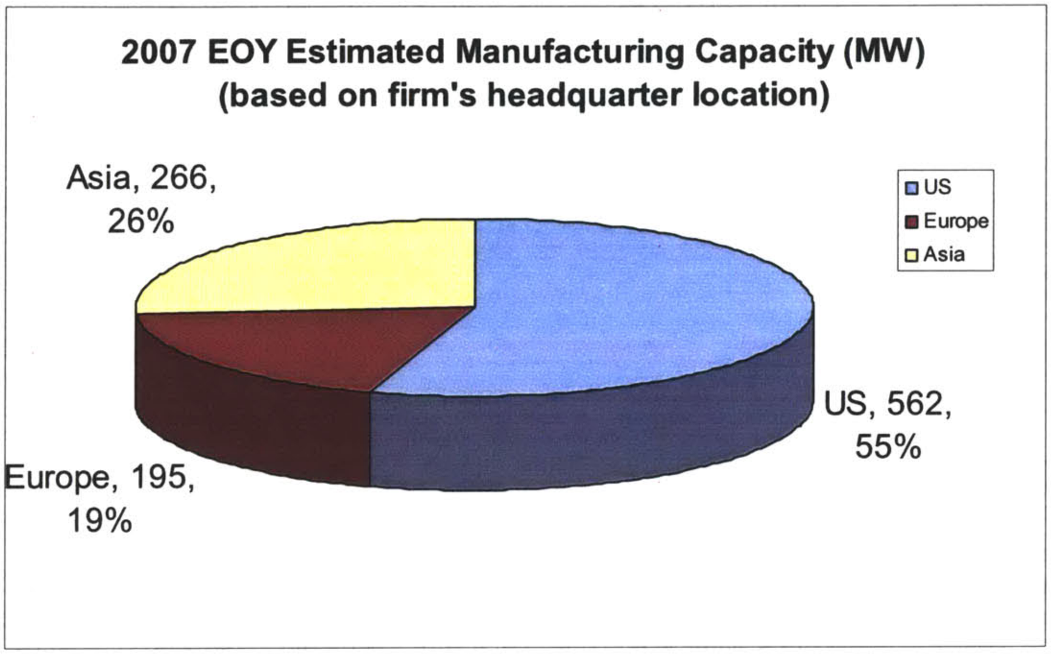

Figure 5-5 – Estimated manufacturing capacity in 2007

5.4 Manufacturing Costs

In general, manufacturing cost is driven by two factors: innovation and production volume. The innovation effect can be broken down into product innovation followed by process innovation. Product innovation in thin-film PV technologies focuses on increasing the efficiency of the solar cell (ie. the amount of power generated per meter square) using novel materials and solar know-how. Process innovation tends to follow product innovation but only after a dominant design has already emerged. With the exception of emerging (3rd generation) thin-film PV technology which is still in a product innovation phase, all other thin-film PV technologies have a dominant design (materials and surface) and have transitioned into the process innovation phase. This process innovation phase focuses on reducing the manufacturing costs (ie. the cost per meter square of producing a cell/module) using equipment scaling and process & yield control[22].

Published and estimated figures for manufacturing cost include raw material cost, labor costs, overhead and utilities and an annual capital recovery cost often estimated at around 14%[23].

CdTe technology, a mature thin-film PV technology, has the lowest manufacturing cost, as demonstrated by industry leader First Solar which recently announced an average manufacturing cost of $1.40/W.

Amorphous-Si technology is not far behind. Lowest manufacturing cost is estimated around $1.50/W, but a-Si still has plenty of room to reduce its cost through process innovation. A number of large equipment manufacturers such as Applied Materials, Moser Baer and Oerlikon have entered this market focusing on increasing manufacturing volume and reducing manufacturing cost by leveraging their proven technologies and processes from optical media and flat panel display industry.

Because of its roll-to-roll capability, higher efficiency and the use of thin, lightweight and flexible substrates, CIGS has the potential to have the lowest manufacturing cost of all thin-film technologies. Production volumes for CIGS are still very low and most manufacturers are not disclosing their manufacturing costs.

New Capital Expenditure

New capital expenditure in thin-film PV (expressed in dollars per Watts) can be tracked using company press releases announcing new plant installations and the corresponding financial outlay. When estimating these figures, however, it is important to distinguish between the capital expenditures for large manufacturing plants (greater than 100 MW) and small manufacturing plants (anything less than 100 MW). Economies of scale make a large plant capital expenditure be significantly lower than the capital expenditures for smaller plants.

New capital expenditure data provided useful information in helping us estimate how quickly a technology can ramp up to large-scale manufacturing. For small plants, both a-Si and CIGS technologies have comparable average capital expenditure costs, but for large plants, CIGS has a significant advantage. This is mainly due to the fact that CIGS tends to use a roll-to-roll manufacturing process that can produce large volumes at lower cost.

Conclusions

We expect that within 5 years, a-Si technology will overtake the CdTe technology as the most mature thin-film technology with the lowest cost manufacturing driven by large volume production and the entry of large players such Applied Materials and Oerlikon in this market.

However, a-Si's reign as the leader in lowest manufacturing may not last long. In the next 5-10 years, CIGS technology could become the lowest cost manufacturing technology because of its lower manufacturing equipment cost and significantly lower ramp up costs due to roll-to-roll capability. Despite this, amorphous-Si will remain the dominant thin-film technology in the thin-film industry. Its transition to roll-to-roll manufacturing coupled with continuous innovation and the simple fact that there is no feedstock limitation, could give a-Si the chance to become the dominant thin-film technology of the future.

6 Market & Applications

Growing concerns over the effects of global warming have increased the acceptance of solar PV technology as a viable renewable alternative to fossil fuels. In addition, government programs in Europe, United States and Japan are stimulating strong demand for solar technologies. Although thin-film PV's market share is still only a small fraction of the overall solar PV market, some of the features of thin-film PV technology open up new markets and make it an ideal technology choice for some applications.

