Global overview of current and future manufacturing capacities for crystalline solar cells and thin-film PV panels

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This paper first appeared in the third print edition of *Photovoltaics International* journal.

ABSTRACT

This review is based on primary research of global solar cell and thin-film manufacturing companies that are currently manufacturing, expanding manufacturing, building facilities for manufacturing or progressing towards establishment of manufacturing facilities. The study looks at historical, present and future name-plate capacities for the global continental regions and also for specific countries with large existing capacity or rapid capacity growth and is based on approximately 600 companies and manufacturing facilities throughout the world. It addresses primary manufacturing technologies including monocrystalline silicon (sc-Si) & multicrystalline silicon (mc-Si) wafer based solar cells, thin-film silicon panels (amorphous, amorphous/micro-crystalline, crystalline on glass), cadmium telluride (CdTe), copper indium (gallium) sulphide/selenide (CIS/CIGS/CIGSe/CIGSSe), dye sensitized solar cells (DSSC/DSC) and other organic solar cells/photovoltaics (OPV). The study acknowledges that there are manufacturers of multi-junction and concentrator solar cell and modules (Fresnell lenses or mirror reflectors) but does not include them in the review.

Introduction

The review details how the global manufacturing capacity has developed and grown from approximately 2GWp/year in 2005 up to almost 13GWp/year in 2008, and from the present figure of 24GWp/year to at least 50GWp/year in 2012 (based on current announcements, without further projection or extrapolation). The figures are taken from a continually updated database, begun in 2003, which collates data based on existing facilities and realistic future figures based on company announcements for development and growth. This paper discusses both the further growth projected past 2012 and the relevant considerations for raw materials availability both up and downstream of cell/thin-film production. The apparently high annual capacity values are more indicative of actual industry capacity growth and under-utilization due to materials shortages and other limiting factors, rather than potentially erroneous over-calculations, which may result from lack of either differentiation between cell and module manufacturing or from companies that utilize multiple marketing methods and strategies. Adjustments in the data to consider the current economic climate would provide an increase in values rather than a reduction, and so have not been performed. Other studies by well-established PV industry analysts and commentators have similarly indicated there will be sufficient future capacity to forecast 25GWp of cell/modules production in 2010 [1].

Industry capacity is increasingly beginning to exhibit growth properties similar to the semiconductor micro-

	2005	2006	2007	2008	2009	2010	2011	2012	Future	No. of Fabs
Capacity MWp/Year (Ex. Conc.)	2213	4534	7169	13009	24445	41173	49611	59115	98544	541

Table 1. Global annual cumulative production capacities MWp/Year (excluding concentrator cells).

electronics industry where Moore's Law postulates a doubling of device performance capability approximately every 18 months. The PV industry demonstrates a similar trend with respect to global cumulative power generation capability, megawatts peak (MWp) or, in recent years, gigawatts peak (GWp). This phenomenal capacity growth is not only produced through manufacturing facilities' expansion and the creation of additional factories, but also through the combined effects of both technological improvements to increase cell conversion efficiencies and greater materials and process equipment utilizations such as thinner wafers and faster or larger format processing. Wafer-based crystalline silicon solar-photovoltaic technologies have been easiest to scale in recent years production capacity-wise; however, along with the accompanying famine of low-cost polysilicon, the utilization of much of the new capacity has been essentially limited to those companies holding supply contracts with the original polysilicon producers. The industry has reacted accordingly to these materials supply bottlenecks and almost all of the existing polysilicon producers have implemented production capacity expansion programmes. There have also been announcements of polysilicon plant developments from a multitude of chemical companies, as well as from others such as producers of cheaper alternative solar grade silicon (SoG-Si).

> "Thin-film technologies are increasingly providing a greater portion of production capacity; soon to approach and eventually exceed one-third of all installed manufacturing capacity in the near future."

Traditionally, the vast majority of manufacturing capacity has been provided by the wafer-based crystalline silicon solar technologies, but this trend is changing. Thin-film technologies are increasingly providing a greater portion of production capacity; soon to approach and eventually exceed one-third of all installed manufacturing capacity in the near future. This proportion will likely increase even more dramatically once the organic-photovoltaic (OPV) technologies become viable and production-ready, almost certainly employing high-volume roll-to-roll manufacturing technologies, as is the case with Konarka. This principle also applies to other materials technologies utilizing other high-volume film-forming techniques such as printing, spray, roller and slot coating.

In the last year or two, there has been a dramatic increase in the number of announcements for new facilities and production capacity for thin-film silicon photovoltaic technologies. Amorphous silicon and tandem cell structures together with microcrystalline silicon predominate due to relatively easy availability of production systems and increase of raw materials supplies, among other factors. Within the next three to five years, thin-film silicon technologies will likely equate to approximately 25% of all solar-photovoltaic production capacity, evidenced by the fact these technologies currently exhibit the fastest capacity growth rate of any solar production technology. It is also noteworthy that an increasing number of equipment fabrication companies are offering either component parts or turnkey systems for thin-film silicon PV production.

Methodology

The review does not include capacity values for proposed expansion projects where there have not been announcements specifically detailing initial or long-term capacity (e.g. Q-Cells Mexico); however, details are included for established solar companies with planned major future capacity increases (e.g. Sharp). The study does not take in to account details or figures for concentrating photovoltaic (CPV) cells and modules, and hence figures for the number of companies, manufacturing facilities and annual manufacturing capacity for those technologies are additional to the figures provided here. Details for CPV manufacturers are published in the second edition of *Photovoltaics International* journal [2].

Each manufacturing facility at a distinct location is recorded, hence companies with multiple production lines in the same building or with production lines in multiple buildings on the same site are recorded as one location; similarly, a company with facilities in different locations on the same business park or facilities in different countries have them recorded separately.

There are several start-up companies that have failed to achieve manufacturing facilities status (e.g. CIS Solar Productions & API GmbH) and also some established manufacturing companies which have gone out of business either permanently or subsequently had the whole business acquired (e.g. Astropower to GE Energy). This study also takes into account that there have been mergers & acquisitions of successful companies (e.g. Ersol and Bosch); re-branding of a company when transitioning from the financing stages to becoming physical facilities (e.g. Next Solar to HelioSphera) and other name changes due to re-branding or other commercial considerations (e.g. EverQ to Sovello).

Capacity growth

The growth in global photovoltaic manufacturing capacity has thus far generally demonstrated a geometric level of growth and is set to continue similar expansion for at least several years to come. This sustained rate of industry expansion has in recent years been maintained by progressive growth in new markets (e.g. China, Germany

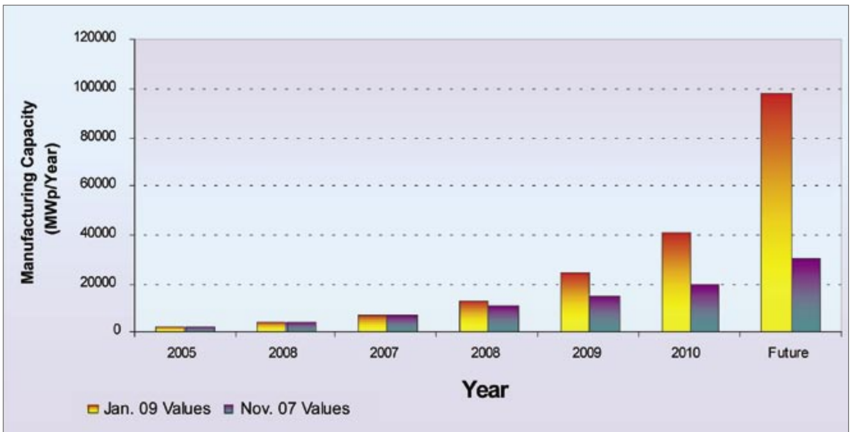

Figure 1. Global annual photovoltaic manufacturing capacities January 2009 vs. November 2007 (All technologies, excluding concentrator cells).