6.1 Market segments

In general, thin-film PV competes with traditional crystalline PV in a market that can be segmented as follows:

1. **Grid-Tied Residential** – small installations (less than 4kW) aimed at reducing the electricity usage in residential dwellings. This is typically a roof-mounted installation.

2. **Grid-Tied Commercial** – larger installations (up to 100s of kW) for commercial buildings. Like in the residential market, a typical installation is roof-mounted.

3. **Grid-Tied Utility** – large installations of solar farms (1 MW or larger) that provide electricity to power utilities. Solar panels are typically installed on the ground and require a large area.

4. **Off-Grid Applications** – typically small installations (up to 100W) used in remote settings to charge batteries and power small appliances. Small consumer products that incorporate solar power fall in this category.

5. **Special Applications** – this category includes miscellaneous applications ranging from powering space satellites to government & military applications and other custom, specialized applications.

Thin-film PV competes in all these market segments with not only traditional PV, but also other forms of renewable energy such as wind power. Some thin-film technologies are a better fit for some of the market segments listed above. Based on interviews with various companies, independent research and the knowledge about the limitations of each technology, we present the target markets for each technology as color coded chart with three levels:

- primary market – the market where the technology has a best fit
- secondary market – market where the technology could compete effectively
- tertiary market – market where the technology could compete in the future

Thin-Film Technology	Grid-Tied Residential	Grid-Tied Commercial	Grid-Tied Utility	Special Applications	Off-Grid Applications
a-Si	**	***	**	*	***
CdTe	*	**	***	*	*
CIGS	***	**	*	***	**
Emerging	**	***	*	**	*

Legend	
	primary (***)
	secondary (**)
	tertiary (*)

Figure 6-1 – Market segment suitability for thin-film PV technologies

We can make the following observations regarding the market segments for thin-film PV:

- All thin-film PV technologies are targeting the **Grid-Tied Commercial** market segment (one of the largest market segments), but the market is a strong focus for a-Si technology and emerging technologies such as DSC.

- CdTe technology is well suited for **Grid-Tied Utility** market which is the focus for industry leader, First Solar. **Grid-Tied Commercial** market also has good potential for CdTe technology. A lack of flexible substrate options make it less suitable for Residential market, but CdTe makes up for this handicap by the fact that it competes well in one of the largest market segments, **Grid-Tied Utility**, which is projected to be a 30 GW market by 2015.

- Amorphous-Si technology is found in many **Off-Grid** applications in developing world countries because of its low cost and low power. **Grid-Tied Commercial** applications in the form of Building-Integrated PV (BIPV) are also an ideal market for a-Si because space is not a constraint and therefore lower efficiency does not present a big handicap.

- Today's CIGS technology shows preponderance for **Special Applications** (which includes Government, Military & Space applications) due to government grants and industry support from the US Government and because the technology can be customized to fit a multitude of form factors and shapes. In the future, CIGS will compete strongly in the **Grid-Tied Residential** market because its higher efficiency allows it to be adapted to applications where space is a legitimate constraint.

6.2 New Applications

Compared with traditional crystalline Si panels, thin-film PV panels generally have lower energy conversion efficiencies and thus require a larger area to generate the same amount of power. In applications where space is not a constraint, thin-film PV panels can be more economical than traditional PV panels because of their lower cost. Solar energy farms and roof-top installations (Grid-Tied Commercial and Utility) are therefore ideal markets for thin-film PV panels.
Within the commercial market segment, a new field of applications called Building Integrated Photovoltaic (BIPV) is starting to emerge as an ideal application for thin-film PV. BIPV applications aim to design and integrate PV panels into the building architecture by replacing conventional building materials with PV panels that could serve as vertical facades, roofing material, semi-transparent skylight systems or awnings. Because thin-film PV panels are less expensive and more aesthetically pleasing, they are better suited for BIPV applications than their crystalline Si counterparts. In addition, because thin-film PV can be deposited on flexible, but durable substrates, it could be used as roofing material in residential applications with the dual purpose of protecting the residence from the elements while generating power at the same time. For these reasons, BIPV is an exciting new field of applications for thin-film PV solar panels and will stimulate a growth rate estimated as much as 60% through 2010[24].

Figure 6-2 – Amorphous Si PV panels used in BIPV application (courtesy Kaneka Silicon)

Thin-film PV ability to be deposited on flexibility substrates is the other important feature that enables a new set of applications which were not possible before with crystalline Si technology. Besides the fact that they could be produced in high volumes and at low cost, flexible PV cells can be integrated into a variety of consumer products such as portable electronics or power-generating fabrics for structures such as tents, awnings and roofs. The roll-to-roll manufacturing process of flexible cells allows manufacturers to customize the size of the solar cell to fit a range of applications from the small consumer electronics to the large panels used in building materials. CIGS technology in particular is well positioned to take advantage of these applications because it has higher conversion efficiency and therefore can generate more power in smaller form-factors.

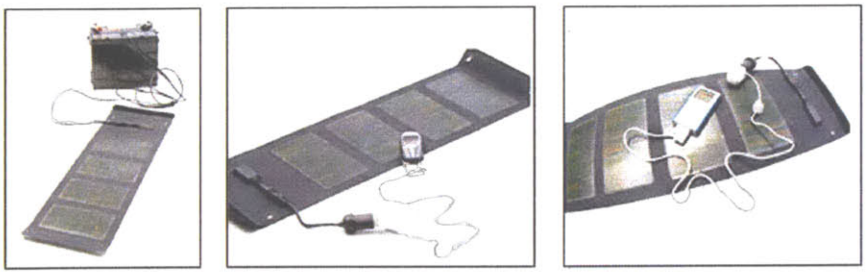

Figure 6-3 – CIGS thin-film PV used in off-grid application (courtesy Global Solar)

6.3 Market Strategies

Analyzing the market segments from a technology strategy point of view, we can see that each thin-film technology has advantages in different market segments. There isn't much overlap between market segments and therefore we see little competition between the different thin-film PV technologies, at the moment. This situation may not remain the same for too long. Emerging technologies like DSC could be disruptive for a-Si because they not only target the same market segments, but could offer similar performance at lower cost. As the production volumes for CIGS technology ramp up, it could start competing with a-Si in the Grid-Tied Commercial market, although a better strategy may be to take on the Off-Grid Applications market where CIGS has a better chance to compete with traditional PV technology.