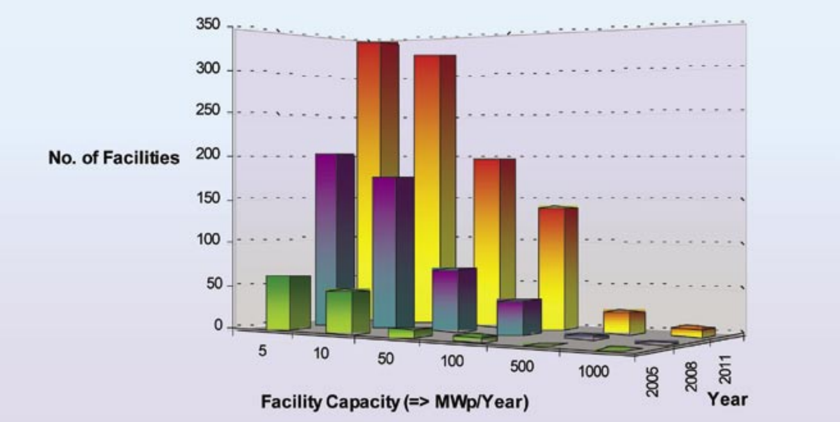

Figure 2. Number of production facilities vs. facility capacity (MWp/year) 2005 to 2011.

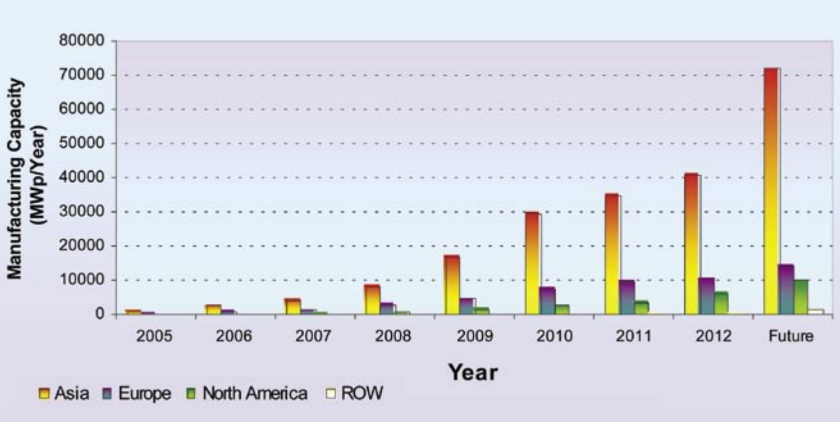

Figure 3. Annual global regional solar cell & thin-film PV manufacturing capacity.

and Taiwan) as others have at times had constraints limiting growth (e.g. Japan and USA). Experienced maturing companies are developing production capacity in more economically attractive areas of the world, from either a reduced cost of production perspective or via incentives supporting product installation and deployment (e.g. EPV Solar, First Solar and SunPower).

The historical figures for global production capacity, together with present and future values, are provided in Table 1. The figures detail the continued geometric growth of the industry globally, however what may be of greater interest is the rate of change of growth, which can be seen in Figure 1. Manufacturing capacity has increased dramatically within the last year, with figures indicating the industry capacity in 2010 will be double that expected from data compiled towards the end of 2007. Future (circa 2012-2015) capacity looks like being close to triple that expected previously at almost 100GWp/year, if not greater.

The growth of the photovoltaic industry global production capacity has seen the industry shift from comparatively small-scale manufacturing plants, with the vast majority of facilities being 10MWp/year or less, to a position where a large proportion have triple-figure manufacturing capacities, with several facilities planning on reaching at least 1GWp/year of production capacity, as detailed in Figure 2. It is relatively rare nowadays for a new production facility to have single-figure megawatt annual production capacity; those that are announced tend to be production development facilities for new technologies or pre-cursors to larger commercial production plants.

Asia

In recent years, Asia has been the leading photovoltaic manufacturing region of the world. This was primarily a result of early development of the solar industry in Japan being supported by national incentive programmes. However, in the last few years, the industry developed at a slower pace as those incentives were removed. Asia has maintained its status as the leading region by rapidly developing capacity, as detailed in Table 2 and presented in Figure 3. China, India and Taiwan are developing large capacities, principally as high-tech and lower-cost export-focused manufacturing nations as shown in Figure 4. These nations are set to become the forces that maintain Asia as the dominant manufacturing region in the future. Large levels of capacity are also being added in other nations such as Korea, Malaysia and the Philippines. The industry looks set to develop rapidly in Korea as a result of recently announced economic stimulation packages, coupled with climate change mitigation and renewable energy development programmes. Japan, once again, will also come to the fore due to similarly announced programmes and the reintroduction of a solar installation incentive scheme.

Europe

Europe has seen significant growth in recent years, driven initially by the German market and incentives, and more recently spurred on by expansion of similar renewable energy laws and incentives throughout Europe. The combination of further European nations introducing renewable energy deployment programmes and incentive schemes along with recent energy security issues will likely maintain the steady industry development within Europe.

Region	2005	2006	2007	2008	2009	2010	2011	2012	LT	No. of Fabs
Asia	1431	2957	4783	8796	17140	29889	35255	41154	71906	311
Australia & New Zealand	33	39	56	56	56	78	108	108	148	6
European Union	559	1182	1664	2999	4782	7631	9599	10459	14246	111
Europe Other	38	66	71	268	294	329	329	359	419	20
Middle East	19	19	49	51	54	181	366	366	1334	11
North America	131	269	545	839	2118	3024	3883	6597	10419	143
South America	2	2	2	2	2	42	42	42	42	3
Africa	0	0	0	0	0	0	30	30	30	1

Table 2. Global regional annual cumulative production capacities MWp/year (excluding concentrator cells).

Crystalline Silicon	2005	2006	2007	2008	2009	2010	2011	2012	Future	No. of Fabs
Monocrystalline Silicon	208	361	839	1578	2803	4189	4468	4468	6316	61
Multicrystalline Silicon	544	957	1170	1935	2925	4260	5990	7630	9675	30
Mono & Multicrystalline Silicon	1049	2483	3871	5506	9399	14646	16536	17391	22246	98
String Silicon	15	45	105	115	275	475	475	1450	1450	3
Silicon Spheres	0	20	20	32	32	32	32	32	32	3
Sliver Silicon	0	5	5	5	5	5	5	5	5	1
HIT-Si	105	165	165	260	340	650	1200	1200	4000	2
Unspecified / Unknown	117	223	278	920	2731	4087	4961	5836	12551	61
Total	2037	4258	6453	10351	18510	28344	33667	38012	56275	259

Table 3. Annual cumulative production capacities MWp/year for crystalline silicon technologies.

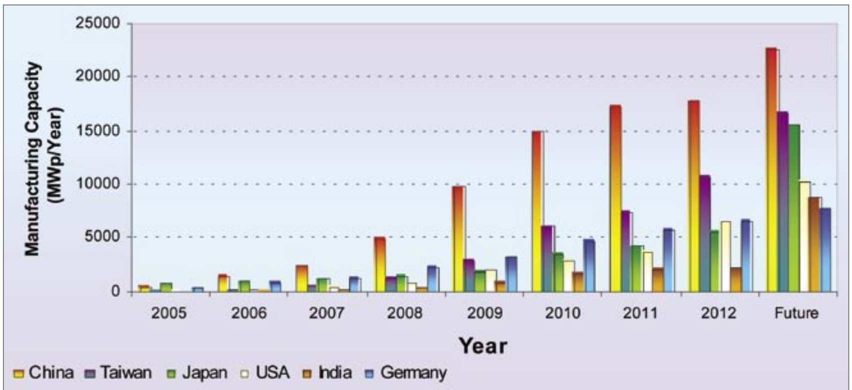

Figure 4. Selected nations annual solar cell & thin-film PV manufacturing capacities.

both introduced programmes to support and develop indigenous solar industries to provide products for installation in the high-insolation home markets. The other ROW nations will begin to develop and gradually increase manufacturing capacity and market share as grid-parity cost approaches and individual nations look to match energy security and climate change mitigation policies. The dynamics of global regional changes in the proportion of production capacity are presented in Figures 5 and 6, which indicate that the European proportion of manufacturing will diminish at the expense of the other global regions.

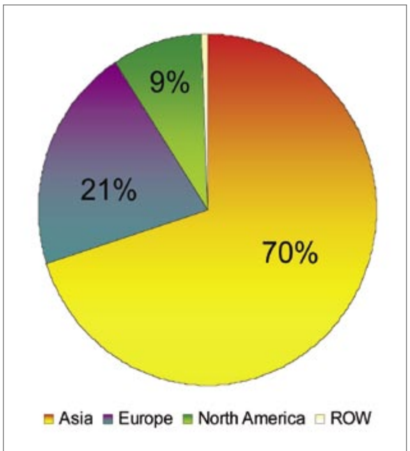

Figure 5. 2009 global regional capacity.