Although the market picture suggests that, at the moment, there is little competition among the thin-film PV technologies, as they mature, they'll start competing with each other at some level. More importantly, we should analyze the potential for thin-film PV to displace the traditional PV technology in the market. Currently, thin-film PV technologies simply expand the existing market. Whether it's through applications such as solar farms (which are relatively new), or developing world applications or BIPV, thin-film PV technology has so far served to expand the overall adoption of solar PV. What will happen when thin-film PV will become a substitute for traditional PV? CIGS has the potential to displace traditional PV in the Residential market because it will offer lower cost alternative at nearly the same conversion efficiency, but will bring a new value proposition through its lightweight and flexibility characteristics. Likewise, amorphous Si can expand beyond BIPV and begin to capture market share from traditional PV in the Commercial market.

7 Industry Snapshot

At last count there are approximately 73 firms in this growing industry. The size of thin-film PV industry has been growing at a steady pace, but the activity has picked dramatically in recent years. Just in the last year, 18 firms have entered the industry in all four thin-film PV categories. This recent upsurge can be attributed to the new geo-political situation that has seen the rise of all renewable energy sectors. Some growth can be attributed to technology development and maturity as in the case of amorphous Si.

The following is a comprehensive list of current thin-film PV manufacturers around the world. The list has been updated constantly to reflect the entry of new firms in this industry up to and including April 2007.

Company	Technology	Region	Country	State	Ownership	Founded
First Solar	CdTe	US	US	AZ	Public	1999
Primestar Solar	CdTe	US	US	CO	Private	
AVA Technologies LLC	CdTe	US	US	CO	Private	2006
Golden Photon	CdTe	US	US	CO	Private	
Canrom	CdTe	US	US	NY	Private	1999
Solar Fields. LLC	CdTe	US	US	OH	Private	2005
Matsushita Battery	CdTe	Japan	Japan		Division	
Antec Solar Energy GmbH	CdTe	Germany	Germany		Private	2003
Global Solar	CIGS	US	US	AZ	Private	1996
Miasole	CIGS	US	US	CA	Private	2004
Nanosolar	CIGS	US	US	CA	Private	2003
International Solar Electric (ISET)	CIS	US	US	CA	Private	
SoloPower	CIGS	US	US	CA	Private	2006
Solyndra	CIGS	US	US	CA	Private	2006
InterPhases Research	nCIS	US	US	CA	Private	
Ascent Solar	CIGS	US	US	CO	Public	2005
ITN Energy Systems	CIS	US	US	CO	Private	
DayStar Technologies	CIGS	US	US	NY	Public	1997
HelioVolt	CIGS	US	US	TX	Private	2001
Honda Soltec	CIS	Japan	Japan		Division	2002
Showa Shell Sekiyu	CIGS	Japan	Japan		Division	2005
Johanna Solar (Aleo Solar)	CIGS	Germany	Germany		Joint-Venture	2006
Wuerth Solar GmbH	CIS	Germany	Germany		Private	1999
Sulfurcell	CI Sulfide	Germany	Germany		Private	2002
Odersun	CIS	Germany	Germany		Private	2002
Solibro GmbH	CIGS	Germany	Germany		Joint-Venture	2006
Solarion GmbH	CIGS	Germany	Germany		Private	2000
Avancis	CIS	Germany	Germany		Joint-Venture	2006
Flisom	CIGS	Europe	Switzerland		Private	2005
Scheuten Solar	CIS	Europe	Netherlands		Private	1999

Company	Technology	Region	Country	State	Ownership	Founded
ICP Solar (Intersolar)	a-Si	US	Canada		Public	1988
XsunX	a-Si	US	US	CA	Public	2003
Gen3 Solar	a-Si	US	US	CA	Private	2005
PowerFilm Solar (Iowa Thin Films)	a-Si	US	US	IA	Public	1988
United Solar	a-Si (3)	US	US	MI	Division	1990
Terra Solar	a-Si	US	US	NJ	Private	2005
Energy Photovoltaics (EPV)	a-Si (2)	US	US	NJ	Private	1991
Sharp	µcSi/a-Si	Japan	Japan		Division	2006
Sanyo Solar	a-Si (HIT)	Japan	Japan		Division	1980
NexPower Technology	a-Si (2)	Japan	Japan		Division	2007
Mitsubishi Heavy Industries	a-Si, µc/a-Si(2)	Japan	Japan		Division	2002
Kaneka Silicon PV	a-Si	Japan	Japan		Division	1999
Fuji Electric	a-Si	Japan	Japan		Division	2004
SCHOTT Solar GmbH	a-Si (2)	Germany	Germany		Division	2006
Ersol Thin Film GmbH	a-Si	Germany	Germany		Division	2006
CSG Solar AG (Pacific Solar)	c-Si	Germany	Germany		Private	2004
Calyxo GmbH	a-Si	Germany	Germany		Division	2005
Brilliant 234 GmbH	µcSi/a-Si	Germany	Germany		Division	2006
Sunfilm AG	µcSi/a-Si	Germany	Germany		Private	2007
API GmbH	a-Si	Germany	Germany		Private	2006
T-Solar	µcSi/a-Si	Europe	Spain		Private	2007
Solems	a-Si	Europe	France		Private	
Solar Cells (Koncar)	a-Si	Europe	Croatia		Private	1987
HelioGrid	a-Si	Europe	Hungary		Private	2007
Heliodomi S.A.	a-Si	Europe	Greece		Joint-Venture	2000
Free Energy Europe	a-Si	Europe	France		Division	1985
Flexcell (VHF Technologies SA)	a-Si	Europe	Switzerland		Private	2004
Tianjin Jinneng Solar Cell Co.	a-Si	Asia	China		Joint-Venture	2004
Sinonar	a-Si	Asia	Taiwan		Private	1994
Shenzhen Topray Solar	a-Si (2)	Asia	China		Private	2002
Moser Baer	µcSi/a-Si	Asia	India		Division	2007
Bangkok Solar	a-Si (2)	Asia	Thailand		Private	2003
Octillion	nano	US	Canada		Private	2006
Innovalight	nano	US	US	CA	Private	2002
Stion	nano	US	US	CA	Private	2006
Konarka	organic	US	US	MA	Private	2001
Global Photonic	organic	US	US	NJ	Private	2002
Plextronics	organic	US	US	PA	Public	2006
Solaris Nanoscience	DSC	US	US	RI	Division	2004
AISIN Seiki	DSC	Japan	Japan		Division	
SCHOTT Solar	DSC	Germany	Germany		Division	
G24 Innovations	DSC	Europe	Wales		Private	2006
Dyesol	DSC	Asia	Australia		Public	2006