North America

The North American market is set to begin growing at a significant rate, following a period of relative dormancy in recent years, with the possibility of an extra growth impetus following the passing of the stimulus bill by U.S. President Barack Obama. Any significant policy change within the U.S. will likely have the effect of confirming the development of manufacturing capacity in Canada and Mexico.

Rest of the world

The rest of the world is showing significant levels of capacity developing in selected nations, specifically Australia and the United Arab Emirates. These nations have

Technology focus

The photovoltaic industry has been dominated by the various crystalline silicon-based solar cell technologies and continues a high rate of capacity development, as can be seen from the data in Table 3. Collectively, these technologies hold the majority of global capacity throughout the foreseeable future. Thin-film technologies, having developed capacity relatively slowly until now, are currently set to achieve up to 40% of all manufacturing capacity within a few years.

Thin-film photovoltaic technologies have progressed over the last few years from small-scale developmental technologies, representing about 5% of annual production capacities, to a current

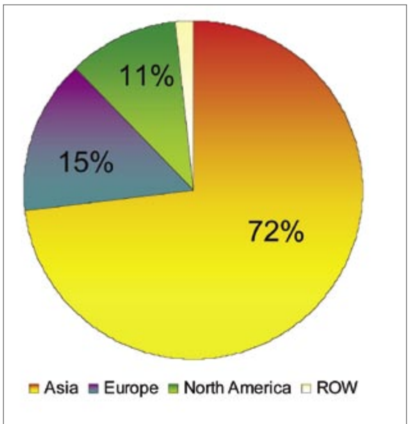

Figure 6. Future global regional capacity.

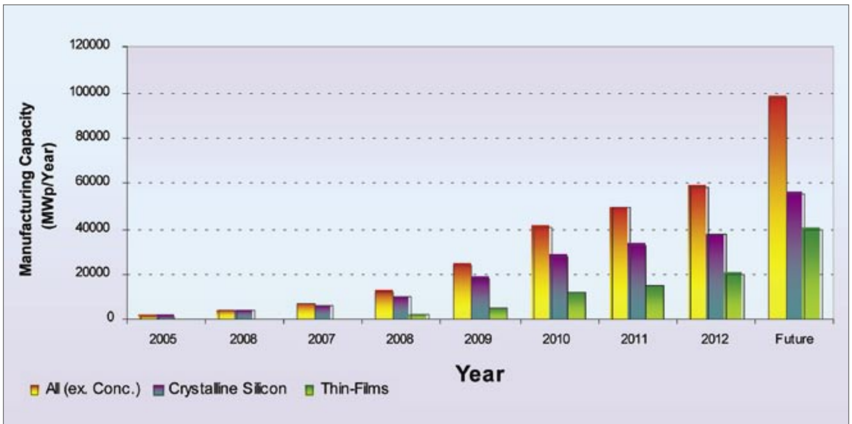

Figure 7. Annual global manufacturing capacity – All technologies, crystalline silicon & thin-films.

Thin-Film	2005	2006	2007	2008	2009	2010	2011	2012	Future	No. of Fabs
Amorphous/Microcrystalline Silicon	142	196	389	1670	4142	9218	11630	14380	30626	133
Amorphous Silicon & CIGS	0	0	0	6	6	25	25	25	100	2
Microcrystalline Silicon on Glass	0	12	15	20	30	130	130	130	130	3
Printed Silicon	0	0	0	0	10	10	10	10	10	1
CIS/CIGS/CIGSe/CIGSSe	6	15	179	378	781	1753	1963	3348	6773	46
Cadmium Telluride	28	51	118	265	615	1235	1517	1517	1517	15
Dye Sensitised Solar Cell	0	1	6	10	39	46	61	61	281	21
Organic Other	1	1	1	1	4	4	4	1003	1003	7
Unspecified / Unknown	0	0	0	0	30	155	531	555	1705	18
Total	176	274	706	2348	5626	12419	15338	20473	40439	221

Table 4. Annual cumulative production capacities MWp/year for thin-film technologies.

figure of around 20% of all capacity. If capacity continues to expand, at similar rates of growth, it will soon be heading towards 50% of all capacity, in both absolute terms & market share and thus reaching parity with the crystalline silicon technologies. Although the manufacturers of the CIS/CIGS and CdTe technologies have been exalted by the media for their rapid commercial development and progress, in reality it is the thin-film silicon PV technologies that are rapidly becoming the market segment leader. Thin film looks like becoming far more dominant from a capacity perspective, as illustrated in Table 4 and represented in Figure 8. The disproportionate growth of thin-film silicon PV is almost certainly a result of the number of companies offering key manufacturing systems and components, often based on standard platforms developed for FPD manufacturers.

Market drivers

There are numerous factors that positively influence the growth of the photovoltaic industry of which installation incentives in the form of grants, tax breaks or feed-in-tariffs are arguably most prominent. These types of incentives – some more generous than others – have in recent years spread throughout Europe and many countries, states and provinces elsewhere throughout the world. Many of the feed-in-tariffs based on the German EEG model have been shown to substantially increase the deployment of installed PV systems whilst assisting development of local PV manufacturing and installation industries.

In some areas of the world, the growth of the PV industries has enabled some technologies to reach grid-parity status. Compared to more traditional forms of power generation, this point becomes more evident when it is taken into account that in many instances grid parity for solar relates to retail power price, rather than wholesale, when the installation is located at the power user's location. There are also some utility-scale solar farm projects that have recently been claimed to have reached grid parity operation. The prevalence of grid parity projects will certainly increase as improvements in the various technologies develop and economies of scale manufacturing are achieved. Once grid parity becomes commonplace, the industry should become self-sustaining and should begin to provide PV systems with power generating capacity to replace existing base load generating capacity that is no longer viable from either an economic or an environmental perspective.

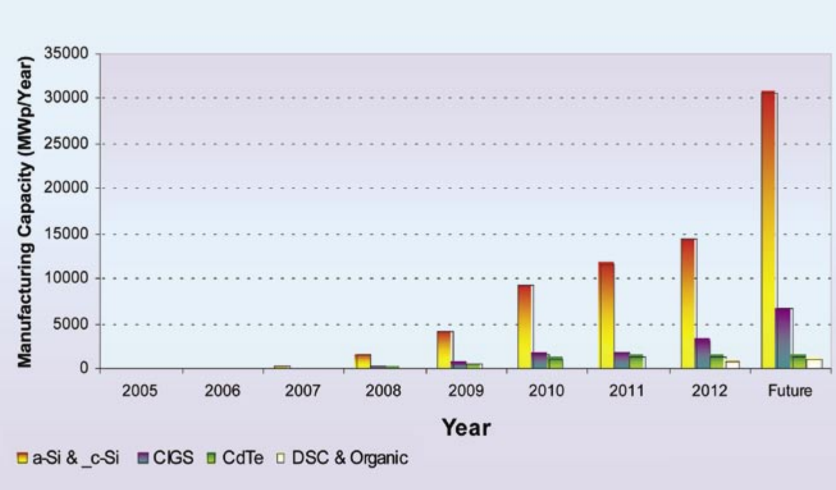

Figure 8. Annual global manufacturing capacity for thin-film technologies.

The creation of relatively large numbers of jobs in a comparatively short period of time is a potential boon for industry development – the EPIA recently estimated that the PV industry creates approximately fifty jobs per megawatt of production capacity [3]. This projection relates to cell and module manufacturing, research and development, and system integration and installation. The estimate does not include the additional jobs that would also be created in the raw materials manufacturing and supply industries. In these economically difficult times, it will likely be viewed positively that an industry exists that can provide rapid job creation coupled with increased renewable energy generating capacity deployment, utilizing a minimal carbon footprint technology.

PV technology is ideally suited to provide much of the power generating capacity that will be required to support other new technologies such as plug-in electric/hybrid vehicles or for hydrogen generation for use in both fuel cell and direct hydrogen combustion vehicles. It is also possible that PV technology could play a large part in powering the emerging inductive power supply/battery charging technologies. Finally, the versatility and variety of PV technologies and means of utilization and deployment provide a far greater level of opportunities compared to other alternative/renewable energy technologies.

Market limiters: materials availability

The PV industry's future rapid growth will likely have the ability to expand at an even greater rate with regard to nameplate production capacity as provided by factory buildings and production systems equipment. The actual use of those facilities will periodically become restricted due to other limiting factors.