7.1 Technology Status by Region

United States region (including Canada) has the largest number of firms in the industry. This count was recently raised by the entry of a few firms in the Emerging (3rd Generation) technology category. Europe is host to the largest number of firms adopting the a-Si technology, but, more noticeable, the firms in Asia are primarily adopters of a-Si technology. This is a result of the fact that a mature technology like a-Si can now be produced by low-cost manufacturers in Asia using manufacturing expertise and equipment that is readily available in Japan.

Whereas US firms are evenly split among all four technology categories, the distribution of European and Asian firms is more polarized. European firms still have a large hold in a-Si technology because of an early start there, but are now making a big push into the new CIGS technology, their confidence boosted by government subsidies which have helped the European solar PV market soar in the last few years.

a-Si	7.0	14.0	11.0
CdTe	7.0	2.0	1.0
CIGS	11.0	9.0	2.0
Emerging	7.0	2.0	2.0
Total	**32.0**	**27.0**	**16.0**

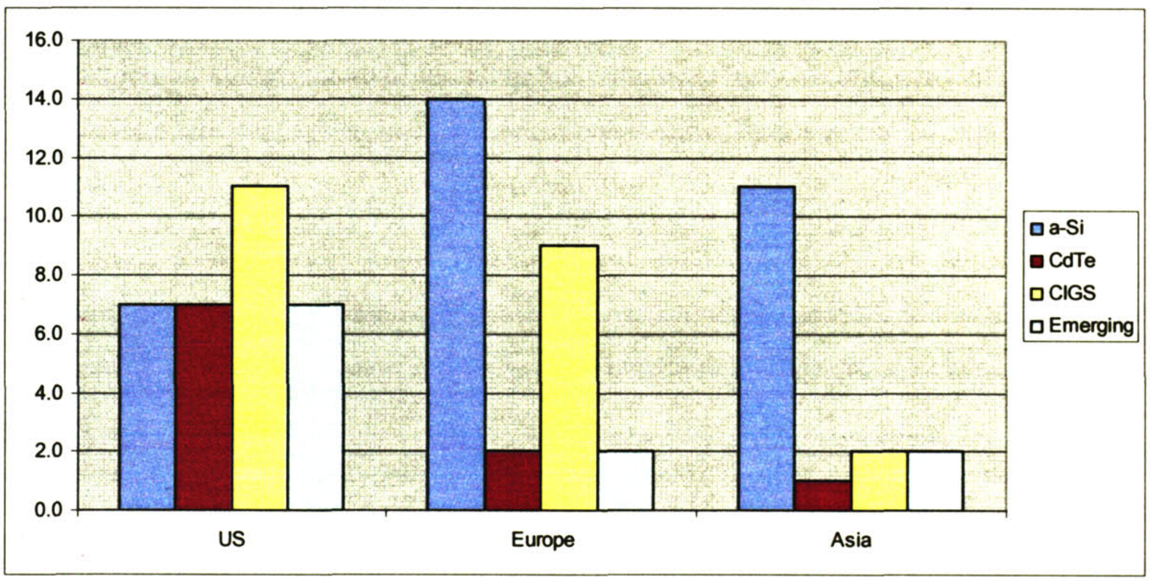

Figure 7-1 – Thin-film PV technology distribution by region

It is difficult to project the distribution of firms in this industry in the next 5-10 years, but generally we could assume that, as technologies mature and the manufacturing cost goes down, more Asian firms will enter the market to capitalize on their low labor cost advantage.

A look at the ownership structure by technology (Figure 7-2) reveals that amorphous-Si, the most mature technology, is supported by divisions of large firms such as Sanyo, Mitsubishi or Sharp, primarily located in the Japan/Asia region. Of the remaining independent firms, very few are public, a sign that the industry is still young and growing. CIGS technology in particular is supported by new start-ups with strong venture capital backing.