Probably the most understood limiting factor within the solar industry thus far has been the availability of raw materials, specifically silicon of sufficient purity for use in solar cells, which was inherited from the microelectronics industry.

However, as the solar industry grew, its demand for raw materials exceeded supply, and, as the value added during microchip manufacture is considerably higher than that of solar cells, the microelectronics market could significantly out-price the solar industry for acquisition of these materials.

To alleviate this restriction in materials availability, the traditional polysilicon manufacturers announced large-scale production expansion plans. Approximately 200 additional refined silicon production projects have been announced throughout the world, which, if the majority come to fruition, could provide approximately one million metric tons of silicon suitable for solar cells. It should be noted that for 2008, the U.S. Geological Survey (USGS) mineral summaries estimate global production of metallurgical-grade silicon to reach about 5.7 million metric tons [4], of which approximately 80% is used directly for ferrosilicon manufacture and the remaining 20% for all other silicon-based applications, including manufacture of polysilicon and silane gases. Thus, it is conceivable that to maintain the use of solar energy in the future, there will be a requirement for additional metallurgical silicon production.

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The dramatic growth of thin-film photovoltaic production capacity presents further problems that need to be considered if this capacity is to be realised to its full potential. In addition to this availability of silane gases, which will see stellar demand, growth from the solar industry also has to provide significant quantities for the FPD industry. The CIS/CIGS/CIGSe/CIGSSe thin-film technologies are all reliant upon indium, requiring approximately 50 metric tons per gigawatt, and also gallium to a lesser extent. These minor metals are currently produced as by-products of base metal refining, with USGS mineral summaries estimating annual production to be comparatively low. Production for 2008 reached 568 metric tons for refined indium [5] and 135 metric tones for gallium [6], including both primary production and scrap refining. These metals being by-products of high volume primary base metals refining will most likely not see them becoming primary refined metals themselves, due to fundamental supply and demand characteristics. Fortunately, global reserves of indium are at present relatively plentiful, being reported as approximately 16,000 metric tons in 2007 [7] (more recent analysis has questioned the accuracy of this data [5]).

The vast majority of the current annual production of indium is utilized for the production of indium tin oxide (ITO) used primarily for TCOs in the FPD industry and also for joining materials (solders) and electronic components. It is also to some extent still utilized in the thin-film PV industry as the TCO front contact of glass superstrate modules. The cumulative production capacity for the CIS/CIGS type thin-film technologies may shortly begin to expand beyond the cost-availability constraints for materials supply for technologies and applications reliant upon unit cost per watt competitiveness. It is conceivable that in the event the FPD industry switches the preferred TCO technologies away from ITO to another suitable material or technology, then the lifespan of cost competitiveness of CIS/CIGS-based photovoltaic technologies would be significantly increased due to the more freely available supply of indium.

A consideration that currently affects both crystalline silicon and thin-film technologies is the availability of low-iron glass at reasonable cost. Although raw materials supply is not a significant factor, the cost and logistics involved in developing production facilities for this type of glass do influence development plans. Nevertheless, as the PV industry grows and ordinarily manufactures modules that provide power at or below grid parity cost, then it is conceivable that lower specification modules may be produced that use ordinary soda-lime float glass rather than high optical clarity glasses.

Construction materials such as those used for module lamination (EVA/PVB) and backing sheets will also need to be provided in significant volumes as the industry expands. Other items such as cables and connectors along with other systems components will also need to be made sufficiently available; however, many of these items are considered as retooling or alternate use applications of existing products and technologies.

The global economic slowdown and recession may have an effect on the availability of some components and materials or result in extended construction times and delays, which will likely be exasperated as companies choose to either postpone or cancel planned projects or even be forced to close businesses due to financial difficulties.

Conclusion

Finally, on a more positive note, there are indications that generally the PV industry as a whole will be actively supported as part of broader renewable energy strategies in efforts towards lifting economic activity in various countries with the aim of either preventing or alleviating recession. Hence, the rate of growth for solar cell and thin-film PV manufacturing capacity may experience a period of uncertainty, but this will likely be relatively brief, returning quickly to the Moore's law-style growth levels.

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