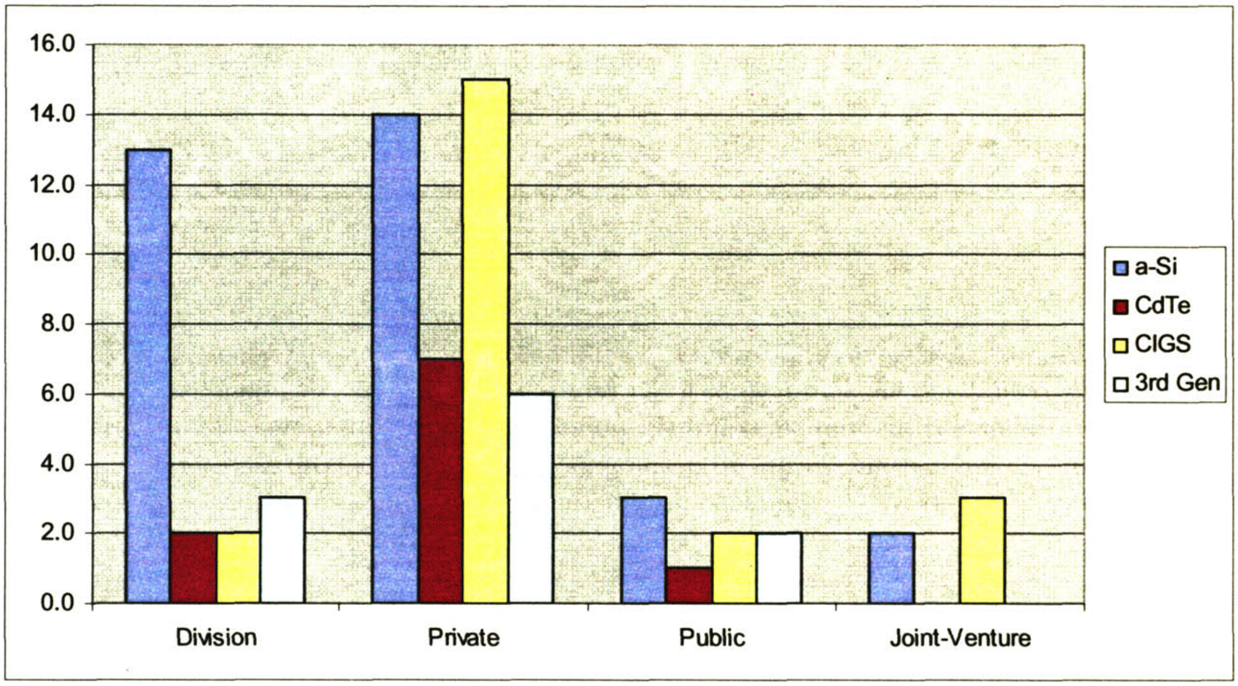

Figure 7-2 – Thin-film PV technology distribution by ownership structure

Total thin-film manufacturing capacity is projected to be around 1 GW by the end of 2007 with US-based firms leading the way. Although the US-region shows the largest production capacity, it is important to note that a large portion of this capacity comes from manufacturing plants that are being commissioned overseas in countries like Germany, Philippines, Thailand, Malaysia and China.

Company	Region	Thin-Film Technology	2007 EOY Capacity (MW) *estimated*
First Solar	US	CdTe	**200**
Miasole	US	CIGS	**200**
United Solar	US	a-Si (3)	**118**
DayStar Technologies	US	CIGS	**10**
PowerFilm Solar (Iowa Thin Films)	US	a-Si	**10**
Energy Photovoltaics (EPV)	US	a-Si (2)	**10**
Global Solar	US	CIGS	**5**
Terra Solar	US	a-Si	**5**
ICP Solar (Intersolar)	US	a-Si	**2.5**
Ascent Solar	US	CIGS	**1.5**
Total	**US**		**562**

Company	Region	Thin-Film Technology	2007 EOY Capacity (MW) *estimated*
Ersol Thin Film GmbH	Germany	a-Si	**40**
Johanna Solar (Aleo Solar)	Germany	CIGS	**30**
G24 Innovations	Europe	DSC	**30**
Antec Solar Energy GmbH	Germany	CdTe	**25**
CSG Solar AG (Pacific Solar)	Germany	c-Si	**20**
SCHOTT Solar GmbH	Germany	a-Si (2)	**18**
Wuerth Solar GmbH	Germany	CIS	**14.8**
Sulfurcell	Germany	CI Sulfide	**5**
Heliodomi S.A.	Europe	a-Si	**5**
Odersun	Germany	CIS	**4.5**
Flexcell (VHF Technologies SA)	Europe	a-Si	**1.25**
Free Energy Europe	Europe	a-Si	**1.2**
Total	**Europe**		**194.75**

Company	Region	Thin-Film Technology	2007 EOY Capacity (MW) *estimated*
Kaneka Silicon PV	Japan	a-Si	**55**
Bangkok Solar	Asia	a-Si (2)	**50**
Mitsubishi Heavy Industries	Japan	a-Si, μc/a-Si(2)	**36**
Fuji Electric	Japan	a-Si	**30**
Honda Soltec	Japan	CIS	**27.5**
Showa Shell Sekiyu	Japan	CIGS	**20**
Shenzhen Topray Solar	Asia	a-Si (2)	**20**
Sharp	Japan	μcSi/a-Si	**15**
Sanyo Solar	Japan	a-Si (HIT)	**5**
Sinonar	Asia	a-Si	**5**
Tianjin Jinneng Solar Cell Co.	Asia	a-Si	**2.5**
Total	**Asia**		**266**

Figure 7-3 – 2007 End-of-Year thin-film PV capacity by firm

7.2 Major Industry Players

Thin-film PV competitive landscape is made up of a few large players with many years of experience and significant manufacturing capacity and many smaller players that have recently entered the industry. Of the small players a few of them have the potential to become significant players in the industry. The next section will highlight some of established firms and the upcoming ones with good potential.

First Solar (CdTe)

First Solar is the industry's largest manufacturer at the moment with a total production of 60 MW in 2006. Although the headquarters are based in Arizona, its current manufacturing facility is located in Toledo, Ohio. The company is in the process of completing a manufacturing plant in Germany and has broken ground on another one in Malaysia. First Solar, which entered the market in 2002, is one of the few public companies in this industry. It recently announced the first profitable quarter in its short history. First Solar has shown that CdTe technology is viable and can be produced in large volumes at an economical cost.

United Solar (a-Si)

United Solar is an industry veteran with an early lead in amorphous-Si research and manufacturing. The company produces thin-film solar panels on stainless steel substrates using a unique triple-junction cell with efficiency as high as 8%, a world-record for a-Si technology. Its manufacturing production has been steadily increasing since 2000 reaching a respectable 28 MW in 2006. Over the years, United Solar has played a significant role in the technological evolution and subsequent adoption of thin-film PV.

Miasolé (CIGS)

Miasole is an example of the new breed of start-ups embracing the promising CIGS technology. Based in Silicon Valley, the company is backed by first-tier VCs and has a strong engineering background in deposition technologies previously used in disk-drive manufacturing. Although the company has no significant manufacturing at the moment, it plans to install a total capacity of 200 MW by the end of 2007 and begin large volume production by 2008. If it all goes according to plan, Miasole, could be one of the top three manufacturers of thin-film PV in the next few years.

A few of the large, established players in traditional PV technology are starting to transition to thin-film PV technology. Among them:

Sharp (a-Si)

Sharp is the largest producer of crystalline silicon-based modules in the world. Its subsidiary in Japan is also a strong player in the amorphous silicon technology using an updated micromorph technology which has the highest efficiency (8%) among all a-Si modules. Although the company's thin-film PV products are only a fraction of the overall PV module output, it still ranked sixth in the world-wide thin-film PV production in 2006 with a total production of 8.2 MW. Its growth in thin-film PV will be moderate (estimated 15 MW capacity by 2008) as the company continues to focus on its traditional line of PV modules.

Q-Cells (a-Si, CIGS)

Q-Cells, a German-based company, is the second largest producer of traditional PV technology behind Sharp. Q-Cells is well known in the industry for its many partnerships and joint ventures in both poly-silicon and thin-film PV technology sectors. Q-Cells is a perfect example of a company aiming to compete in all sectors of solar PV. Its investment in Solibro, a German company, gives it a foothold in the promising CIGS technology category. Amorphous silicon however seems to be the preferred technology for its diversified investment strategy. Q-Cells has invested or spun-off no less than four different companies competing with amorphous silicon technology: Brilliant 234 and Calyxo are wholly owned subsidiaries while CSG Solar and Flexcell are partial investments.

Avancis (CIGS)

Avancis is a joint venture between Shell and St. Gobain aiming to produce a glass-based CIGS module. This is a notable development not so much because of a technology breakthrough, but because of a radical breakthrough in business strategy. Shell (which for many years was a major player in traditional PV sector producing as much as 59 MW of crystalline Si modules in 2005), has completely divested its interests in crystalline silicon technology and is now focusing solely on CIGS technology. In cooperation with St. Gobain of France, Shell formed Avancis a new company in 2006 and is planning to install up to 20 MW of CIGS module capacity by 2008. This is the first industry player that has completely transitioned from the old technology to the new thin-film technology.

A closer look at the make up of the traditional PV industry shows that half of the top ten firms in that industry are currently producing thin-film PV products, and, perhaps more importantly, have plans to increase their thin-film PV capacity suggesting an increasing adoption of the technology.

2006 Rank	Company	2006 Traditional PV Production (MW)	2006 Thin-Film PV Production (MW)	2007 Thin-Film PV Capacity (MW)
1	Sharp	425.8	8.2	15
2	Q-Cells	253	0.5	21
3	Kyocera	180	-	-
4	Suntech	158	-	-
5	Sanyo	150	5	5
6	Mitsubishi	111	13	36
7	Motech	110	-	-
8	Schott Solar	96	3	18
9	Deutsche Solar / Shell	86	-	-
10	BP Solar	86	-	-

Figure 7-4 – Traditional PV manufacturers transitioning to thin-film PV

7.3 Industry Evolution

A picture of the entire thin-film PV industry would not be complete without a look at its evolution over the years. Mapping the number of firms that have entered (and exited) the thin-film PV industry and comparing it with the traditional PV industry provides additional insight for a technology strategy discussion.

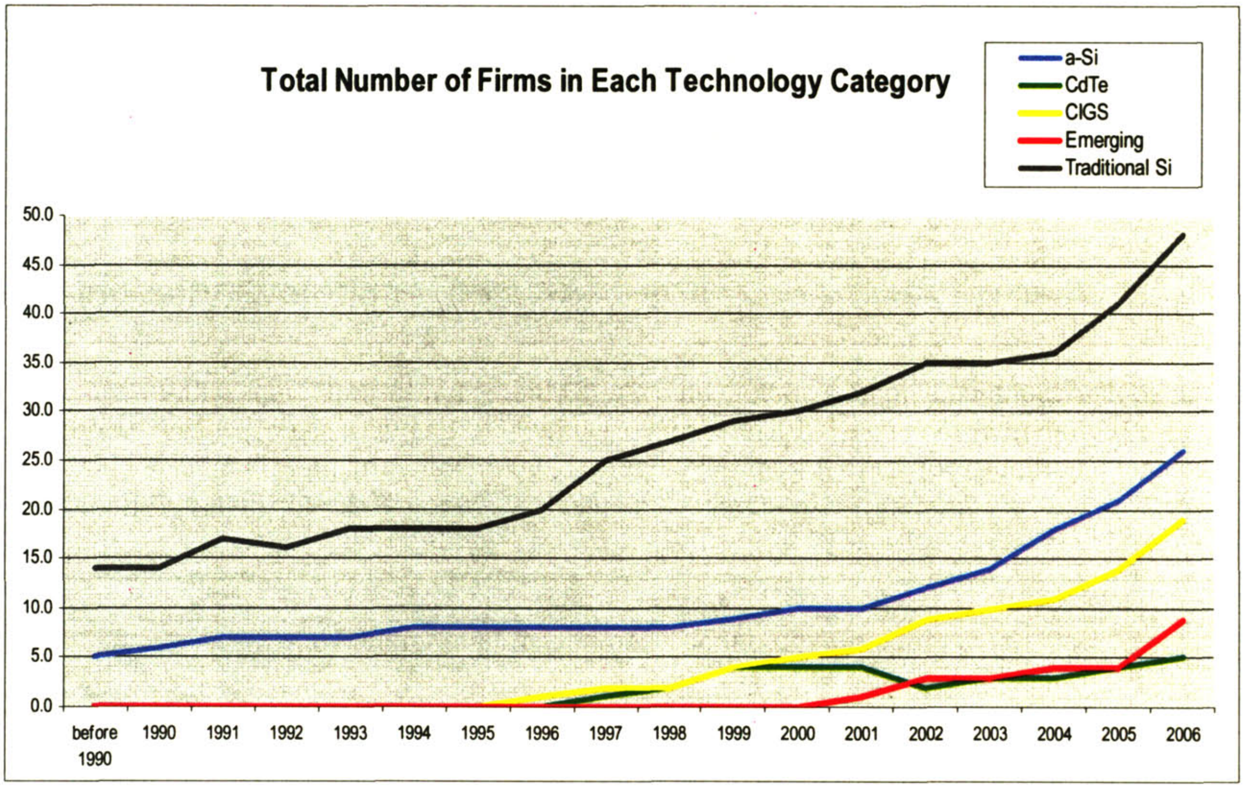

Figure 7-5 – Industry evolution from 1990 to present

Up to 2004, the traditional PV industry exhibits the classic S-shaped diffusion curve. As that industry matured, the thin-film PV industry sub-segment began its growth phase. Everything seemed to go according to plan… until 2004. After 2004, all industry sub-segments exhibit an upsurge with many new players entering the industry to capitalize on the increased demand for solar power products. It remains to be seen if this upsurge is temporary or will have long-lasting effects on the industry.

We could hypothesize how the industry would have evolved if this recent surge in demand didn't happen. For example, CdTe technology may have fallen out of favor. Two firms actually exited the CdTe industry sub-segment in 2003 due to difficulties in manufacturing the product (BP Solar) and raising funds (Antec Solar). CIGS and the other emerging thin-film technologies may have taken longer to incubate not ready yet to compete with amorphous silicon as the next challenger to traditional PV technology. Amorphous-Si would have continued to grow, albeit at a slower pace, and perhaps even level off, a sign of a mature industry segment.

The question "Could thin-film PV displace traditional PV?" often comes up when looking at all this. To answer this question it helps to analyze the situation using Clay Christensen's disruptive technology framework[25]. When it comes to new, innovative technologies, Christensen distinguishes between two types of technologies: *sustaining* and *disruptive* technologies.

Sustaining technologies improve along the same lines of performance that mainstream customers have traditionally valued. In the case of solar PV, that could be: lower cost (ie. using less silicon material) and higher efficiency. Examples of sustaining technologies in the solar PV industry are the ribbon technology pioneered by Evergreen Solar and the multi-crystalline technology.

Disruptive technologies, on the other hand, tend to have worse product performance (at least in the near term), but they bring a whole new value proposition that has not been available before in the market. Disruptive technologies almost always have lower performance and lower cost, and are typically simpler and more convenient to use.

Using this framework we can see how thin-film PV could be a disruptive technology to traditional poly-silicon PV. First, thin-film PV is less efficient, but costs less. It does well in emerging markets where customers value small form-factors and lower price. But, most importantly, thin-film PV brings a whole new value proposition with its flexible substrates and lightweight properties. Currently these properties make it ideal of a new range of off-grid and special applications (ie. new markets), but these same properties along with installation convenience (as in the case of BIPV products) could be very useful in the same markets where traditional PV dominates. Thus, thin-film PV technology has all the characteristics of a disruptive technology.

Is thin-film then a disruptive technology? The answer is: not yet. The market for solar power products is growing rapidly and thin-film PV has not significantly displaced or threatened traditional PV's hold on the market. So far, thin-film PV has helped expand the market and filled in those applications where traditional PV could not meet the demand due to its world-wide silicon shortage. Only when the growth of the solar power market levels off (or perhaps the market contracts) will thin-film will begin to show its disruptive potential to traditional PV.

8 Conclusions & Recommendations

The research presented here was sparked by a personal interest in renewable energy and, in particular, solar energy. That research later gathered its focus on the thin-film solar photovoltaic industry when it became apparent that no one had done a thorough survey of this emerging and dynamic industry. The chance of creating a brand-new industry survey including the most up-to-date and comprehensive industry information provided a strong motivation to continue and finish this study.

The goal of this survey was to analyze the industry from a technical perspective rather than an economic perspective, looking at the patterns and trends in thin-film technology, industry and markets. Thus, in reaching our recommendations we rely less on economic analysis such as projected costs and prices and more on technical facts, survey data and statistical analysis. Although an economic analysis of projected costs and prices is an important element of any forecasting tool, we considered it to be outside the scope of this thesis because the data, when available, is often distorted by different interpretations and varying estimates.

The survey was structured as a side-by-side comparative analysis of the different thin-film technologies to understand their relative advantages and disadvantages. In doing so, our goal was to answer two of the questions we posed at the beginning of our study: "Which thin-film technology is better?" and "Which thin-film technology will dominate?" Furthermore, to understand their disruptive potential, we compared the thin-film PV technologies with traditional poly-silicon PV technology that currently dominates the solar power market. This helped us answer another important question that often comes up: "Will thin-film PV technology replace traditional PV technology?"

Among the thin-film technologies, CIGS technology stands out as the better technology because it exhibits high conversion efficiency and can be produced in large volumes using a roll-to-roll manufacturing process. However, CIGS technology is still in infancy with large volume production scheduled to begin in 2008. Only when large volume production commences will the CIGS technology be able to prove that it can dominate the thin-film market. Even then, CIGS could be limited by its reliance on indium, a rare-earth material that could cause a supply bottleneck.

Amorphous silicon technology, on the other hand, does not have any of these drawbacks. It is currently produced in large volumes in low-cost manufacturing centers such as China and does not suffer from a supply bottleneck because it relies on common silicon alloys as primary PV material. Amorphous silicon is the dominant thin-film technology at the moment, and, we believe, will remain the dominant thin-film technology as new industry players with deep experience in deposition technologies, such as Applied Materials and Oerlikon, are entering the market supporting an updated version of a-Si technology. If amorphous silicon technology can transition to roll-to-roll processing and demonstrate that it can effectively be deposited on very thin substrates, as PowerFilm Solar is currently doing, then this technology will have a clear path to grow and compete strongly with CIGS technology despite its lower conversion efficiency.

CdTe technology is neither the better nor the dominant thin-film technology despite the fact that its leading proponent, First Solar, is the largest thin-film manufacturer in the world at the moment. CdTe technology is supported by few industry players and may have even fallen out of favor if it wasn't for the recent upsurge in demand for solar power modules (CdTe is the only technology category where two industry player actually exited the industry, this at a time when the industry was still growing). This is not to say that CdTe is not a good technology. Clearly, it is economically viable and can be produced effectively in large volumes and at low cost, as demonstrated by First Solar (one should never under-estimate the value of getting up to scale quickly). But because of its lack of support and possible feedstock limitation, CdTe technology will remain a niche player in the solar industry with few companies manufacturing it for applications such as solar farms.

Firms contemplating entering this industry could follow these possible strategies:

1. enter the market in the CIGS sub-segment, a less-crowded field with future potential, lots of investor attention, but also much higher risks. This strategy is suited for new entrants in the solar industry (start-ups) and established players that want to re-focus on a new technology. Examples of companies adopting this strategy are Miasole, a Silicon Valley startup, and Shell Solar, who completely divested its interest in traditional PV to focus on CIGS through a joint venture with St. Gobain.

2. enter the market in the amorphous silicon sub-segment, a more crowded field, but a mature technology with less risk and better chance of finding partners and equipment. One should never under-estimate the value of having a strong manufacturing base and industry expertise. This strategy is well suited for established players who want to diversify, but not completely give up on traditional PV. As shown earlier, a number of established players such as Sharp, Q-Cells and Schott Solar have adopted this strategy.

3. enter the market with a new technology (or a new combination of existing technologies) that differentiates it from the other competitors and allows it to dominate a niche market. Among these less-known, but promising technologies and combinations are:

    a. Dye-sensitized solar cells (DSC)
    b. Crystalline-silicon on glass (CSG)
    c. Amorphous-silicon on super-thin, plastic substrates

The final question "Will thin-film PV technology replace traditional PV technology?", is more difficult to answer. This thesis presented the case that thin-film PV technology as a whole could be disruptive to traditional PV technology. It exhibits the characteristics of a disruptive technology: lower cost, lower performance, smaller form-factors and less significant applications. Thin-film PV is currently expanding the solar market by offering solutions in areas where traditional PV does not compete very strongly (or is limited by its inability to meet the demand): small & portable applications, developing world applications, BIPV and large solar farms. Thin-film also creates new markets using novel value propositions such as flexibility, customization and lightweight.

As industrial economies move away from centralized energy production towards smaller, distributed energy production, thin-film PV technology is well positioned to take advantage of a paradigm shift in the overall energy infrastructure. In the battle between centralized and distributed energy generation models, solar PV as a whole could be a formidable disruptive force similar to the way distributed, personal computing was to monolithic, centralized mainframes.

Thin-film PV will join forces with traditional PV and other forms of renewable energy generation to displace the centralized energy model with a distributed, renewable energy model. This larger battle will minimize the internal disruptive forces within the PV industry. Because of this, thin-film PV technology may never completely replace traditional solar PV technology. Instead it will provide a viable alternative to traditional technologies promoting non-renewable fossil fuel energy sources.

9 Appendix

Research Methodology

The research approach included an extensive interview program of all major firms in the thin-film solar industry. Data collected during these interviews was entered into a database allowing us to perform statistical analysis, side-by-side comparison and graphical presentations. A total of 22 firms ranging from industry leaders to small start-ups, have responded to our survey. Representatives from a number of larger firms were interviewed directly over the phone and asked to assist us with questions and clarifications. A number of firms were surveyed during plant visits and meetings with top-level management.

The information extracted from the interview data was augmented with an in-depth research of technical literature, web sites, trade journals and discussions with industry veterans. Because of the fast-growing nature of this industry, a lot of the research relied on information found on company websites, in press releases and recent industry articles. Our database was updated almost on a daily basis with new information about companies entering this dynamic industry.

We chose to not publish the names of the firms and individuals who contributed to our survey to protect the confidentiality of the information that they provided. We greatly appreciate their contribution and support.

I would like to thank Travis Bradford and Paul Maycock, current and past editors of PV News, the industry's oldest newsletter. Their knowledge, expressed verbally and through PV News archives, was an important source of information for this survey. I would also like to thank Mary Tripsas, my thesis advisor, who provided much needed direction for the industry and technology strategy analysis as well as constant support and encouragement.

Sample Survey Form

PV Industry: Thin Film Survey 2006

Company Name

COMPANY INFORMATION

Region		Country		State	

Contact Name	
Phone	
Email	
Address	
Website	

Ownership Structure		Venture Capital Funded (Y/N)	
Major Investor/Partner/Parent			

Target Applications	
Product Differentiators	

Business Model
(mark with "X' all appropriate)

Cell	Module	Process Equipment	Whole System

Market Segments
(mark with "X' all appropriate)

Grid-Tied Residential	Grid-Tied Commercial	Grid-Tied Utility	Govt. & Military	Off-Grid Applications	Space Applications

TECHNOLOGY INFORMATION

Thin-Film Technology Type	
Year Company Entered the Market	
Production Cell Efficiency (%)	
Substrate Type	
Manufacturing Method	
Product Warranty (years)	
New Plant CapEx ($/Wp-DC)	

CAPACITY AND PRODUCTION

Please enter the manufacturing production and capacity (in MW-DC) in the following table:

	2000	2001	2002	2003	2004	2005	2006	2007E	2008E	2009E	2010E
Production (MW)											
Manufacturing Capacity (MW)											

2006 DATA ITEMS

Please enter 2006 results in the following fields:

Geographical Markets (%)

Germany	Europe	US	Japan	Asia	ROW

Sales Channels (%)

End-User	Distributor	Integrator	Other Manuf.

Year-end Number of Employees	

2006 Sales Revenue ($million)	
2006 Manuf. Cost ($/Wp-DC)	
Average Selling Price ($/Wp-DC)	
Gross Margin (%)	

Other Information

Figure 9-1 – Sample survey form used to collect industry data

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